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Back on track: remediating developmental dyslexia with a home-based multi-component program

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Abstract
Developmental dyslexia (DD) is associated with multiple cognitive deficits. This study examined whether digital training of specific cognitive components is feasible and effective, whether parental involvement increases training intensity, and whether a multi-component intervention yields specific and cumulative benefits for reading fluency, spelling, and reading comprehension. We developed a multi-component digital intervention targeting visual-attentional (VA), auditory-phonological (AP), and cross-modal processes. In a pre-registered multiple single-case (within-subject) intervention study (ClinicalTrials.gov: NCT04028310), 144 children with DD aged 8 to 13 years participated. The first two training components (VA vs. AP) were counterbalanced across participants. Each training phase lasted 2 months, with home-based practice 5 days per week for 15 min per session under parental supervision. Before and after the digital intervention phases, children received conventional remediation once per week for 2 months, serving as a within-subject baseline. Training effects were component-specific: VA training led to greater improvements in visual-attentional skills than AP training, whereas AP training yielded greater gains in phoneme awareness than VA training. Across the full three-stage program, cumulative improvements were observed in reading fluency, spelling, and reading comprehension that exceeded gains during conventional remediation alone. Starting with VA training resulted in larger reading fluency gains than starting with AP training. These findings provide a proof of concept that a scalable, home-based, multi-component digital intervention can induce specific cognitive improvements and cumulative gains in reading and spelling skills in children with DD, while remaining feasible for large-scale implementation.

Keywords Dyslexia · Intervention · Attention · Phonology · Auditory · Training · GraphoGame

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Introduction

Developmental dyslexia (DD) is a severe and long-lasting neurodevelopmental disorder that results in difficulty acquiring fluent and automatic reading skills despite normal intelligence and appropriate socio-educational opportunities for learning-to-read and in the absence of any neurological, psychiatric or sensory anomalies (Carroll et al., 2025). The detrimental effects of DD on academic and professional success and personal well-being are well documented (Esser et al., 2002; McGee et al., 2002), thus making its remediation of tremendous societal importance. In many countries, dyslexia remediation is performed by speech-and-language therapists in weekly sessions with fairly limited home training.

Multifactorial nature of developmental dyslexia

Although impaired phonological processing has been identified as one of the main pathways that lead to dyslexia (Snowling & Melby-Lervåg, 2016), many studies converge to suggest that the causes of dyslexia are multifactorial (Carroll et al., 2025; Pammer & Vidyasagar, 2005; Peterson & Pennington, 2015; Ziegler et al., 2019). Three types of underlying cognitive deficits have been described. First, there is strong evidence that some of the phonological deficits result from lower-level deficits in auditory processing (Goswami, 2011; Serniclaes et al., 2015; Tallal, 1980) and could lead to impairments in identifying, storing, retrieving or manipulating syllables and phonemes, which is crucial for the initial stages of learning-to-read (Ziegler et al., 2014).

Second, there is additional evidence that visual-attentional deficits are associated with DD (for review, see Valdois, 2022). For some dyslexic readers, visual-attentional processing deficits could cause deficits in letter identification, letter position coding, the processing of letter strings in parallel, parafoveal preview and the programming of eye movements, all of which are necessary ingredients for developing automatic word recognition and reading skills.

Finally, there is evidence that dyslexic readers have specific deficits with cross-modal integration (Blomert & Froyen, 2010) of letters and speech sounds (Blau et al., 2009; Froyen et al., 2011). Crossmodal (or audiovisual) integration refers to the ability to automatically combine visual letters and their corresponding speech sounds into a single functional unit during reading. In typical reading development, letters and sounds are not only associated but rapidly integrated into an automatized audiovisual object, allowing fluent decoding and reading. In dyslexia, this integration process is often impaired: although children may learn explicit letter–sound correspondences, the simultaneous and automatic binding of letters and sounds is slowed or inefficient (Blomert & Froyen, 2010). This deficit in crossmodal integration disrupts the establishment of stable links between orthographic and phonological representations, thereby limiting the automatization of word decoding and reading fluency (Blau et al., 2009). Training studies further indicate that interventions specifically targeting audiovisual integration can lead to improvements in reading accuracy and speed, particularly when combined with phonological instruction (e.g., Kujala et al., 2001; Fraga González et al., 2015; Lassault et al., 2022). Such deficits in cross-modal integration would have tremendous consequences on learning the cross-modal mapping between visual and spoken units at various grain sizes (Ziegler & Goswami, 2005).

Designing a multi-component intervention program for dyslexia

Given the multifactorial nature of dyslexia described above, an efficient intervention should not only target reading and spelling skills but also their underlying cognitive deficits that constrain their development (Menghini et al., 2010; Pasqualotto & Venuti, 2020; Ramus, 2003; Saksida et al., 2016; White et al., 2006; Ziegler et al., 2008; Zoubrinetzky et al., 2014). To date, however, most intervention programs have focused either on training reading processes directly—such as grapho-phonological or orthographic skills—or on remediating isolated underlying cognitive deficits (e.g., auditory-phonological, visual-attentional, or audiovisual processing), with relatively few approaches combining both levels within the same intervention framework (for a meta-analysis, see Galuschka et al., 2014). Moreover, existing combined approaches typically target only one cognitive domain alongside reading instruction, and therefore do not fully address the heterogeneity of cognitive profiles observed in dyslexia.

Building on this literature, the main objective of the present study was to develop and evaluate a multi-component remediation program that simultaneously targets auditory-phonological, visual-attentional and cross-modal processes, in addition to reading and spelling. Importantly, we aimed to maximize ecological validity by designing an intervention that could be implemented in everyday clinical practice, relying primarily on digital applications and requiring only minimal weekly supervision by a speech-and-language therapist.

To treat the underlying cognitive deficits, we selected remediation programs that had already shown positive effects on reading. First, we chose three auditory-phonological trainings that targeted phoneme categorization (Zoubrinetzky et al., 2019), rapid automatized naming (Pecini et al., 2019) and phonological short-term memory (Luo et al., 2013; Yang et al., 2017). Second, we used a training program that focused on improving visual-attentional span (i.e., the number of letters processed simultaneously during an eye fixation) and visual attention for global and local levels of analysis (Franceschini et al., 2017; Zoubrinetzky et al., 2019). Third, we used the French version of GraphoGame (Lassault et al., 2022), which is a cross-modal (i.e., audio-visual) training that aims at automatizing the mapping between orthography and phonology at various grain sizes, such as letters, graphemes, syllables and whole words. This version of GraphoGame produced positive effects on phoneme awareness, orthographic memory, and reading fluency (Lassault et al., 2022). We will refer to this intervention as orthography-to-phonology association and automatization training (OtP).

Furthermore, it has been suggested that remediation programs that combine remediating both underlying cognitive deficits and reading processes may be more effective than programs that intervene only at the level of underlying cognitive deficits (for a meta-analysis, see Galuschka et al., 2014). We therefore added reading-related activities with the parents to each digital intervention. In the Auditory-Phonological (AP) intervention, we included fusion and segmentation exercises. In the Visuo-Attentional intervention (VA), we included orthographic memory training. Finally, in the Orthography-to-Phonology (OtP) intervention, we included a reading fluency training.

The present study

The primary goal of this study was to develop and test an innovative multi-componential remediation program with high ecological and clinical validity that included the three types of interventions described above: auditory-phonological (AP), visual-attentional (VA), orthography-to-phonology (OtP). Our first objective was to provide a proof of concept, namely to demonstrate that an intensive (i.e., daily) computer-based remediation program for dyslexic readers can be delivered at home by caretakers while being supervised by speech-and-language therapists during weekly sessions, with minimal intervention from researchers. The second objective was to test the specificity of the VA and AP trainings, such that VA training would improve visual-attentional skills (e.g., VA span) more than AP training, whereas AP training would improve auditory-phonological skills (e.g., phoneme awareness) more than VA training. The third objective was to assess whether each intervention phase produced significant gains in reading fluency relative to the pre-intervention baseline (i.e., conventional reading remediation). The fourth objective was to examine whether the order in which AP and VA interventions were delivered differentially affected reading outcomes. Finally, we examined the proportion of dyslexic readers who reached age-appropriate performance on a standardized reading fluency test following completion of the three-stage intervention.

Methods

The study protocol was pre-registered (ClinicalTrials.gov: NCT04028310) and published prior to data collection (Harrar-Eskinazi et al., 2022). The study received ethical approval from two independent ethics committees: the French National Committee for the Protection of Persons (CPP Île-de-France IV; IRB 00003835, reference 2019/50, ID-RCB 2019-A01453-54) and the Ethics Committee for Non-Interventional Research at Université Côte d'Azur (CERNI; reference 2019-7)). The study was conducted in accordance with the Declaration of Helsinki and the French law governing research involving human participants (Decree No. 2016−1537, November 16, 2016). Written informed consent was obtained from the parents of all participating children.

Participants

Details of participant inclusion, randomization, and flow through the study are reported in the online supplementary materials (Figure S1), using a CONSORT flow diagram (Schulz et al., 2010). Sample size calculations are provided in the published study protocol (Harrar-Eskinazi et al., 2022).

At study entry, 144 French-speaking children aged 8 to 13 years with developmental dyslexia (DD), diagnosed according to DSM-5 criteria, were recruited nationwide by 94 certified speech-language therapists. Parents completed a questionnaire covering medical history, development, school difficulties, and associated disorders.

All participants had normal nonverbal intelligence, age-appropriate oral language skills, normal hearing, and normal or corrected-to-normal vision. None had a history of neurological disease, brain injury, developmental language disorder, or attention disorder, and all attended school regularly. Prior to the start of the intervention program, participants were required to score at least 1.5 standard deviations below age norms on standardized reading and spelling assessments.

Table 1 presents participants' demographic characteristics and the psychometric properties of all study variables, including raw scores, standardized scores (z-scores), and distributional characteristics.

Design and procedure

The study contained three phases (see Fig. 1). Phase 1 consisted of an 8-week pre-intervention baseline during which all participants received conventional reading remediation (CRR) once per week for 30 min, delivered by a certified speech-and-language therapist (total: 4 h). CRR typically included reading and spelling exercises together with basic pho-

Table 1 Descriptive statistics of the population and the dependent variables measured at T1 along with different deficit estimates (i.e., deviance scores) in comparison to published norms

Variables	*n*	Mean	SD	Range	Skew	Kurtosis	Deficit
Age (months)	144	122.71	17.12	96–164	0.42	-0.69	N/A
Grade	144	4.76	1.44	3–8	0.52	-0.63	N/A
Mother's education level	144	3.21	1.6	1–6	-0.104	-1.35	N/A
Reading Fluency							
Meaningless text[1] (reading age)	144	92.49	11.10	78–138	1.27	1.95	-30.22[a]
Meaningless text[2] (words/min)	144	43.86	24.58	4-108	0.62	-0.43	-1.92[b]
Meaningful text[3] (words/min)	144	62.69	32.74	8-154	0.64	-0.13	-2.11[b]
Words[4] (words/min)	144	52.80	18.57	6–92	-0.13	-0.24	-1.61[b]
Reading Aloud[5]							
Regular words (efficiency)	132	9.52	3.01	4–18	0.51	-0.32	-2.24[b]
Irregular words (efficiency)	144	8.13	3.43	0–17	-0.06	-0.09	-2.60[b]
Pseudowords (efficiency)	139	5.21	1.94	1–13	0.75	0.83	-1.33[b]
Spelling[6]							
Number of errors	140	42.44	17.02	8–96	0.35	-0.16	-2.90[b]
Reading Comprehension[7]							
Accuracy	144	47.16	22.95	0–97	-0.06	-0.67	3.58[c]
Phonological Skills							
Syllable awareness[5] (efficiency)	137	235.79	121.45	53–707	1.15	1.71	-0.78[b]
Phoneme awareness[5] (efficiency)	143	139.39	87.11	0-531	1.00	2.20	-1.35[b]
RAN colors[5] (efficiency)	135	11.43	3.63	5–32	1.58	6.88	-1.36[b]
Phonological Span[5]	136	4.29	0.92	3–6	0.09	-0.92	-0.47[b]
Oral Language Skills							
Vocabulary[8] (accuracy)	144	148.71	11.43	118–167	-0.49	-1.19	0.00[b]
Oral comprehension[9] (accuracy)	142	5.10	2.96	0–15	0.52	0.09	0.30[b]
Visual-Attentional Skills							
Global letter span[10]	144	3.36	0.72	1.7–5.3	0.20	-0.52	-1.56[b]
Partial letter span[10]	142	4.07	0.67	2.4–5.9	-0.18	-0.08	-0.03[b]
Executive Functions							
Digit Span[8]	143	3.53	1.06	1–7	-0.32	-0.64	-1.31[b]
Visual-spatial span[11] (forward)	143	5.04	0.97	2–9	0.443	0.51	-0.25[b]

Test names:1 = L'Alouette; 2 = DeltaText; 3 = Mouette/Pingouin (Evaléo); 4 = Eval2M (Evaléo); 5 = Evalec; 6 = Chronosdictées; 7 = ORLEC L3; 8 = Evaléo; 9 = E.CO.S.SE; 10 = Evadys; 11 = Corsi Block

Superscripts in the Deficit column indicate the metric used to quantify deviation from normative performance: a = reading age lag (reading age minus chronological age, in months); b = z-score relative to age-based normative data; c = quartiles (1–4): 1 = best performance (≥75th percentile), 2 = average (50–74th), 3 = below average (25–49th), 4 = pathological range (<25th percentile)

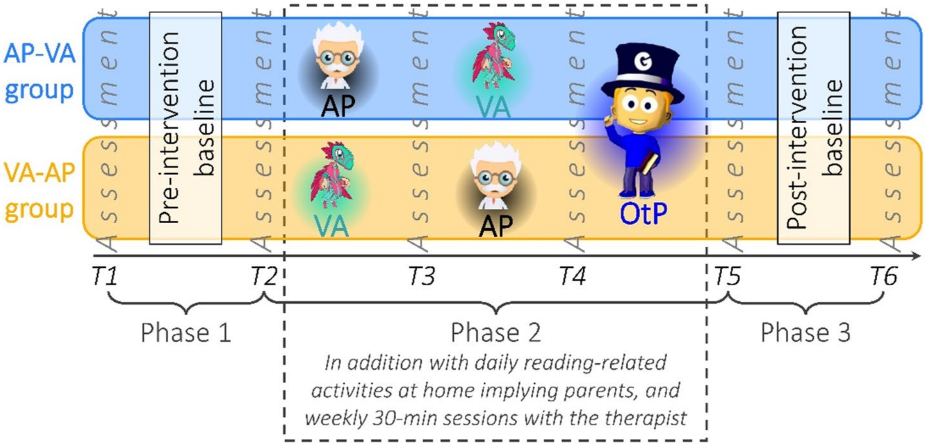

Fig. 1 Experimental design showing the three phases of the multi-component remediation program. AP: auditory-phonological intervention. VA: visual-attentional intervention. OtP: orthography-to-phonology association intervention. Each intervention lasted 8 weeks

nics training. No intensive home-based training was provided during this phase. For each participant, change in standardized test scores between T1 and T2 served as the pre-intervention baseline. At the end of Phase 1, participants were randomly assigned (non-stratified) to one of two groups determining the order of the first two intervention programs: Auditory-Phonological followed by Visual-Attentional (AP–VA) or Visual-Attentional followed by Auditory-Phonological (VA–AP).

Phase 2 corresponded to the intensive intervention phase. Participants completed three home-based digital intervention programs Auditory-Phonological (AP), Visual-Attentional (VA), and Orthography-to-Phonology (OtP)] administered 5 days per week for 15 min per day (total: 30 h). Each program lasted 8 weeks and was separated by a 15-day break. The order of the AP and VA programs was counterbalanced across groups (AP–VA: $n=49$; VA–AP: $n=47$; see Fig. 1), whereas the OtP program was administered last for all participants. Weekly sessions with the speech-and-language therapist were maintained throughout Phase 2 and were used to monitor progress, ensure correct implementation of the home training, and adapt the content to individual needs. Therapists received remote training from the principal investigator to support standardized implementation. A post-intervention assessment was conducted at the end of each program (T3, T4, and T5).

Phase 3 consisted of an 8-week post-intervention baseline identical to Phase 1, during which participants again received weekly CRR only (4 h total), with no intensive home training. The study concluded with a final assessment at T6.

Measures

A brief description of the standardized test battery is given below. Full details, including task characteristics and reliability indices, are reported in the online supplementary materials (Appendix S1).

Reading fluency

Reading fluency was assessed at T1, T2, T3, T4, T5, and T6 using four standardized reading-aloud tests. Two tests involved meaningless texts, *Alouette* (Lefavrais, 1967) and *DeltaText* (Bedoin, 2017), one contained two meaningful texts, *Mouette/Pingouin* (Launay et al., 2018), and one assessed reading of isolated words, *Eval2M* (Launay et al., 2018). Fluency was defined as the number of correctly read words per minute. *DeltaText* and *Mouette/Pingouin* include parallel forms, allowing control for test–retest effects. The *Alouette* test was additionally used to derive reading age.

Reading comprehension

Reading comprehension was assessed at T1, T2, and T5 using the *ORLEC L3* standardized reading comprehension test (Lobrot, 1967; Piérart & Grégoire, 2004). Participants completed 36 sentence-completion items by selecting one word among five alternatives within a 5-minute time limit.

Spelling

Spelling was assessed at T1, T2, and T5 using the standardized *Chronosdictées* test (Baneath et al., 2006), which consists of two dictated texts (6–8 sentences) with parallel forms adapted to grade level.

Phonological skills

Phonological awareness (syllable and phoneme deletion), rapid automatized naming (color naming), and phonological short-term memory (pseudoword repetition) were assessed using the *Evalec* battery (Sprenger-Charolles et al., 2018) at T1, T2, T3, and T5. For each task, reaction times and accuracy were combined into an efficiency score (accuracy/reaction time × 100).

Oral language skills

Oral language abilities were assessed at T1 only. Vocabulary and lexical knowledge was measured using the *Evaléo* Battery 6–15 (Launay et al., 2018), and oral comprehension was assessed using the *E.CO.S.SE* test (Lecocq, 1998).

Visual-attentional skills

Visual-attentional (VA) span was assessed at T1, T2, T3, and T5 using standardized tests from the *Evadys* battery (Valdois et al., 2017) based on global and partial report of briefly presented consonant strings. Visual-attentional focus (global and local interference) was assessed at the same time points using the *Sigl* battery (Bedoin & Medina, 2014).

Short term and working memory skills

Verbal short-term memory was assessed at T1, T2, and T5 using the digit span subtest of the *Evaléo* Battery 6–15. Visual–spatial short-term memory was assessed at the same time points using an adaptation of the *Corsi* block-tapping test (Fournier & Albaret, 2013).

Intervention program

An overview of the multi-component intervention program is provided below. Detailed descriptions of all intervention modules, including task structure and adaptive parameters, are available in the online supplementary materials (Appendix S2). The full program combined training of auditory-phonological (AP), visual-attentional (VA), and orthography-to-phonology (OtP) processes, together with reading and spelling training.

Auditory-phonological intervention program

The AP intervention targeted core phonological processes implicated in dyslexia. Categorical speech perception was trained using the *RapDys* software (Collet et al., 2017), which aims to shift perception from an allophonic to a phonemic mode. Phonological serial memory was trained using the *PhonopidoW* program (Medina, 2010). Rapid automatized naming was trained using a custom program inspired by *Run the RAN* (Pecini et al., 2019). Finally, phoneme blending and segmentation skills were trained using the *BlendSeg* program (Lang & Villuendas, 2011).

Visual-attentional intervention program

The VA intervention targeted both the capacity and control of visual-attentional processing. Visual-attentional span was trained using the *Maeva* software (Zoubrinetzky et al., 2019), an adaptive program designed to increase the number of visual elements processed simultaneously within a single fixation. Visual-attentional focus and flexibility were trained using the *Switchipido* software (Bedoin & Medina, 2013), which targets switching between global and local levels of visual processing. Orthographic memory was trained using the *ELOR* program, which focuses on the encoding, storage, and retrieval of orthographic representations through structured reading and writing activities.

Orthography-to-phonology intervention program

The OtP intervention targeted the mapping between written and spoken language. Orthography-phonology associations were trained using the French version of GraphoGame (Lassault et al., 2022; Richardson & Lyytinen, 2014), which provides audio–visual training across multiple grain sizes (letters, graphemes, syllables, and whole words). Reading fluency was further trained using a custom program involving repeated reading of short texts under varied reading conditions (Leloup et al., 2021).

Fidelity of implementation

Fidelity of implementation was monitored in terms of adherence (delivery of the planned content) and dosage (completion of the prescribed training). Parents recorded each home training session in standardized log sheets, documenting the type of training, session duration, and any technical difficulties encountered. These logs were reviewed weekly by the speech-and-language therapist to verify adherence and adjust the training plan when necessary. Overall, fidelity to the intervention protocol was considered satisfactory among families who completed the program, indicating that the prescribed training content and dosage were largely respected.

These fidelity measures were collected primarily to document adherence to the intervention protocol rather than to support formal dose–response analyses. Because the intervention was not designed to manipulate dosage experimentally and most participants followed a highly standardized training schedule, variability in exposure was relatively limited. Furthermore, differences in adherence likely reflect child- and family-level factors (e.g., motivation, parental support, engagement) that are themselves associated with outcomes, making causal interpretation difficult. Future randomized controlled trials will incorporate predefined fidelity metrics into the statistical analysis plan to allow a more rigorous examination of implementation effects.

Statistical analyses

An intention-to-treat (ITT) analysis was conducted including all 144 initially enrolled participants. Following the ITT principle, all available data were analyzed using likelihood-based mixed-effects models, which retain participants with incomplete data and provide unbiased parameter estimates under a Missing At Random (MAR) assumption.

To further assess the robustness of the findings with respect to missing data, we conducted sensitivity analyses using conservative best-case and worst-case assumptions. In the best-case scenario, mean progression scores were calculated for each intervention phase (separately by group, except for T1–T2). Missing values were then imputed by adding the corresponding mean phase-specific progression to the participant's score at the previous assessment time point. In the worst-case scenario, individual progression during the pre-intervention baseline (T1–T2) was calculated and assumed to reflect conventional reading remediation and maturation-related change. For participants who dropped out before T2, the mean T1–T2 progression was used. Missing values at subsequent time points were imputed by adding this baseline progression to the participant's score at the previous assessment time point.

Analyses were conducted with R version 4.3.0 (R Core Team, 2023). Mixed-effects models were computed using the lmer function from the lme4 package (Bates et al., 2015, 2023). As the analyses rely on factorial designs, main effects were assessed with the method of Estimated Marginal Means (Searle et al., 1980) using the joint tests function from the emmeans package (Lenth, 2023) while post-hoc comparisons were computed through the glht function of the multcomp package (Hothorn et al., 2023). This method estimates the marginal means predicted by a given model and proceeds with estimation of various types of contrasts with Tukey adjustments.

To select the model that best fitted the data, we computed several models containing different covariate structures. We then compared them to the simplest model and to each other through the anova function from the lme4 package (Bates et al., 2023). The best adapted model was determined by using the lowest Akaike information criterion (Matuschek et al., 2017).

All code necessary to reproduce the analyses, tables and figures is available at https://osf.io/e6xqf.

Results

Attrition

Cumulative attrition rates at each assessment time point are presented in Table 2. T1 corresponds to study entry. T2 reflects attrition occurring during the pre-intervention baseline period. T3–T5 reflect cumulative attrition across the successive stages of the multicomponent intervention. T5 corresponds to attrition at the end of the full intervention program, and T6 reflects attrition at the follow-up assessment. As shown in Table 2, overall attrition at the end of the intensive multicomponent intervention was 33.3%. However, there was already a substantial attrition of 11.6% after the pre-intervention baseline before the intensive intervention phases began. Attrition then increased by approximately 10% after the first intervention stage, 7% after the second stage, and 5% after the third stage. Thus, there was no evidence of stage-specific attrition peaks; if anything, dropout rates tended to decrease across successive intervention phases. This pattern argues against selective attrition driven by intervention-related difficulty or lack of response.

Information from the log sheets (see Fidelity of Implementation section) supported this interpretation. Participants who did not complete the protocol discontinued for reasons that were not related to weak or disappointing intervention effects. Instead, two primary reasons emerged. First, some caretakers reported difficulties in maintaining the required weekly sessions with speech-and-language therapists, a challenge that was exacerbated by the constraints of the COVID-19 pandemic. Second, as documented in the log sheets, several families discontinued participation due to persistent technical issues with the intervention software that could not be resolved and led to frustration and disengagement. These issues mainly involved incompatibilities between operating systems, outdated hardware, and instability when running multiple software packages on family-owned computers. Importantly, these problems were heterogeneous and intermittent rather than systematic, and they pri-

Table 2 Cumulative attrition rates (%) at each assessment time point

	Time points					
Group	T1	T2	T3	T4	T5	T6
AP-VA Group	0	6.9	20.8	26.4	31.9	33.3
VA-AP Group	0	16.2	22.7	30.6	34.7	37.5
All	0	11.6	21.8	28.5	33.3	35.4

T1 corresponds to study entry. T2 reflects attrition occurring during the pre-intervention baseline period. T3–T5 reflect cumulative attrition across the successive stages of the multicomponent intervention. T5 corresponds to attrition at the end of the full intervention program, and T6 reflects attrition at the follow-up assessment marily affected session feasibility rather than participants' engagement with the intervention itself.

Baseline differences between completers and non-completers

Because only 96 of the 144 initially enrolled participants completed the pre-intervention baseline and all stages of the intervention protocol, we examined whether baseline differences existed between participants who completed the protocol ("completers") and those who did not ("non-completers"). Across all baseline variables reported in Table 1, only mother's education level and oral comprehension differed significantly between the two groups. Specifically, non-completers had lower maternal education levels and poorer oral comprehension than completers (*t*s > 2.02, *p*s < 0.05). No other baseline measures—including age, grade level, reading fluency, spelling, phonological skills, and visual-attentional skills—showed reliable group differences.

These findings suggest that attrition may have been amplified in families with fewer educational resources and in children with weaker oral language skills, the two aspects being likely interrelated. Importantly, the absence of group differences across the large majority of baseline measures argues against systematic attrition driven by initial reading severity or general cognitive functioning.

Does the three-stage intervention program improve text reading fluency?

All results reported below are based on intention-to-treat (ITT) analyses including all 144 enrolled participants, using likelihood-based mixed-effects models as described in the Statistical Analyses section.

Improvement in text reading fluency was analyzed through performances (i.e., number of correctly read words per minute) obtained on three different standardized tests (*Mouette-Pingouin*, *Alouette* and *Delta-Text*). We examined the evolution of the reading scores over time for each group by computing a linear mixed-effects model containing two fixed effects (i.e., *group*: AP-VA and VA-AP; *time*: T1 to T6), their interaction, and two random effects (i.e., *subject* and *text*). We also added three covariates to control for interindividual differences in mean performance prior to training (mean pre-intervention performance (μ[T1, T2]), *age*, and *reading delay* (lag in reading age). Results are presented in Fig. 2.

As can be seen on Fig. 2, text reading fluency of both groups increased over time. The overall mixed-effects analysis revealed a significant main effect of *time* ($F(5,1887) = 113.35$, $p < .001$), no effect of *group* ($F(1,129) = 3.63$, $p = .059$), and a significant interaction between *group* and *time* ($F(5, 1908) = 3.76$, $p < .002$).

Planned post-hoc comparisons revealed that text reading fluency did not improve during the pre-intervention baseline (T1–T2) or during the follow-up period after the intervention had ended (T5–T6), indicating the absence of maturation-related gains during periods without intensive training (both *p*s > 0.45). In contrast, robust and statistically significant improvements were observed during each active intervention phase (T2–T3, T3–T4, T4–T5), all *p*s < 0.001. Full post-hoc statistics, including model estimates and test statistics, are reported in Supplementary Table S1. Together, these results indicate that gains in reading fluency were temporally aligned with the intervention phases rather than with the mere passage of time.

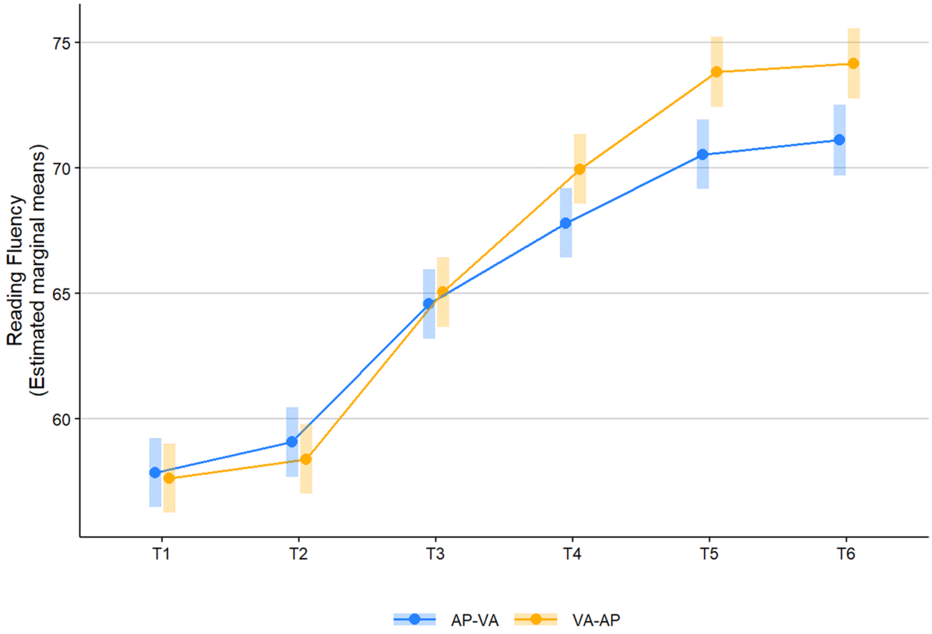

Fig. 2 Estimated marginal means of text reading fluency (words per minute) over time for each group, based on intention-to-treat (ITT) mixed-effects models including all enrolled participants ($N = 144$). Error bars represent standard errors

Order-dependent effects emerged selectively during the first two intervention phases, with larger gains when visual-attentional training preceded auditory-phonological training. These effects correspond to the significant Group × Time interaction observed in the omnibus model and are documented in the phase-specific post-hoc comparisons (see Supplementary Table S1).

Specificity of VA and AP training effects on underlying cognitive skills

As a validity check of the multicomponent intervention, we examined whether the VA and AP training phases selectively improved the cognitive functions they were designed to target. After the first intervention phase (T3), visual-attentional skills were assessed using partial and global report tasks, and phonological skills were assessed using a phoneme deletion task.

Linear mixed-effects models revealed a significant Group × Time interaction for visual-attentional span, indicating that children who received VA training showed greater improvements in VA skills than those who received AP training ($F(1,120) = 7.04$, $p = .009$). Conversely, a significant Group × Time interaction was observed for phoneme awareness, with larger gains following AP training than VA training ($F(1,120) = 10.70$, $p < .001$).

These dissociations confirm that the cognitive training components produced specific effects on their intended target functions, supporting the mechanistic validity of the intervention (see Figure S2).

The effects of order on reading fluency: VA-first versus AP-first

The two randomized groups received exactly the same interventions but differed with respect to the order in which they were delivered. Importantly, at T4, both groups had completed both the VA and AP interventions, albeit in a different sequence. If the order of interventions had no impact on reading outcomes, both groups would be expected to reach a comparable level of reading fluency at T4, even if the two intervention components differed in overall effectiveness. In statistical terms, the absence of order effects would be reflected by a non-significant interaction between *group* (VA–AP vs. AP–VA) and *time* (T2 vs. T4). In contrast, if order mattered, we would expect a significant interaction. The results from the linear mixed-effect model with *time* and *group* as fixed effects, *subject* and *text* as random effects and the three covariates showed a significant interaction between the effects *time* and *group* ($F(1,609)=6.29$, $p<.01$). This interaction indicates that the group receiving visual-attentional training before auditory-phonological training showed significantly larger gains in reading fluency than the group receiving the same interventions in the reverse order. These order-dependent effects are illustrated in Fig. 3.

Intervention-specific improvements in literacy outcomes

We further investigated whether each intervention type yielded greater gains in literacy outcomes (reading fluency, spelling, and reading comprehension) than conventional reading remediation delivered during the pre-intervention baseline. To do so, we computed linear mixed-effects models comparing each intervention type (separately) to the pre-intervention baseline (i.e., T1–T2). These mixed-effects models contained two fixed effects (i.e., *inter-*

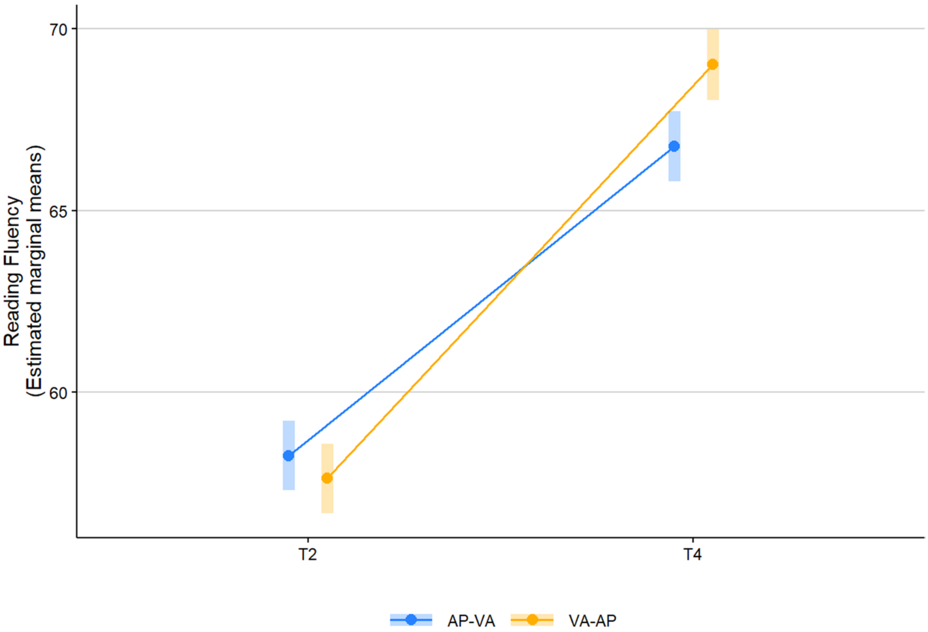

Fig. 3 Effects of the order in which VA and AP interventions were delivered on text reading fluency (Estimated Marginal Means). Error bars represent standard errors

vention: intervention vs. baseline; *time*: pre-test vs. post-test), their interaction, three covariates (i.e., μ(T1,T2), age, and reading age lag), and two random effects (i.e., subject and text).

Mean reading fluency at pre- and post-training assessments for each intervention type is shown in Fig. 4. For each intervention (AP, VA, and OtP), linear mixed-effects models revealed significant Time × Intervention interactions, indicating that gains in reading fluency were significantly larger during the intervention phases than during the pre-intervention baseline. Specifically, significant interactions were observed for the AP intervention ($F(1,1399)=37.44$, $p<.001$), the VA intervention ($F(1,1380)=35.02$, $p<.001$), and the OtP intervention ($F(1,1292)=8.60$, $p<.01$). In contrast, when comparing the pre-intervention baseline to the post-intervention baseline, no Time × Intervention interaction was observed ($F(1,1255)=0.30$, $p=.58$), indicating an absence of continued gains once intensive intervention had ceased. In summary, AP, VA, and OtP interventions each produced gains in reading fluency that significantly exceeded those observed during the two-month pre-intervention baseline.

To further quantify the magnitude of these effects, we computed standardized effect sizes (Cohen's d) indexing within-participant change during the active intervention period (T2–T5) relative to change observed during the pre-intervention baseline (T1–T2) for each outcome measure. These effect sizes are therefore intended as comparative indices of change across study phases, rather than as treatment–control estimates. As shown in Fig. 5, standardized gains during the intervention period were consistently larger across all literacy outcomes (ds ≈ 0.59–0.73) than gains observed during the pre-intervention baseline (ds ≤ 0.23). This pattern indicates that improvements were temporally aligned with the intervention phases and exceeded those expected from conventional remediation and repeated testing alone. Although these effect sizes should not be interpreted as estimates relative to an

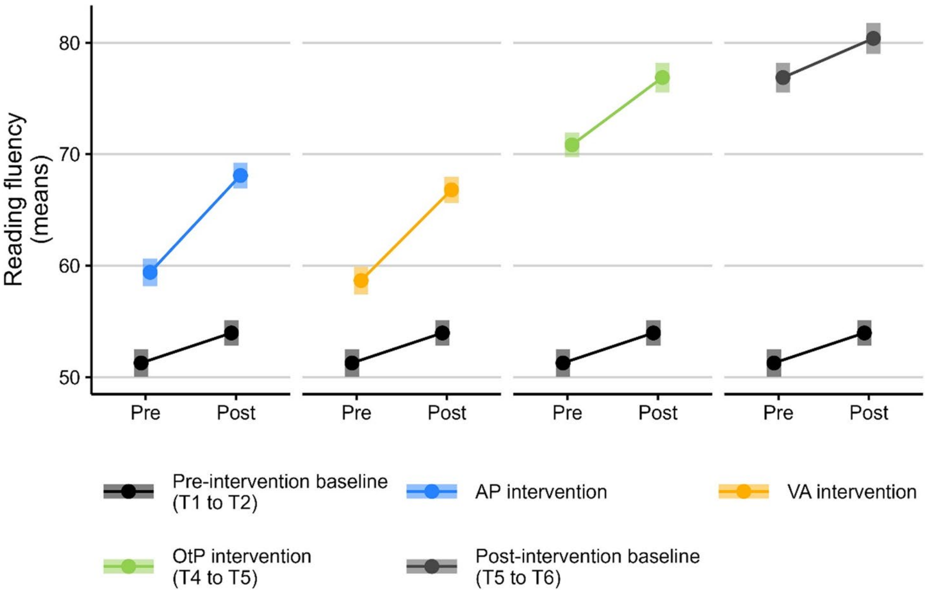

Fig. 4 Means of text reading fluency for each intervention type compared to the pre-intervention baseline. Error bars represent within-subjects confidence intervals (95%). The "Pre" labels on the x-axis refer to the pre-training assessments. while the "Post" labels refer to the post-training ones

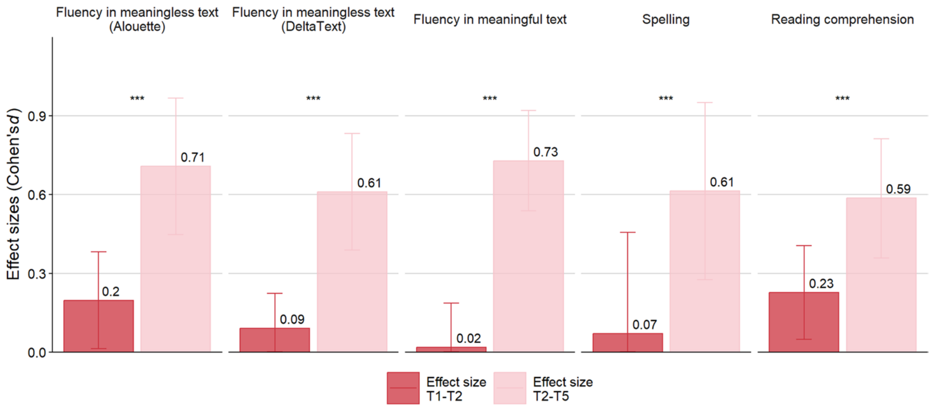

Fig. 5 Standardized effect sizes (Cohen's d) indexing within-participant change for reading fluency, spelling, and reading comprehension. Dark bars represent change during the pre-intervention baseline period (T1–T2; conventional remediation only), whereas light bars represent change during the active digital intervention period (T2–T5). Effect sizes quantify the magnitude of improvement within each phase and are intended as comparative indices of change across study phases rather than treatment–control estimates. Error bars represent standard deviations. Asterisks denote significant differences between baseline and intervention-related change (*** $p < .001$)

untreated control group, they provide a conservative indication that gains observed during the intervention phases were substantially larger than those occurring during conventional remediation alone.

To assess the robustness of these findings to assumptions about missing data, we conducted complementary sensitivity analyses using conservative worst-case and best-case scenarios for participants with incomplete data (see Statistical Analyses). As shown in Supplementary Figures S3 and S4, both the overall intervention effects (Fig. 4) and the pattern of standardized gains across outcomes (Fig. 5) were preserved under both scenarios, with intervention-related improvements consistently exceeding those observed during the pre-intervention baseline. This convergence across analytical approaches indicates that the main conclusions are robust to different assumptions about missing data and are unlikely to be solely attributable to attrition-related artifacts.

Improvement in text reading fluency relative to normative data

In a final descriptive analysis, we examined changes in reading fluency relative to age-based normative benchmarks in order to assess the clinical significance of the intervention at the individual level. For this purpose, participants' reading fluency scores were compared to normative data from the standardized *Mouette–Pingouin* reading fluency test, which provides percentile ranks adjusted for chronological age. These percentile ranks allow for a clinically interpretable characterization of reading impairment severity.

The distribution of participants across percentile categories at each assessment time point is shown in Fig. 6, with corresponding absolute numbers reported in Table 3. Scores below the 7th percentile indicate severe reading impairment, scores between the 7th and 20th percentiles indicate moderate impairment, and scores at or above the 21st percentile indicate age-appropriate reading fluency.

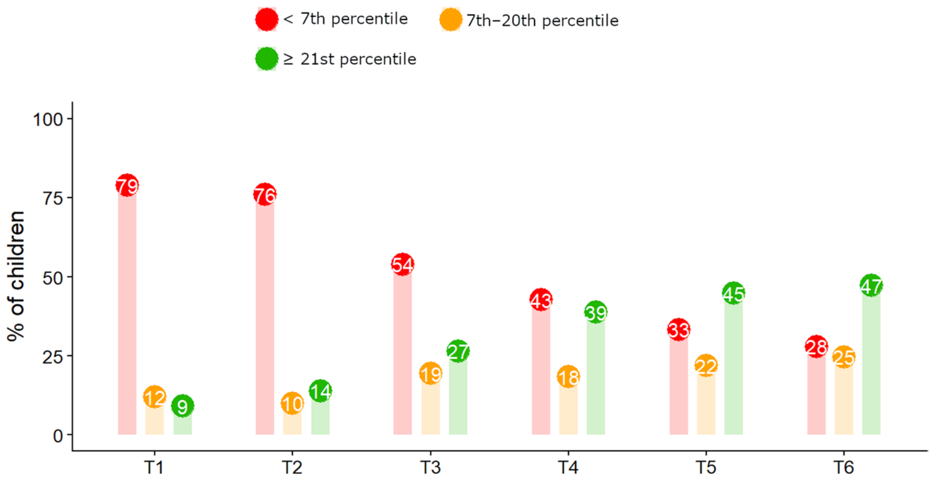

Fig. 6 Distribution of reading fluency performance relative to age-based norms across assessment time points. Percentages of children scoring below the 7th percentile (severe impairment), between the 7th and 20th percentiles (moderate impairment), and at or above the 21st percentile (within the age-appropriate normative range) on the standardized *Mouette–Pingouin* reading fluency test at each assessment time point (T1–T6). Percentages are calculated relative to the number of children assessed at each time point; corresponding absolute numbers are reported in Table 3

Table 3 Distribution of participants across percentile-based categories of reading fluency performance at each assessment time point on the Mouette–Pingouin reading fluency test. Values represent the percentage of children in each category, with absolute numbers shown in parentheses

Percentile category	T1	T2	T3	T4	T5	T6
<7th percentile	78.9% (n=112)	76.0% (n=98)	54.0% (n=61)	42.7% (n=44)	33.3% (n=32)	28.0% (n=26)
7th-20th percentile	12% (n=17)	10.1% (n=13)	19.5% (n=22)	18.4% (n=19)	21.9% (n=21)	24.7% (n=23)
21st-38th percentile	4.2% (n=6)	6.2% (n=8)	15% (n=17)	12.6% (n=13)	16.7% (n=16)	17.2% (n=16)
39th-62nd percentile	3.5% (n=5)	4.7% (n=6)	4.4% (n=5)	13.6% (n=14)	17.7% (n=17)	15.1% (n=14)
63rd-80th percentile	1.4% (n=2)	3.1% (n=4)	4.4% (n=5)	4.9% (n=5)	5.2% (n=5)	7.5% (n=7)
>80th percentile	0.0% (n=0)	0.0% (n=0)	2.7% (n=3)	7.8% (n=8)	5.2% (n=5)	7.5% (n=7)

Percentile categories correspond to the normative classification of the Mouette–Pingouin reading fluency test: Impaired range (<7th percentile), At-risk range (7th–20th percentile), Low-average range (21st–38th percentile), Average range (39th–62nd percentile), High-average range (63rd–80th percentile), and Superior range (>80th percentile)

The distribution of reading fluency scores shifted markedly across the intervention period (see Table 3). The proportion of children in the impaired range (<7th percentile) decreased from 78.9% (n=112) at T1 to 28.0% (n=26) at T6. Conversely, the proportion of children performing within the age-appropriate normative range (≥21st percentile) increased from 9.2% (n=13) to 47.3% (n=44).

Importantly, improvements were not restricted to children reaching the lower end of the normative range. By T6, 17.2% of participants (n = 16) were performing within the low-average range (21st–38th percentile), 15.1% (n = 14) within the average range (39th–62nd percentile), 7.5% (n = 7) within the high-average range (63rd–80th percentile), and 7.5% (n = 7) within the superior range (> 80th percentile), compared with 4.2%, 3.5%, 1.4%, and 0%, respectively, at baseline.

These results indicate a substantial reduction in the prevalence of severe reading impairment over the course of the intervention, with a sizeable subset of children no longer meeting criteria for impaired reading fluency and performing within the age-appropriate normative range. Percentages are calculated relative to the number of children assessed at each time point, and absolute sample sizes are therefore reported to account for attrition. These descriptive findings complement the intention-to-treat and sensitivity analyses reported above, which showed that intervention-related gains were robust to different assumptions about missing data.

Discussion

Overview and feasibility of a home-based multicomponent intervention

The overarching goal of this study was to develop and test an innovative multi-component remediation program for dyslexic readers with high ecological and clinical validity that included three types of interventions: auditory-phonological (AP), visual-attentional (VA), orthography-to-phonology association (OtP). Methodologically, the present study was designed as a multiple single-case (within-subject) intervention study, an approach commonly used in clinical and cognitive neuropsychology when ethical and practical constraints limit the use of waiting-list control groups.

Two thirds of the dyslexic readers completed the full program, which required 30 h of home training, the delivery and use of software, the involvement of parents, numerous assessments, and close collaborations between the speech-and-language therapists and the parents. Thus, we managed to provide the proof-of-concept that an intensive (i.e., daily) computer-based remediation program for dyslexic readers can indeed be delivered at home by their caretakers while being supervised by speech-and-language therapists in their weekly sessions with minimal intervention of researchers. One third of the dyslexic readers did not complete the protocol. However, most of the intervention program was conducted during the COVID-19 pandemic, and some parents found it challenging to maintain the weekly meetings with the speech and language therapists. Others indicated that they stopped because the different software packages, which ran on different operating systems, did not work well on their computers.

Effects of the multicomponent intervention on reading

We showed that the three-stage multicomponent training improved reading fluency, spelling and reading comprehension. Although we did not have a between-subject control group that did not receive the intervention, each of the specific intervention programs that lasted for two months (i.e., VA, AP, OtP) could be compared to the pre-intervention baseline, which also lasted two months and during which the dyslexic readers received CRR on a weekly basis. Crucially, each two-month intervention program produced greater benefits than the 2-month CRR baseline. The absence of comparable gains during the pre-intervention and post-intervention baselines makes a pure maturation account unlikely. From the present results, it is not possible to disentangle whether the superior gains of our intervention programs compared to CRR are due to the increased intensity of the training, the impact of computer-assisted software or the reading-related activities with the parents. We currently investigate this question in a 5-arm RCT.

It is nevertheless reassuring that each specific training program (VA, AP) had specific effects on improving VA skills or AP skills, that is, when VA was trained, the group that received the VA training showed superior VA skills after the training than the group that was trained on AP. Similarly, the group that was trained on AP showed superior AP skills after training than the group that was trained on VA. Thus, two of our computer-assisted programs produced specific effects on remediating underlying components (see also Zoubrinetzky et al., 2019), which was one of the objectives of the three-stage multicomponent intervention program.

The magnitude of the observed improvements in reading fluency (ds $\approx$ 0.59–0.73) also appears clinically meaningful when considered in relation to the intervention literature. Galuschka et al. (2014), in a meta-analysis of randomized controlled trials for children and adolescents with reading disabilities, reported generally small-to-moderate treatment effects on reading outcomes, with phonics-based interventions yielding an average effect size of $g = 0.32$. Direct comparisons should be interpreted cautiously because the present study reports within-subject effect sizes rather than treatment–control group differences. Nevertheless, the magnitude of the gains observed here is broadly consistent with those reported in successful remediation studies targeting cognitive mechanisms associated with dyslexia (e.g., Zoubrinetzky et al., 2019), suggesting that the intervention produced gains that are not only statistically reliable but also educationally and clinically meaningful.

Gains relative to standardized norms

To assess the clinical significance of the observed improvements, we examined changes in reading fluency relative to age-based normative benchmarks derived from a standardized reading fluency test. This analysis complements the intention-to-treat and sensitivity analyses by providing an interpretable description of how participants' performance evolved relative to clinically meaningful thresholds.

At study entry, the large majority of assessed children performed in the severely impaired range, with nearly 80% scoring below the 7th percentile. Across successive intervention phases, the proportion of children in this lowest percentile range decreased steadily, reaching approximately 28% at follow-up. Conversely, the proportion of children performing within the age-appropriate range (above the 21st percentile) increased from 9.2% at baseline to 47.3% at follow-up.

These findings indicate a substantial reduction in the prevalence of severe reading impairment over the course of the intervention, with a sizeable subset of participants reaching performance levels that fall within the normative range for their age. Importantly, these estimates are based on standardized norms rather than researcher-developed outcome measures, which have been shown to yield inflated effect sizes in intervention studies (Cheung

& Slavin, 2016; de Boer et al., 2014). Although not all children reached age-appropriate performance levels, the marked shift out of the severely impaired range suggests that intensive, multicomponent, home-based remediation can lead to meaningful functional gains in a substantial proportion of children with developmental dyslexia.

Maintenance and generalization of intervention effects

A central question for any remediation program concerns the maintenance and generalization of intervention effects beyond the training period. In the present study, follow-up assessments conducted two months after the end of the intervention showed that gains in reading fluency were maintained over time, with no evidence of regression once intensive training had stopped. While longer-term follow-up will be needed, the present results suggest that a multicomponent approach targeting both reading skills and underlying cognitive mechanisms may promote stable reading improvements.

Order effects and theoretical implications

One question that can be addressed independently of a between-subject control group concerns whether the order in which the intervention components were delivered influenced outcomes. To examine this issue, participants were randomized to two groups that received the same interventions in different sequences (visual-attentional first vs. auditory-phonological first). Results showed that children who began with the visual-attentional intervention exhibited larger gains in reading fluency than those who began with the auditory-phonological intervention. Importantly, these differences persisted after both intervention phases had been completed (i.e., after T4), indicating a lasting order effect rather than a transient training advantage.

This finding suggests that initiating remediation with a visual-attentional intervention may provide a more favorable foundation for subsequent learning than beginning with auditory-phonological training. From a theoretical perspective, this pattern is consistent with the view that efficient visual-attentional processing constitutes a prerequisite for effective reading-related learning. Strengthening visual-attentional skills may facilitate subsequent access to phonological representations (Boets et al., 2013; Ramus & Szenkovits, 2008) and support the development of an efficient decoding network that maps graphemes onto phonemes (Perry et al., 2019; Ziegler et al., 2020). More generally, this interpretation aligns with evidence suggesting that attentional capacities constrain learning efficiency across domains and developmental stages (Horowitz-Kraus et al., 2014; Pasqualotto et al., 2022; Pasqualotto & Venuti, 2020).

Innovative characteristics of the intervention: home-based delivery, multicomponent design, and individualization

The encouraging results observed in the present study are likely linked to three innovative characteristics of the remediation program. First, the home-based nature of the intervention with strong involvement of parents allowed for substantially increased training intensity, which is likely to have promoted faster learning and generalization. Sustaining children's engagement in daily training required a structured partnership between parents and speech-and-language therapists. Parents were trained by the therapists to implement the program at home and effectively acted as informed assistants, ensuring that training procedures were repeated on a daily basis under professional supervision. This partnership is essential, as intensive and repeated practice is necessary for newly acquired skills to become automatized and transferable, a level of repetition that cannot be achieved within the limited time of weekly therapy sessions alone. Despite these supports, maintaining long-term adherence remained challenging for some families, highlighting the need for clear methodological frameworks to guide parent–therapist collaboration in future home-based interventions.

Second, the intervention was designed as a multimodal and multicomponent program, targeting visual-attentional, auditory-phonological, and audiovisual processes that are frequently impaired in dyslexic readers. Rather than focusing on a single deficit, this approach reflects converging evidence that dyslexia is associated with heterogeneous combinations of underlying cognitive impairments and therefore requires interventions that operate across multiple modalities (Carroll et al., 2025; Ziegler et al., 2019, 2020). Within each modality, the remediation programs were themselves multicomponent, consistent with numerous case studies documenting combined auditory-phonological, visuo-attentional, and audiovisual deficits in dyslexia across languages and orthographies (e.g., Ramus, 2003; Saksida et al., 2016; White et al., 2006; Zoubrinetzky et al., 2014).

Third, interventions within each remediation phase were tailored to the individual semiological profiles of the children, in line with additive models of dyslexia (O'Brien & Yeatman, 2021) and evidence for individual variability in the organization of reading-related brain networks (Gordon et al., 2017). Each program specifically targeted the impaired processes identified during the initial assessment of auditory-phonological, visual-attentional, and reading-related skills. Such individualized interventions are likely to be more effective than one-size-fits-all approaches, particularly when they are developmentally appropriate and designed to promote motivation, a sense of achievement, and positive self-esteem.

Limitations and future directions

There are a number of limitations that need to be acknowledged. The most important limitation of the present study is the absence of a randomized between-subject control group. Although the use of a within-subject pre-intervention baseline provides a useful point of comparison, alternative explanations such as maturation, repeated testing, or other uncontrolled influences cannot be completely ruled out. A randomized controlled trial therefore remains necessary to establish causal efficacy.

This design choice was motivated primarily by practical and ethical considerations. The study lasted more than 12 months, making it difficult to justify a prolonged waiting-list condition for children with developmental dyslexia who would otherwise not receive intensive intervention. The present study was therefore conceived as a proof-of-concept investigation aimed at evaluating feasibility and preliminary efficacy relative to a pre-intervention baseline and standardized normative data.

Several aspects of the findings nevertheless argue against a purely maturation-based explanation. In particular, gains in reading fluency flattened once intensive training ended (T5–T6), improvements were specific to the trained cognitive domains (visual-attentional vs. auditory-phonological), and reliable order effects were observed. Nevertheless, replication in a randomized controlled trial is required. The present work is currently being extended in a pre-registered randomized controlled trial involving approximately 400 children with developmental dyslexia and multiple intervention and control groups.

A second limitation concerns attrition. Approximately one third of the initially enrolled participants did not complete the full intervention, which may limit the generalizability of the findings. Although we now report intention-to-treat analyses and conservative sensitivity analyses to reduce bias due to missing data, attrition was not random and appeared to be higher in families facing greater logistical and technological constraints and in children with weaker language skills. As a consequence, the present findings may generalize more readily to children with developmental dyslexia whose families are able to sustain a relatively intensive home-based intervention and whose language difficulties are primarily related to reading. In contrast, caution is warranted when extrapolating the present results to children from more educationally disadvantaged backgrounds or to those presenting broader oral language impairments, as these groups were underrepresented among study completers. Future intervention studies should therefore develop additional support mechanisms specifically designed to facilitate participation and retention in these more vulnerable populations.

A third limitation relates to intervention fidelity. Although fidelity was monitored throughout the study to ensure adequate implementation and feasibility in a real-world clinical context, fidelity measures were not designed for fine-grained quantitative modeling of dose–response or fidelity–outcome relationships. Systematic investigation of these relationships therefore represents an important objective for future randomized controlled trials, where fidelity measures can be prospectively standardized and optimized for such analyses.

A fourth limitation concerns developmental heterogeneity. The sample spanned a wide age range (8–13 years), encompassing different developmental stages and potentially different profiles of dyslexia. Although the intervention was adaptive and individualized based on each child's cognitive profile rather than chronological age, and age was included as a covariate in the analyses, this approach cannot fully capture qualitative developmental differences. Future randomized controlled trials with larger samples should therefore examine developmental stage as a moderator of intervention response, for example using age-stratified designs or non-linear modeling approaches.

Finally, we could not systematically investigate therapist effects, that is, variability associated with the speech-and-language therapists who implemented and supervised the home-based interventions. Although therapist supervision was standardized, many therapists included only a single participant, which precluded modeling therapist-level effects in the mixed-effects analyses. Future large-scale trials with clustered designs will be better suited to address this issue.

Conclusion

The present study provides a proof of concept that it is possible to improve reading skills of dyslexic readers through an intensive (i.e., daily) computer-assisted remediation program delivered in the homes of dyslexic readers by their caretakers and supervised by speech-and-language therapists in their weekly sessions with minimal intervention of researchers. At the end of the intervention program, 47.3% of the dyslexic readers were in the age-appropriate normative range. The gains remained stable once the intensive intervention was stopped. Finally, although both VA and AP interventions significantly improved reading fluency, the gains were greater when the intervention started with the VA than the AP training. In sum, we presented the results of a scalable, home-based intervention program for the remediation of dyslexia that offers an easy-to-implement, highly effective, and cost-efficient solution for treating dyslexia. We fully recognize that, by targeting so many different skills within our intervention, our approach aims at impact rather than elucidating further mechanisms. Yet, we believe that the time is ripe for doing such ambitious, impact-driven research because the need for effective interventions is greater than ever before.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11881-026-00378-x.

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Data availability All datasets and analysis scripts required to reproduce the results, tables, and figures reported in this study are publicly available in the Open Science Framework (OSF) repository: https://osf.io/e6xqf.

Declarations

Ethics approval This study received ethical approval from two independent ethics committees: the French National Committee for the Protection of Persons (CPP Île-de-France IV; IRB 00003835, reference 2019/50, ID-RCB 2019-A01453-54) and the Ethics Committee for Non-Interventional Research at Université Côte d'Azur (CERNI; reference 2019-7). The study was conducted in accordance with the Declaration of Helsinki and the French Jardé law governing research involving human participants (Decree No. 2016−1537, November 16, 2016). Written informed consent was obtained from the parents of all participating children.

Competing interest The authors declare that they have no financial or non-financial interests that are directly or indirectly related to the work submitted for publication.

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