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The Role of Auditory and Visual Components in Reading Training: No Additional Effect of Synchronized Visual Cue in a Rhythm-Based Intervention for Dyslexia

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Abstract: Based on the transfer effects of music training on the phonological and reading abilities of children with dyslexia, a computerized rhythmic intervention—the Rhythmic Reading Training (RRT)—was developed, in which reading exercises are combined with a rhythmic synchronization task. This rehabilitation program was previously tested in multiple controlled clinical trials, which confirmed its effectiveness in improving the reading skills of children and adolescents with dyslexia. In order to assess the specific contribution of the visual component of the training, namely, the presence of a visual cue supporting rhythmic synchronization, a controlled experimental study was conducted. Fifty-eight students with dyslexia aged 8 to 13 years were assigned to three conditions: (a) RRT auditory and visual condition, in which a visual cue was synchronized with the rhythmic stimulation; (b) RRT auditory-only condition, in which the visual cue was excluded; (c) no intervention. Comparisons of the participants' performance before, after, and 3 months after the end of the intervention period revealed the significant immediate and long-term effect of both RRT conditions on reading, rapid naming, phonological, rhythmic, and attentional abilities. No significant differences were found between visual and auditory conditions, therefore showing no additional contribution of the visual component to the improvements induced by the RRT. Clinical Trial ID: NCT04995991.

Keywords: dyslexia; rhythm; visual cognition; temporal anticipation; intervention

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1. Introduction

The potential of music in improving reading in developmental dyslexia has been explored with promising results [1]. More precisely, evidence from research on auditory and music-based interventions for dyslexia supported the notion that music has a positive impact on phonological abilities and auditory temporal processing [1]. The hypothesis of a transfer effect of music on reading stemmed from theoretical frameworks, which linked the dyslexia-related phonological deficits to a perceptual auditory impairment, specific for the temporal aspect of sound processing. Among those, the Temporal Sampling (TS) theory [2,3] focused on the role of temporal acoustic components carrying information about the rhythmical structure of speech and non-speech sound streams. The sensitivity to speech rhythm via a synchronous oscillatory neural activity at Delta and Theta bands in the auditory cortex, which were found to be disrupted in dyslexia [2,4], is indeed crucial for the development of phonological abilities [5,6]. It is worth mentioning that although the phonological deficit is extensively described in dyslexia literature, e.g., [7–9], other explanatory theories have been posited, such as the visuo-spatial attention deficit, e.g., [10] and the magnocellular theory, e.g., [11]. Considering the multimodal nature of the disorder, the most recent advances in dyslexia research converged on a multi-componential etiological theory [12,13].

The potential use of music for dyslexia rehabilitation is further supported by the notion that rhythm generates temporal expectancies in the listener. When we expect something to happen, we react quicker and more efficiently to events [14–16]. Expectancies enable individuals to anticipate future events, both in terms of *what* is going to happen and *when* it will occur. Beneficial effects of temporal expectancies on verbal processing are reported when monitoring phonetic form [5], detecting word changes [17], perceiving spoken words [16], or resolving syntactic ambiguities [18]. An impaired rhythmic sound perception was described in children with dyslexia [19]. Such impairment was hypothesized to stem from a difficulty in anticipating and, therefore, predicting events in temporal succession [20]. To confirm this hypothesis, other studies have shown that students who received a timing/rhythm intervention, designed to reduce response latency to a metronome beat, improved significantly in reading fluency [21].

To take advantage of the rhythm potential, an innovative approach to dyslexia rehabilitation, the Rhythmic Reading Training (RRT), was devised by Cancer and colleagues [22] by embedding reading tasks into rhythm-based training activities. The hypothesis supporting the development of RRT was that synchronizing speech production during reading to a regular acoustic stimulus would improve temporal processing by coupling the cross-frequency oscillatory activity in auditory and visual areas, thus enhancing the precision of timing perception.

Previous controlled studies tested the efficacy of RRT in samples of children and adolescents with dyslexia. In the first trial [23], significant improvements in reading speed and accuracy were found in comparison to a no intervention condition after 9 RRT sessions. The following comparison studies included active control conditions, namely, a language-based traditional intervention [24] and a technologically advanced visual-based intervention for reading [25]. In both trials RRT produced global reading improvements which did not differ from the control interventions. However, significant larger effects of RRT on non-word reading speed were found. Furthermore, medium-term significant effects on the outcome measures were found in a longitudinal study [26]. RRT efficacy was recently confirmed in a study testing the effect of a telerehabilitation version of the intervention [27].

The RRT software includes the option to add a visual cue to the reading exercises, which highlights portions of the text which has to be read in synchrony with the rhythmic base. Such a setting was originally introduced to facilitate the synchronization task during reading and it was meant to be turned off by the trainer as soon as the participant was able to accurately coordinate their reading to the beat without any visual aid. The personalized use of the visual cue setting in RRT made it impossible to control for the specific effect of the visual component of the intervention in the previous RRT clinical trials.

Temporal anticipation can, indeed, be generated not only by auditory stimuli, such as the beats of a metronome or a music piece, but also by visual stimuli. Selective attention to a spatial location has been shown to enhance perception and facilitate response times to attended visual stimuli compared to unattended visual locations [28]. Several authors have investigated the relationship between temporal and spatial expectancies proving an additive effect when both are matched [29]. Likewise, in rhythm task, multisensory rhythms temporally aligned (e.g., auditory and motor) can also enhance expectancies and boost human behaviour [17]. Reading, by definition, begins in the visual system with a perceptual segmentation of the letters string into its constituent graphemes and involves an accurate and rapid shifting of visuo-spatial attention. A deficit in visual attention shifting has been demonstrated to play a critical role in dyslexia [30,31]. Although the role of auditory temporal expectancies has already been investigated in dyslexia [20], to our knowledge the combined role of visuospatial and auditory expectancy was not. In naturalistic environments, we perceive objects through our different senses and redundant intersensory information is bound together, with cross-modal enhancement taking place at multiple levels. A striking example comes from face-to-face dialogue where audio-visual synchronized information facilitates detection of amodal features (e.g., prosody) [32], as predicted by intersensory redundancy hypothesis [33]. Based on previous literature on the additional anticipatory effect of auditory and visual rhythms, it is possible that the combination of the auditory and visual components of RRT would maximize the effect of the intervention in terms of reading improvements.

The present study aimed to assess the specific contribution of the visual component of the training, namely, the presence of a visual cue supporting rhythmic synchronization. To do so, two RRT administration conditions were implemented: (a) RRT auditory and visual condition, in which a visual cue is synchronized with the rhythmic stimulation (i.e., Visual cue); (b) RRT auditory only condition, in which the visual cue was excluded (i.e., Rhythm).

2. Materials and Methods

2.1. Participants

Participants were recruited among patients of the Learning Disorders (LDs) Service of the Fondazione IRCCS Istituto Neurologico Carlo Besta of Milan, Italy, on the basis of the following inclusion criteria: (a) formal diagnosis of developmental dyslexia (ICD-10 code: F81.0) [34]; (b) age 8–14 years; (c) normal intellectual functioning, as measured by the Total IQ composite score derived from the Wechsler Intelligence Scale for Children–Forth Edition [35] (TIQ $\geq$ 85); and (d) absence of psychiatric and/or neurological conditions.

Fifty-eight children and adolescents, aged 8–14 years (M = 10.8; S.D. = 1.64), were selected on the basis of the reported criteria and enrolled in the study after written informed consent was obtained from their parents. A sample size of 58 was a priori calculated to be enough to detect a medium effect size (η^2 = 0.06) in the planned GLMs and achieve a power of 0.97, setting alpha at 0.05.

2.2. Procedure

The clinical trial was pre-recorded on ClinicalTrial.gov (Clinical Trial ID: NCT04995991).

Participants were assigned to one of three experimental conditions (Visual cue: n = 21; Rhythm: n = 21; No intervention: n = 16) by stratifying the sample for age, sex, total IQ, and baseline reading performance. The no intervention condition was included in order to control for test–retest learning effects.

Participants assigned to the Visual cue and Rhythm conditions received 10 individual RRT training sessions of 45 min, supervised by an expert trainer, over 5 weeks. All participants underwent three assessment sessions (i.e., pre-training, post-training, and 3-month follow-up), in which the primary outcomes of the intervention (i.e., reading speed and reading accuracy) were measured. To further analyse the specific differences between RRT conditions, additional testing, including secondary outcome measures (i.e., rapid automatized naming, phonological, attentional, and rhythmic abilities), was applied only to participants assigned to the intervention conditions (i.e., Visual cue and Rhythm).

2.3. Interventions

RRT is a rhythm-based intervention for reading. Exercises are delivered through a desktop app, which is managed by an expert RRT practitioner during one-on-one training sessions with the participant. The app includes specific modules of reading tasks combined with the synchronization to an isochronous rhythm [22]. Each module includes exercises addresses specific reading sub-process: (a) in the 'Syllable' module, participants are asked to read aloud lists of syllables presented on the screen in synchrony with the pace of a rhythmic base. (b) In the 'Merging' module, syllables are sequentially presented on the screen, in synchrony with a rhythmic base; participants are required to merge syllables together and pronounce the resulting word or non-word. (c) In the "Words and Non-words" module, participants are asked to read aloud lists of word and non-words, adjusting the pace of their reading to that of the rhythmic base. Furthermore, this module includes phrases and nursery-rhymes reading exercises. Either a regular metronomic beat or a simple pentatonic melody serves as the rhythmic base in each exercise. The accented pattern on the linguistic material matches the metrical structure of the rhythmic base, so that each music beat stresses the accented components of language during reading. The tempo of the rhythmic base is gradually increased throughout each training session to improve reading fluency. The exercises' settings can be adjusted by the trainer by modulating the rhythm speed and the complexity of the verbal material. Reading accuracy is constantly monitored by the trainer, who is instructed to advance based on accuracy rate (90% threshold) in each activity.

In the present study, RRT exercises were delivered in two modalities: (a) during rhythmic reading, a visual cue–synchronized with the rhythmic beats–sequentially highlights each verbal stimulus on the screen through changing-colour text (the text turns red simultaneously to each rhythmic beat); (b) During rhythmic reading, static verbal stimuli are presented on the screen, without any additional visual aid. In both modalities, the verbal material (i.e., syllables, word, non-words, phrases) is presented on the screen in rows and it has to be read from left to right, from the top row to the bottom row, as in typical reading. Only the modules which allowed the selection of the visual cue setting (syllable, word, non-word, and sentence reading exercises) were used in the present trial.

2.4. Measures

Prior to enrolment, the clinical documentation of each participant was analysed to check for inclusion criteria. Such clinical documentation included the latest certification of dyslexia, previously made by clinical practitioners of the IRCCS LDs Service following the formal Italian Learning Disorders' diagnostic practice [36]. Medical history and a measure of intellectual functioning (i.e., total IQ derived from the Wechsler Intelligence Scale for Children–Forth Edition [35]) were retrieved from the dyslexia certification.

2.4.1. Primary Outcomes

A battery of standardized tests was applied to measure reading abilities. Word and non-word reading was assessed using the "Assessment battery for Developmental Reading and Spelling Disorders-2" [37], which comprises 4 lists of 28 words and 2 lists of 16 non-words. Text reading was assessed using the age-normed Reading task from the 'MT-3 Clinical Tests' [38]. For all reading tasks, z-scores of reading speed (measured as syllable per second) and reading accuracy (measured as number of errors) were computed.

2.4.2. Secondary Outcomes

The following standardized tests were used to assess the secondary outcome measures.

'Word and pseudo-word reading test' [39]. Additional reading tasks were used to collect further measures of the reading subprocesses. More precisely, the test included 4 lists of 30 words, varying according to length and frequency of use, and 2 lists of 30 non-words, varying according to length. Reading speed (as number of seconds) and accuracy (as number of errors) z-scores were computed.

'Rapid Automatized Naming test (RAN)–Figures' test [40]. In this test, rapid and sequential naming of 50 black and white figures (i.e., pear, train, dog, star, hand) is recorded. RAN speed (as number of seconds) z-scores were considered.

'Phonemic awareness task–Phonemic elision' [41]. In this task, the participants listen to 40 words pronounced by the examiner. For each word they are instructed to omit a given phoneme from the word and to pronounce the resulting non-word. Scores are expressed in total number of errors.

'NEPSY-II–Visual Attention Test' [42]. In this cancellation test participants are required to mark out all visual targets distributed on a paper sheet among similar stimuli (i.e., black and white cartoon faces) within 180 s. Accuracy standard scores were computed by subtracting the number of commission errors (i.e., marked distractors) from the number of correctly detected targets.

'Rhythm reproduction task' [43]. In this task participants are instructed to reproduce a sequence of rhythmic patterns, composed by 3–8 beats of increasing complexity, by tapping a pencil on the desk, after the examiner's presentation. Accuracy scores are recorded as number of errors.

'Tapping and Continuation Task (TCT)' [44]. In this computerized tapping task, participants are instructed to tap along with an isochronous rhythm for 15 s and to continue tapping at the same tempo (ISI = 500 ms) for 15 s after the rhythm stops, using a computer mouse. A tapping variability score is calculated as the average SD of the inter-tap intervals (ITIs) synchrony across six trials, dived by the average ITI.

Unfortunately, it was not possible to administer the complete battery of additional tests in the follow-up assessment session for organizational reasons. More precisely, the Visual attention and Tapping scores were collected only for the first two time-points (pre- and post-training).

2.5. Analytic Plan

The first step of the analyses was to test the homogeneity of the stratified subgroups (i.e., Visual cue, Rhythm, No intervention) based on age, gender, total IQ, and baseline reading abilities. To do so, global reading speed and reading accuracy scores were computed by averaging pre-training word, non-word, and text reading scores. Comparisons were tested using one-way ANOVA for continuous variables and Chi-squared test for categorical variables.

Secondly, we compared immediate effects on the primary outcome measures (i.e., reading speed and accuracy) between the conditions (i.e., Visual cue vs. Rhythm vs. No intervention). More precisely, a mixed factorial ANOVAs $2 \times 3 \times 3$ (Phase: pre vs. post; Test: word vs. non-word vs. text; Intervention type: Visual cue vs. Rhythm vs. No intervention) was performed for each reading outcome parameter (i.e., speed and accuracy).

Thirdly, we tested the specific immediate effects of each RRT condition (i.e., Visual cue vs. Rhythm) on the secondary outcome measures (i.e., additional reading tasks, RAN, phonemic elision, visual attention, rhythm reproduction, tapping) using a mixed factorial ANOVA 2×2 (Phase: pre vs. post; Intervention type: visual cue vs. rhythm).

Afterwards, we compared medium-term effects between three conditions using a mixed factorial ANOVA $2 \times 3 \times 3$ (Phase: pre vs. follow-up; Test: word vs. non-word vs. text; Intervention type: Visual cue vs. Rhythm vs. No intervention) for each reading outcome parameter (i.e., speed and accuracy).

Finally, we tested the specific medium-term effects of each RRT condition (i.e., Visual cue vs. Rhythm) on the secondary outcome measures using a mixed factorial ANOVA 2×2 (Phase: pre vs. follow-up; Intervention type: Visual cue vs. Rhythm).

For each GLM, post hoc pairwise comparisons were computed using Tukey's Test.

3. Results

3.1. Participants' Characteristics

Participants were attending school grade 3rd to 8th and had normal intelligence (total IQ: M = 103, S.D. = 11.3).

Comparisons between groups (i.e., Visual cue, Rhythm, No intervention) revealed nonsignificant differences in age ($F(2,55) = 0.31$; $p = 0.73$), sex ($\chi^2 = 0.24$; $p = 0.89$), general intelligence (TIQ: $F(2,46) = 0.22$; $p = 0.81$) and baseline reading measures (speed: $F(2,55) = 0.24$; $p = 0.78$; accuracy: $F(2,55) = 1.30$; $p = 0.28$). Descriptive statistics are reported in Table 1.

Table 1. Descriptive statistics (mean and standard deviations) of participants' characteristics and baseline reading measures.

	Visual Cue	Rhythm	No Intervention
Age	10.7 (1.71)	10.6 (1.41)	11.0 (1.89)
Sex [1]			
Male	12 (57.1)	12 (57.1)	8 (50.0)
Female	9 (42.9)	9 (42.9)	8 (50.0)
Total IQ [2]	104 (13.3)	104 (10.3)	101 (10.4)
Pre-test reading			
Speed (z-scores)	−1.81 (0.71)	−1.73 (0.69)	−1.66 (0.57)
Accuracy (z-scores)	−2.62 (2.17)	−2.11 (1.49)	−3.25 (2.72)

[1] Frequencies (Percentages). [2] Total IQ composite score derived from the Wechsler Intelligence Scale for Children–Forth Edition.

3.2. RRT Immediate Effects

3.2.1. Pre-Post Effects on Primary Outcomes

Regarding reading speed, a significant Phase × Condition interaction effect (F(2,110) = 83.4; $p < 0.001$; $\eta^2 = 0.01$) was found. Post hoc analyses revealed pre-post significant improvements in both Visual cue (t(55) = −7.81; $p < 0.001$) and Rhythm conditions (t(55) = −6.92; $p < 0.001$). Conversely, pre-post differences within the No intervention control condition were nonsignificant (t(55) = −1.65; $p = 0.57$).

Although the Phase × Condition interaction effect on reading accuracy was nonsignificant (F(2,18) = 2.1; $p = 0.132$), post hoc comparisons showed a significant pre-post effect of the Visual-cue intervention on reading accuracy (t(54) = −3.23; $p = 0.024$). Reading accuracy did not change in either the Rhythm (t(54) = −1.98; $p = 0.367$) nor the No intervention (t(54) = −0.05; $p = 0.100$) conditions.

3.2.2. Pre-Post Effects on Secondary Outcomes

Reading speed of words and non-words improved significantly after intervention within both RRT conditions (i.e., Visual cue and Rhythm) and no difference was found for any of the considered psycholinguistic characteristics of the verbal materials (i.e., length and frequency of use). More precisely, a significant Phase main effect was found on reading speed of short non-words (F(1,35) = 34.55; $p < 0.001$; $\eta^2 = 0.11$), long non-words (F(1,35) = 17.55; $p < 0.001$; $\eta^2 = 0.06$), high-frequency short words (F(1,35) = 11.77; $p = 0.002$; $\eta^2 = 0.04$), high-frequency long words (F(1,35) = 23.07; $p < 0.001$; $\eta^2 = 0.04$), low-frequency short words (F(1,35) = 15.85; $p < 0.001$; $\eta^2 = 0.05$), and low-frequency long words (F(1,35) = 13.30; $p < 0.001$; $\eta^2 = 0.02$). No significant Phase × Condition interaction effect was found (ps ranging from 0.14 to 0.94).

Reading accuracy was improved after RRT for low-frequency short words (Phase: F(1,35) = 6.71; $p = 0.014$; $\eta^2 = 0.03$) and low-frequency long words (F(1,35) = 5.11; $p = 0.030$; $\eta^2 = 0.01$), without significant Phase × Condition effects (low-frequency short words: F(1,35) = 0.62; $p = 0.435$; low-frequency long words: F(1,35) = 0.32; $p = 0.574$). Accuracy of the other reading materials (i.e., short non-words, long non-words, high-frequency short words, and high-frequency long words) was not improved after RRT (ps ranging from 0.11 to 0.96).

A significant pre-post RAN improvement was found (Phase: F(1,35) = 5.90; $p = 0.020$; $\eta^2 = 0.03$) with no difference between conditions (Phase × Condition: F(1,35) = 0.42; $p = 0.520$).

Performance in phonemic elision improved significantly after both interventions (Phase: F(1,35) = 9.39; $p = 0.004$; $\eta^2 = 0.02$) and no difference was found between conditions (Phase × Condition: F(1,35) = 0.002; $p = 0.963$).

Consistently with the other secondary outcomes, visual attention was increased after treatment in both conditions (Phase: F(1,18) = 13.26; p = 0.002; η^2 = 0.23) and the changes did not differ between interventions (Phase × Condition: F(1,18) = 6.79; p = 0.370).

Rhythmic abilities improved significantly after RRT, following the same pattern. Pre-post changes were found in the rhythmic reproduction (Phase: F(1,34) = 8.17; p = 0.007; η^2 = 0.01) and tapping (Phase: F(1,16) = 11.39; p = 0.004; η^2 = 0.21) tasks and the Phase × Condition interaction effect was nonsignificant (Reproduction: Phase: F(1,34) = 3.19; p = 0.083; Tapping: F(1,16) = 0.15; p = 0.703).

3.3. RRT Medium-Term Effects

3.3.1. Pre-Follow-Up Effects on Primary Outcomes

Figure 1 shows reading speed improvements for each test (word, non-word, and text) in each condition. Phase × Condition interaction effect on reading speed did not reach statistical significance (F(2,92) = 2.96; p = 0.06) in the pre-follow-up comparison. Indeed, Phase × Test × Condition pairwise comparisons revealed a test–retest effect on Text reading speed specifically, as showed by the pre-follow-up significant difference in the No intervention control group (t(46) = −4.88; p = 0.002). Conversely, word reading speed increased significantly at follow-up only in the Visual cue group (t(46) = –5.20; p < 0.001), but not in the Rhythm (t(46) = −3.22; p = 0.155) nor the No intervention group (t(46) = −2.18; p = 0.753). Finally, a pre-follow-up effect on Non-word reading speed was found in both RRT conditions (Visual cue: t(46) = −5.20; p < 0.001; Rhythm: t(46) = −4.64; p = 0.003) but not in the control group (t(46) = −1.61; p = 0.973).

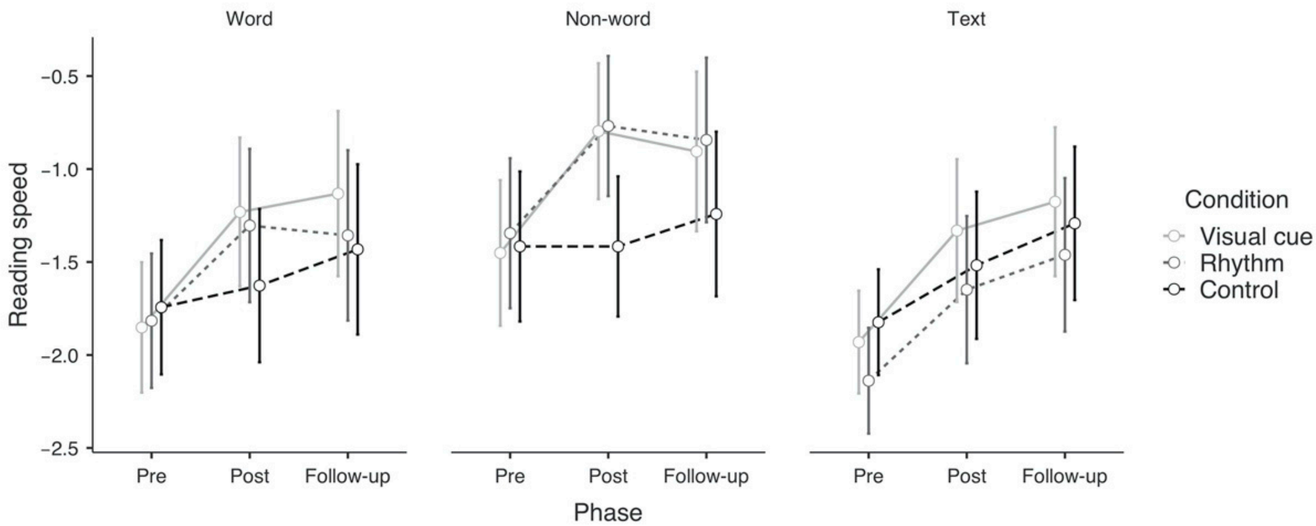

Figure 1. Reading speed z-scores under the three conditions (i.e., Visual cue, Rhythm, No intervention) at each timepoint (i.e., Pre, Post, Follow-up).

Reading accuracy did not change 3 months after intervention in any condition (Phase: F(1,92) = 3.42; p = 0.071; Phase × Condition: F(2,92) = 0.11; p = 0.888).

3.3.2. Pre-Follow-Up Effects on Secondary Outcomes

Reading speed of all verbal materials was still improved 3 months after the end of the interventions, as showed by significant Phase main effects (short non-words: F(1,31) = 32.9; p < 0.001; η^2 = 0.13; long non-words: F(1,31) = 23.60; p < 0.001; η^2 = 0.08; high-frequency short words: F(1,31) = 28.78; p < 0.001; η^2 = 0.09; high-frequency long words: F(1,31) = 12.73; p = 0.001; η^2 = 0.04; low-frequency short words: F(1,31) = 16.94; p < 0.001; η^2 = 0.06; low-frequency long words: F(1,31) = 11.08; p = 0.002; η^2 = 0.03). No significant Phase × Condition effect was found on any reading speed test (ps ranging from 0.22 to 0.72).

Non-significant pre-follow-up accuracy changes were found in any reading test (ps ranging from 0.06 to 0.96).

Pre-follow-up comparisons were significant for RAN (Phase: $F(1,31) = 4.16$; $p = 0.050$; $\eta^2 = 0.03$), with no difference between RRT conditions (Phase × Condition: $F(1,31) = 0.27$; $p = 0.607$).

Similarly, phonemic elision was improved 3 months after intervention (Phase: $F(1,31) = 6.65$; $p = 0.015$; $\eta^2 = 0.04$) and no difference between conditions emerged (Phase × Condition: $F(1,31) = 0.02$; $p = 0.884$).

Finally, Rhythm reproduction was significantly higher at follow-up (Phase: $F(1,28) = 14.64$; $p < 0.001$; $\eta^2 = 0.04$) in both RRT conditions (Phase × Condition: $F(1,28) = 1.81$; $p = 0.190$).

Descriptive statistics of pre, post, and follow-up measures are reported in Table S1.

4. Discussion and Conclusions

Results showed significant reading improvements in both RRT conditions (i.e., auditory and visual cue and auditory rhythm only), as compared to the No Intervention control condition. The overall results revealed that reading speed of words and non-words was significantly improved after both RRT conditions, both immediately after and three months after the end of the intervention. In addition, reading accuracy improvements were specifically recorded for low-frequency words immediately after both RRT conditions. Since a test–retest significant effect on text reading was found at follow-up, as measured by improvement in the No Intervention control group, this measure could not be considered as a medium-term outcome of the intervention.

RRT's foundation lies within the fact that children with dyslexia fail to identify suprasegmental speech cues, namely, rhythm, pitch, and stress [45,46], prior to showing weaknesses in manipulating segmental cues, this being an essential ability to acquire grapheme-phoneme correspondences [47]. RRT might support children in segmenting hierarchical acoustic rhythm structures in language connected to phonological units by stressing syllables and on-set-rimes. The found effects on reading speed and accuracy support such hypothesis and are consistent with previous RRT studies [22,23,25,26].

Interestingly, all secondary outcome measures (i.e., rapid automatized naming, phonological, attentional, and rhythmic abilities) improved in both conditions, without significant differences. These findings are consistent with the relationships between reading abilities and non-linguistic abilities, as visuo-spatial attention, rhythmic abilities, and rapid automatized naming previously described in dyslexia [31]. A previous study in which RRT was compared with a training aimed at the visual components of reading [25] reported better results for the latter in the RAN test, while better results for RRT in the phonological tests. Based on these results, we initially expected that visuo-attentional abilities and RAN would be better targeted by the RRT Visual cue condition; however, the results showed that the auditory anticipation in the Rhythm condition was enough to ameliorate the visuo-spatial components and visuo-auditory integrations involved in the reading process.

In summary, no significant differences were found between the auditory and visual conditions, therefore showing no additional contribution of the visual component to the RRT effect. Such results suggest that RRT's effect on reading is mainly supported by the improvement in auditory temporal processing.

The literature pointed to a potential additional effect of the visual component of the intervention on reading-related cognitive processes, through a facilitation of anticipatory mechanisms [17], no specific contribution of the visual cue setting was found. Such a discrepancy can be read by considering the contrasting neurophysiological literature on temporal processing. Pasinski and colleagues [48] used ERP to investigate whether temporal processing was modality specific or modality general. The contingent negative variation (CNV), a negative potential which has been strongly linked to temporal encoding and anticipation, showed a larger amplitude for the auditory modality compared to the visual modality, suggesting that the brain is more responsive during the encoding of auditory timing information compared to during encoding of visual timing. According to these findings, the visual modality may be less equipped to form temporal expectancies [48]. This hypothesis is consistent with the results from the RRT training, which demonstrated that rhythm processing depended on the auditory modality and multimodal presentation did not add advantages. In line with this, according to Goswami [2], visual attention and auditory-visual integration anomalies in dyslexia [49] would stem from difficulties in forming an internal representation of rhythmic timing and would be mostly explained by the impaired rhythmic auditory entrainment. Moreover, dyslexia has been associated with deficits in multisensory integration and cross-modal learning [50]. A recent study on individuals with dyslexia confirmed impairments in audio-visual speech integration and demonstrated lack of cross-modal enhancement, which has been ascribed to dysfunctions in superior temporal regions [51].

Other training interventions for dyslexia involving visual processing only, without any linguistic component, were previously studied [52–54]. More precisely, training children with dyslexia using action videogames (AVG), without any concomitant phonological training, was found to significantly improve reading scores in Italian children with dyslexia [52,53] through improved visuospatial attention capabilities.

Although attentional shifting is also supported by the Visual cue of RRT through visual anticipation, in RRT the visual guide is based on a predictable rhythmic base. Therefore, it differs from AVG training based on attention shifting, in which the target appears in random locations on the screen at randomized time-intervals. These features make it difficult to specifically compare the AVG and the RRT Visual cue modality results. However, in a previous study the effects of the RRT traditional version (which included a non-controlled use of the visual cue) was compared to those of the AVG training combined with a linguistic tachistoscopic intervention [25]. Findings from this study revealed comparable overall results on reading performance, although different cognitive mechanisms were found to support the outcomes in the two types of training, namely, phonological awareness for RRT and rapid automatized naming for AVG and tachistoscopic training.

A potential methodological limitation of the present study is the increased probability of incorrectly rejecting the null hypotheses (Type I error) due to multiple hypotheses being tested simultaneously. Nevertheless, the probability of a type I error cannot be decreased without increasing that of a type II error, such that real differences may not be detected. Although we opted against the application of p-value adjustments, tests were carried out with pre-planned hypotheses and convergent measures for reading skills were used. Therefore, the reported results can be considered sufficiently reliable.

Overall, RRT efficacy in improving reading skills, producing both immediate and medium-term effect, was confirmed by the present study. Narrative experiential reports from the clinical practitioners who administered RRT revealed that the absence of a visual cue enhanced children's engagement by making the synchronized reading task more challenging, and thus supporting motivation. On the other hand, children's comments during training suggested that the visual cue was particularly useful to reinforce the auditory modality. To further the understanding of the perceived utility of RRT settings by children and practitioners, future studies should include self-report measures of effectiveness and usability collected from RRT users.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app12073360/s1, Table S1: Descriptive statistics of pre, post and follow-up scores for all outcome measures.

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