

## ARTICLE OPEN ACCESS

# Integrating Executive Function Activities Into a Computerized Cognitive Training to Enhance Reading Comprehension in Primary Students

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## ABSTRACT

It is acknowledged the need for interventions to improve reading comprehension and its cognitive underpinnings, such as executive functions. The present study implemented a computerized cognitive training for enhancing reading comprehension in primary school children through EF activities embedded in text comprehension exercises. 263 third and fourth graders were involved in this study and randomly divided into experimental ( $n = 156$ ,  $M_{\text{age}} = 9.06$ ,  $SD = 0.62$ ) and control ( $n = 107$ ,  $M_{\text{age}} = 9.21$ ,  $SD = 0.63$ ) groups. All the children of the experimental group attended 9 training sessions, twice a week, for approximately 1 h and 30 min each within the school context during teaching hours. The intervention proposed several exercises requiring EF processes implicated in text comprehension (e.g., identifying incongruences in the text, ordering events) through a metacognitive approach. The intervention was as standardized as possible through digitalization of the activities and videotaped explanations and demonstrations. The intervention proved to be feasible and effective in enhancing processes relevant for reading comprehension, verbal updating working memory, and nonverbal reasoning, and individual differences in pre-test performances and EF predicted the gains obtained by the training. The study provides a good model of intervention on the cognitive control processes underpinning text comprehension in primary graders.

## 1 | Introduction

Reading comprehension, a complex cognitive process, involves mentally constructing the meaning of a text by integrating information gathered from the text with the reader's prior knowledge (Kintsch 1998). Acquiring good text comprehension skills at school age is central to achieving success in school and personal life. Reading comprehension is indeed transversal to all school disciplines (e.g., Gray 2017; Kamil 2003; Ricketts et al. 2014). However, recent evidence shows that difficulties in reading comprehension reach around 10% of the school population (Hulme and Snowling 2011). Considering the cross-cutting nature of

reading comprehension and the impact it has in many school and non-school domains (e.g., Pimperton and Nation 2010; Sparapani et al. 2018), it is crucial to intervene early and prevent any difficulties and problems in this domain that could spill over into other complications (McArthur and Castles 2017; Stevens et al. 2024).

### 1.1 | Reading Comprehension

Several theoretical models have been proposed in the literature to understand the mechanisms involved in

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reading comprehension (for a review, see McNamara and Magliano 2009). Since the seminal work of Daneman and Carpenter (1980), a substantial body of research has highlighted the relevance of working memory (WM) and executive functions (EFs) in reading comprehension in both typical (e.g., Spencer et al. 2020) and atypical development (e.g., Carretti et al. 2009).

With WM and EFs, we refer to two constructs that encompass various interrelated and partially overlapping cognitive control processes (Baddeley 2000; Diamond 2013). But why are WM and EFs crucial for reading comprehension? To comprehend a text, a reader must form a coherent mental representation based on information in the text and their background knowledge. This seemingly simple output requires a series of mechanisms that rely on executive resources. Some information must indeed be actively maintained due to its relevance (WM capacity), while irrelevant information should be suppressed (inhibition). Additionally, certain information may need to be updated (updating), and in some cases, new information requires changes in the mental representation (flexibility).

As noted by Butterfuss and Kendeou (2018), explicit references to WM and EFs are limited in models and theories of reading comprehension, even though many implicitly assume mechanisms that rely on these cognitive resources (see also McNamara and Magliano 2009 for a discussion). The only exception is Gernsbacher's framework Gernsbacher et al. (1990). In her Structure Building Framework, reading comprehension results from three main processes. First, the reader uses initial information from the text to *lay the foundation* of a mental representation. Second, this initial structure is integrated with new information through a *mapping* process. Third, through a process called *shifting*, the reader modifies the mental representation when new information does not align with the existing structure. These three processes are sustained by two mechanisms: enhancement and suppression. Enhancement involves maintaining relevant information in an active state, while suppression inhibits irrelevant information. These mechanisms directly engage WM and EFs, as demonstrated in studies on “poor comprehenders”—readers who exhibit specific difficulties in understanding text despite strong decoding abilities. Research by Gernsbacher et al. (1990) and Gernsbacher and Faust (1991) has shown indeed that the difficulties encountered by poor comprehenders are linked to deficits in suppression mechanisms, a finding replicated in studies involving WM tasks (e.g., Borella et al. 2010; Cain 2006; Carretti et al. 2004).

Another way through which EFs can support text comprehension is through comprehension monitoring strategies. Comprehension monitoring involves tracking the progress of one's understanding, ensuring the process remains effective, and taking corrective actions when needed (Baker and Brown 1984). Comprehension monitoring itself involves a self-directed awareness that enables readers to recognize and address gaps in their understanding (Thiede et al. 2003). In this sense, monitoring is an essential aspect of self-regulated learning (SRL) that refers to the process by which learners actively manage their own learning through goal setting,

monitoring, and adjusting their strategies to achieve desired outcomes (Zimmerman 2002).

In this context, EFs play a foundational role by supporting the metacognitive and self-regulatory skills, i.e., the comprehension monitoring process, essential for reading comprehension.

## 1.2 | EFs

EFs are a family of mental abilities that enable individuals to reach a goal by exerting control over thoughts and behaviors and overriding habits and impulses (Diamond 2013). Among cognitive components, EFs have received much attention in relation to reading comprehension (Cartwright 2012; Cartwright and Duke 2019; Follmer 2018).

In order to understand how EFs can support reading comprehension, it is first necessary to comprehend the complexity and multi-componentiality of the EF construct. In literature, there are various EF explicative models, the most widespread of which is the model of Miyake et al. (2000), enriched then by Adele Diamond's contributions (2013). According to Diamond's model (2013), three central executive components can be differentiated even if strictly interrelated: inhibitory control, WM, and cognitive flexibility. Inhibitory control consists of the possibility of resisting carrying out an automatic activity in favor of a new one (response inhibition) and in controlling interference (interference control). Interference control can be divided into cognitive inhibition, that is the inhibition of thoughts and memories, and selective attention, that is the inhibition at the level of attention. WM allows us to check and monitor information in mind, and specifically the updating process helps to modify the memory's contents by substituting them with newer input. Cognitive flexibility is defined as the ability to shift from one set rule to another, based on contextual or mental information.

EFs continue to develop through late adolescence (Zelazo et al. 2008), with the most significant changes occurring during the preschool years. During this period, EFs play a key role in shaping and interacting with self-regulation skills, which encompass children's ability to manage their cognitive, emotional, and behavioral states (Howard et al. 2020). The preschool years are marked by rapid advancements in both the cognitive and neurofunctional aspects of EF development (Garon et al. 2008). Research highlights a gradual differentiation within the executive domain during this stage, beginning with the emergence of inhibition and WM, followed by cognitive flexibility (De Luca and Leventer 2008; Diamond 2013; Miller et al. 2012; Monette et al. 2015; Lee et al. 2013; Usai et al. 2013). These foundational components, in turn, support the maturation of more advanced EFs, such as abstract reasoning, problem-solving, and planning, which form the basis of fluid intelligence (Collins and Koechlin 2012; Diamond 2013; Lunt et al. 2012).

## 1.3 | The Involvement of EFs in Reading Comprehension

In general, EFs enable goal setting, monitoring progress, adapting strategies, and maintaining focus—core aspects of SRL (van

der Schoot et al. 2012). In the reading comprehension domain, these complex functions can support self-regulatory abilities. As children progress in literacy and self-regulation, they develop from simpler, foundational EFs to more complex skills. This progression is part of a re-organizational process where children learn to integrate and coordinate new skills with existing ones, ultimately enhancing their literacy and self-regulation capabilities synergistically (Hanno et al. 2020). For these reasons, EFs are linked to both early literacy skills and advanced competencies such as reading comprehension, as demonstrated by many studies (e.g., Best et al. 2011; Jones et al. 2016). Research has also shown that learning to read and self-regulation skills enhance each other; interacting with external factors, indeed, literacy and self-regulation develop concurrently in a bidirectional relationship (Hanno et al. 2020).

Specifically, evidence suggests that each EF component plays a specific role in supporting reading comprehension (Cartwright 2015; Cartwright et al. 2020; Follmer 2018; Spiegel et al. 2021). For instance, response inhibition allows suppression of irrelevant mental and textual information by focusing only on what is relevant to the task (e.g., De Beni and Palladino 2000). Control of interference helps to inhibit incorrect and interfering information, to choose which section of material to read, to emphasize one sentence but not another, and to choose one interpretation of a complex topic instead of another (e.g., Borella and De Ribaupierre 2014; De Beni et al. 1998). Also, the second EF component, WM, plays a central role in reading comprehension. It makes it possible to simultaneously activate and work on a limited number of concepts to be chosen based on relevance criteria during reading, to foster inferences, and to update prior knowledge with incoming information and ideas (Carretti et al. 2005; Follmer 2018; Palladino et al. 2001; Ruffini et al. 2023). WM can also contribute to text comprehension by supporting general logical reasoning processes, both in verbal and nonverbal modalities (Mammarella et al. 2015). Lastly, cognitive flexibility underlines the ability of readers to integrate two or more text processing systems (e.g., phonetics and use of semantic context cues) to read a text, flexibly use different reading strategies as well as flexibly move from one text to another (Cartwright et al. 2010; Yeniad et al. 2013). A recent meta-analysis exploring the relations between EFs and academic outcomes, including reading comprehension, showed that the relationship between reading comprehension and WM and shifting remained consistent throughout the primary graders, although the association with inhibitory control tended to decline (Spiegel et al. 2021).

#### 1.4 | Training Reading Comprehension Through EF Activities

Considering the relevant role of EFs in reading comprehension, it is not surprising that many studies attempted to ameliorate reading comprehension skills through the improvements of EFs (e.g., Dunning et al. 2013; Gray et al. 2012; García-Madruga et al. 2016; for a review: Melby-Lervåg and Lervåg 2014).

For what concerns interventions focused only on EFs, different training procedures have been proposed in the literature (for a

review see Diamond and Ling 2020), adopting some acknowledged principles such as novelty, usability, and activities challenging the current executive skills (Diamond and Lee 2011). Interventions primarily vary in terms of duration, frequency, administration type (e.g., by clinician or teacher), setting, and targeted executive component. Specifically, there have been many attempts in the literature to verify the efficacy of training targeting WM. For instance, a recent meta-analysis of WM training studies, encompassing 87 publications, revealed immediate improvements on intermediate transfer measures, such as verbal and visuospatial WM following training (Melby-Lervåg et al. 2016). However, there was insufficient evidence to support reliable improvements in measures that are “far” from the skill trained, including reading comprehension. Accordingly, even if some new interventions targeting other EF components, such as cognitive flexibility, in school-age children improved both related skills and academic skills, including reading comprehension (Cartwright et al. 2020), a common feature of EF intervention is the limited transfer of their effects to untrained skills, the so-called “far-transfer effects” (see meta-analyses: Bombonato et al. 2023; Melby-Lervåg and Hulme 2013; Melby-Lervåg and Lervåg 2014).

Thus, it has been suggested that activities training exclusively specific EF components make it difficult to transfer the effects of EF training to other domains, such as reading comprehension. The lack of far-transfer effects on academic skills could also be linked to other methodological characteristics such as the implementation of individual home sessions rather than “ecological” school settings, or the use of outcome measures that only scratch the surface of reading comprehension or of some dimensions without aligning with the objectives and content of the intervention (Clemens and Fuchs 2022).

#### 1.5 | Embedding EF Exercises Within Reading Comprehension Tasks

In view of the importance of EFs for promoting a self-regulated approach to reading comprehension, the key elements of effective training could be embedding EF activities within reading comprehension exercises. Indeed, new directions suggest how important it is to promote cognitive training activities that overlap as much as possible with academic tasks to produce higher effects (Cartwright and Palian 2024; Peng and Swanson 2022). Embedding EF tasks within a learning setting means integrating activities that explicitly target EF skills—such as WM, cognitive flexibility, and inhibitory control—into the regular instructional context. This approach goes beyond incidental engagement of EF processes by deliberately structuring tasks to explicitly integrate these cognitive components as central elements. The tasks incorporate features such as incremental difficulty to challenge WM, reflective opportunities for students to articulate their strategies and enhance metacognitive awareness, and requirements to shift perspectives or strategies, thereby fostering cognitive flexibility. These elements align with established principles for EF development, such as increasing task complexity, promoting awareness of cognitive processes, and maintaining a high level of challenge suited to the learner’s capacity. By embedding EF-focused design elements, this approach ensures that both EF skills and learning skills are actively targeted, supporting their

synergistic development and fostering broader cognitive abilities like self-regulation, adaptability, and higher-order thinking (Cartwright and Palian 2024).

Specifically, these tasks are designed to enhance cognitive processes while simultaneously engaging learners in subject-specific content. For example, in mathematics, students might solve multi-step word problems requiring them to focus on holding intermediate results in mind while processing further information (e.g., Peng et al. 2016; Ruffini et al. 2024). Furthermore, in a history lesson or during a group activity, students could become aware of analyzing primary sources from different perspectives, requiring them to switch between interpretations and evaluate conflicting viewpoints (e.g., Blair and Raver 2015; Drovandi et al. 2023). These embedded EF tasks align cognitive skill-building with curriculum goals, promoting deeper learning and better academic outcomes. By improving these skills through structured interventions, students can achieve better outcomes in their learning (see Hanno et al. 2020 for a revision of various intervention studies that simultaneously captured self-regulation, literacy, and their contexts). This permits implicitly activating also emotional and motivational aspects (such as beliefs about their capabilities and managing feelings of frustration or excitement) which are crucial for understanding and integrating new information (Massey and Miller 2017). Furthermore, by adapting EF tasks to literacy activities, interventions could foster a metacognitive approach to reading, where students are actively engaged in modulating their cognitive control processes in response to task demands. Finally, conducting an intervention aimed at promoting executive processes within learning activities in the school context can favor the involvement of the whole class simultaneously.

For what concerns specifically, reading comprehension interventions are supposed to be effective when students are trained in skills that directly involve written text comprehension (Melby-Lervåg and Lervåg 2014). In this sense, training that includes EF activities within text comprehension exercises would represent a direct intervention in text comprehension acting on the underlying mechanisms.

Based on our knowledge, only a few trainings have embedded EF activities into reading comprehension tasks (Carretti et al. 2017; Cirino et al. 2017; García-Madruga et al. 2013). Cirino et al. (2017) conducted an EF training integrated with SRL strategies and embedded into reading comprehension tasks among third graders at school. The training was found to be effective in promoting reading comprehension measured with texts whose content, but not exact wording, was covered in the training, but not with texts with different contents and background knowledge related to them. The authors recognized some methodological limitations that could have influenced the results, for instance, challenges in measurement of the targeted constructs (e.g., sensitivity, accuracy) as well as the short duration of the intervention, which lasted 2 weeks for a total of ten 35-min sessions. García-Madruga et al. (2013) conducted a training embedding EF in reading comprehension tasks on third graders within the school context. This intervention progressively trained the executive processes essential for text comprehension, beginning with simpler tasks, such as rearranging basic sentences, and advancing to more complex tasks that involve integrating

information within a detailed text. Embedding EF tasks within reading comprehension, therefore, involves designing activities that require students to apply progressively more complex EF skills continuously, as they engage with key reading comprehension skills, rather than including separate tasks that train EF skills in isolation. This is in line with results from a recent meta-analysis by Cartwright and Palian (2024) which emphasizes that reading-specific EF interventions need to focus on cognitive processes directly involved in reading tasks. For example, among the training tasks, selective attention was stressed in a task that required identifying inconsistencies in the texts presented, and more attention was required as the task became more difficult. Overall, it was found an improvement in reading comprehension and nonverbal reasoning; moreover, results highlighted that the group with a low level of reading comprehension improved more than the group with high reading comprehension levels. However, the study by García-Madruga et al. (2013) did not include a control group; thus, the gains recorded could not be attributed directly to the training. Carretti et al. (2017) proposed a similar version of the García-Madruga et al. (2013) training, with some revisions, for third-grade children. Children participated in diverse reading activities, implicating WM alongside four distinct active processing components: i.e., focusing on relevant information, connecting new information with long-term knowledge, updating WM content, and controlling irrelevant information. As in the original study, the training proved to be effective in improving components of reading comprehension directly targeted during the training and WM updating. In addition, immediate transfer effects to standardized reading comprehension tasks were reported, not maintained, however, at 2 months follow-up. Both trainings also used a metacognitive approach prompting children to reflect during activities on the cognitive processes they were implementing. The procedural features of the training proposed were intensity (twice-weekly), length (medium: approximately 2 months), and context-true as activities were conducted at class level within the school context.

In sum, the few studies described above support the importance of combining EF exercises with activities of reading comprehension, but further evidence is needed in order to support the efficacy of such a procedure and to find tools and methods that are agile and suitable for routine school activities.

## 1.6 | Digitalized Training for Reading Comprehension

The digitalization of educational practices has introduced innovative approaches to enhancing reading comprehension within the framework of computer-assisted delivery (CAD) learning. Digitalized training leverages technology-driven tools and platforms, such as adaptive e-learning systems, gamified reading applications, and interactive multimedia content, to engage learners in more dynamic and personalized ways (e.g., Hashim et al. 2019).

These methods aim to address the limitations of traditional paper-based instruction by incorporating interactivity, immediate feedback, and data-driven customization to meet diverse learner needs (e.g., Capodieci et al. 2020). In contrast to interventions promoting EF, which are very common

in digital mode, albeit especially in clinical populations with telerehabilitation (Capodiecì et al. 2022; Diamond and Ling 2020; Graziani et al. 2024), digital text comprehension interventions are less common (but see Snow et al. 2016). In fact, this component is still commonly trained in the standard paper-and-pencil mode, at least in Italian school contexts. As global educational systems increasingly prioritize technology integration (Agenda 2030, OECD 2021), understanding the efficacy and impact of digitalized training on reading comprehension becomes crucial for informing curriculum design and instructional strategies.

In this context, taking inspiration from previous research (Carretti et al. 2017; García-Madruga et al. 2013) and attempting to overcome some of the limitations of the studies, in this study a digitalized training was implemented. In comparison to classic paper-based methods, digital text comprehension interventions contribute to standardization, scalability, and engagement.

Firstly, digital tools ensure consistent training delivery by automating content presentation. Previous studies (Carretti et al. 2017; García-Madruga et al. 2013) conducted training in schools led by experts, either researchers themselves or individuals trained by them. Digitizing the training facilitates integration into academic settings, addressing challenges related to teacher training and mitigating issues of teacher-dependent variability in motivation, skills, and knowledge. Tools such as video tutorials and automated content delivery ensure standardization and replicability, reducing dependence on individual instructors. This advantage has been demonstrated in both children and university students (Martin et al. 2007; Serrano-Mendizabal et al. 2023). For example, teachers' self-efficacy beliefs, which vary across classrooms and significantly influence student outcomes, are factors largely beyond researchers' control but can impact the consistency of intervention results (Caprara et al. 2006). Secondly, digital interventions can enhance children's motivation, as digital tools introduce novelty to the Italian school context (e.g., Ciampa 2013; Passey et al. 2004). Digital technology also increases appeal by enabling customization, such as font sizes and colors selected for relevance (e.g., Oliver 2010). Additionally, computerized training allows real-time monitoring of participants' responses and provides immediate feedback (Morgan et al. 2020). This helps children identify and correct ineffective strategies, reducing error persistence and fostering adaptive learning (e.g., Tucci et al. 2015). Finally, digitized training promotes scalability, enabling the inclusion of large participant groups without compromising quality. Remote access removes geographical barriers, extending the reach to diverse populations, including underserved and rural areas, and ensuring broad applicability.

All these findings highlight the promising opportunities for using digital tools in reading comprehension interventions.

## 1.7 | Aim of the Study

The present study deals with the implementation of a computerized cognitive training designed to improve reading comprehension by boosting the main EF components in 3–4 graders. Accordingly, the first aim of the study was to evaluate

the feasibility and fidelity of the training investigating teachers' feedback (Research Aim 1-RA1). The second aim was to study the efficacy of the training program on the cognitive processes involved in text comprehension (RA2). Lastly, this study aimed to investigate whether the cognitive pre-test profile of the children could predict the efficacy of the training (RA3).

To reach these aims, a combination of measures ensures a comprehensive assessment of the intervention's effectiveness across both specific and general domains, allowing us to understand not only immediate gains in the trained skills but also the potential for broader cognitive benefits that might extend to untrained, yet relevant, areas.

We hypothesized finding higher improvements in reading comprehension tasks, verbal updating in WM, and nonverbal reasoning in the trained group in comparison to the passive control group. We also expected that differences in pre-test functioning among children would explain the variability in the effectiveness of the training, specifically that children who began with a lower level of performance experienced greater improvements.

## 2 | Method

### 2.1 | Participants

Recruitment took place on a voluntary basis. The schools that are in connection with the University of Florence, FORLILPSI Department, were invited to participate in this project by means of an interview with the school Director. In case of acceptance by the school Director, the classes whose teachers were willing to host the project in their class were included in the present study. Signed consent from both parents and verbal consent from the children were always collected before starting the training. The project took place in the second semester of the school year 2022/2023.

18 classes from the Tuscan region in central Italy took part in the project and were randomly assigned to either the experimental ( $n = 11$ ) or the control ( $n = 7$ ) groups.

For the objectives of the present study, children with Neurodevelopmental Disorders ( $n = 26$ ) or other Special Education Needs ( $n = 30$ ) were excluded from the overall sample, since they underwent all the intervention sessions but with an adapted version of the training specifically designed by the research group, or they were participating in a medical and neuropsychological diagnosis path. Four children did not participate in the post-test assessment since they were absent from school at the time of evaluation. Thus, the total sample consisted of 263 children ( $M_{\text{age}} = 9.12$ ,  $SD = 0.63$ ; 119 3rd, 144 4th graders; 114 F, 129 M) divided as 156 children ( $M_{\text{age}} = 9.06$ ,  $SD = 0.62$ ; 73 3rd, 83 4th; 69 F, 87 M) in the experimental group and 107 children ( $M_{\text{age}} = 9.21$ ,  $SD = 0.63$ , 46 3rd, 61 4th; 45 F, 62 M) in the control group. All schools shared a similar socio-cultural and geographical background as well as similar pedagogical approaches and educational projects.

Socio-economic status (SES) was evaluated with a questionnaire investigating the school qualification (elementary

school, middle school, diploma, degree) of both parents (2: both parents with an elementary license; 8: both parents with a degree) and was middle/high ( $M = 5.75$ ,  $SD = 1.2$ ;  $Min = 3$ ,  $Max = 8$ ).

## 2.2 | Design

Besides feasibility measures, collected by a teachers' feedback questionnaire at the end of the training (RA1), a cluster-randomized pre-post test experimental design was used to analyze the efficacy of the training (RA2) and to investigate whether the cognitive pre-test profile of the children could predict the efficacy of the training (RA3). We used cluster-randomized trials (Roberts et al. 2022) because the random assignment of individuals was not feasible. We were not able to randomize students in a teacher's classroom. Instead, it was more manageable for us to randomize at the class level, with some classes receiving the intervention and others receiving typical curriculum lessons.

Assessments were conducted during the first and last week of the project. In the intermediate 5 weeks, the experimental group conducted the training, and the control group continued with the regular teaching activities. Assessments were both collective and individual. Two collective assessment sessions of around 1 h each were scheduled on two different days within the same week. In the first session, the children performed a test of nonverbal reasoning followed by an aligned test of reading comprehension. In the second session, a test of verbal WM and another test of reading comprehension were provided. During the same week, each child participated individually for 45 min in an assessment of EF through the TeleFE digital platform (Anastasis Cooperative; Hogrefe Eds., Rivella et al. 2023) guided by a psychologist thoroughly trained in the administration of the tasks.

## 2.3 | Materials

### 2.3.1 | Feasibility Measures

To evaluate the feasibility of the training program and capture participants' experiences, we developed a questionnaire tailored for teachers. The questionnaire was informed by previous feasibility studies on game-based training (Corti et al. 2018; Görden et al. 2020; Rivella et al. 2024) and was designed to provide a comprehensive understanding of the program's impact, assessing satisfaction, usability, and potential areas for improvement from multiple perspectives. By gathering feedback from teachers, we sought to evaluate not only the children's engagement and motivation but also the overall practicality and adaptability of the program in everyday educational settings.

Teachers' feedback questionnaire. At the end of the training, teachers from the experimental group filled out a questionnaire with nine ad hoc questions on a Likert scale (from *not at all* [1] to *completely* [5]) and two open questions.

Q1. I am satisfied with having taken part in the intervention project.

Q2. I think the training was useful.

Q3. I have noticed improvements at the class level in carrying out daily teaching activities after the training.

Q4. The instructions for the children included in the various stages were sufficient to understand the activities.

Q5. Children enjoyed carrying out the activities.

Q6. I would recommend this training to other teachers.

Q7. It was difficult to fit the weekly training sessions into the school timetable.

Q8. It was difficult to get a tablet/PC and headphones to carry out the activities.

Q9. There were connection problems that made it impossible to carry out the activities.

Q10. If you could change something, what changes would you suggest?

Q11. What do you think about trying to combine the use of technological tools with the enhancement of text comprehension?

### 2.3.2 | Efficacy Measures

As far as the effectiveness of the intervention is concerned, we selected outcome measures based on prior research in the field (Carretti et al. 2017; García-Madruga et al. 2013), focusing on reading comprehension, verbal updating in WM, and nonverbal reasoning. Given the complexity of reading comprehension as a multifaceted cognitive process, we implemented a range of measures to capture both immediate and broader effects of the intervention. Specifically, we arranged these measures along a continuum from aligned, directly trained tasks to non-aligned tasks that still relate to reading comprehension but engage other cognitive processes (Clemens and Fuchs 2022). This spectrum-based approach allowed us to evaluate the effectiveness of training both through near-transfer effects (improvements on tasks directly related to the intervention) and far-transfer effects (improvements on related but untrained tasks) (Melby-Lervåg and Hulme 2013; Sala and Gobet 2016, 2017). We assessed specific training effects on an aligned reading comprehension test and verbal updating in WM, which reflect the directly targeted cognitive skills of the intervention. These tasks were selected to measure improvements in the precise areas trained, thus capturing near-transfer effects. In parallel, we assessed far-transfer effects through a standardized test of reading comprehension and a nonverbal reasoning task, which were not directly trained but are cognitively associated with the intervention. The standardized reading comprehension test enabled us to evaluate whether improvements in comprehension extended to a broader, standardized context beyond the specific training exercises. Similarly, the nonverbal reasoning measure provided insight into whether the training impacted reasoning, which is indirectly related to EF and reading, further evidencing far-transfer effects.

### 2.3.3 | Specific Effects

**2.3.3.1 | Reading Comprehension (DARC).** Text comprehension was assessed with a task belonging to the Diagnostic Assessment of Reading Comprehension battery (DARC; August et al. 2006). The task was previously adapted to Italian and used in other Italian studies (Carretti et al. 2017). Children were asked to read silently and individually a text consisting of four short paragraphs describing transitive relationships among a set of real and unreal objects (e.g., Maria likes to eat fruit. Most of all, she likes to eat nuras. A nura is like an orange. But a nura is bigger than an orange). Three invented words were inserted into the text that referred to unreal objects but whose characteristics could be inferred by referring to real objects. After reading the text, the children had to answer 15 comprehension questions coded as 0 (correct answer) or 1 (incorrect answer). Four scores were calculated: (1) Knowledge access: accessing prior knowledge by retrieving information from long-term memory (row scores from 0 to 2 points); (2) Text memory: remembering specific information presented in the text (row scores from 0 to 3 points); (3) Inferences: making inferences from the information in the text (row scores from 0 to 4 points); (4) Integration: integrating prior knowledge with the information in the text (row scores from 0 to 6 points). Two parallel texts from the same battery were used pre- and post-test.

**2.3.3.2 | Working Memory Updating (WMU).** To assess WM, a verbal updating task was also used (Carretti et al. 2017; Palladino et al. 2001). The examiner read aloud six lists of eight words each (common and familiar natural objects) to the whole class and asked the children to remember the three smallest objects from each list in the order of presentation. The number of words remembered correctly was used as the dependent variable (row scores from 0 to 18). The proportion of intrusion errors (i.e., words recalled by participants that did not refer to the smallest objects) calculated out of the number of words correctly remembered was considered a measure of inhibition (Borella and De Ribaupierre 2014; Carretti et al. 2017). Two parallel sets of words from the same battery were used for the pre- and post-test.

### 2.3.4 | Transfer Effects

**2.3.4.1 | Standardized Reading Comprehension Test.** An Italian standardized test (Cornoldi et al. 2017) to measure text comprehension was also used. The children were asked to read a passage individually and silently, selected on the basis of the class they attended, and to answer 12 or 14 questions, for third and fourth graders, respectively. Two parallel versions of the test were used pre- and post-test. Row scores, given by the number of correct responses, were converted to z scores and considered as dependent variables.

**2.3.4.2 | Nonverbal Reasoning (Nonverbal Reasoning Scale 2 of Cattell's Culture Fair Intelligence).** Non-verbal intelligence was measured through a standardized and widespread tool (Cattell and Cattell 1965) consisting of four blocks of visual stimuli requiring the identification of which stimulus among five completes a sequence of four stimuli (block 1,

12 stimuli), which of five stimuli differs from the others (block 2, 14 stimuli), which of five stimuli completes a matrix of four stimuli (block 3, 12 stimuli), and which of five stimuli relates to a specific figure (block 4, 8 stimuli). The sum of the correct answers was the dependent variable (row scores from 0 to 46). The task included two parallel versions, which were administered pre- and post-test.

### 2.3.5 | Analysis of the Predictors of the Training Effects

**2.3.5.1 | EF.** The assessment of the basic components of EF (response inhibition, interference control, cognitive flexibility, WM) was done by computer-based tests through the TELEFE battery (for details: Rivella et al. 2023). The same tasks' order assigned with the Latin square at the pre-test was used during the post-test. Three tasks were used:

- *Go/No-Go task.* This task measured inhibition control. The child was asked to press the spacebar as fast as possible when a target stimulus (Go stimulus) appeared on the screen and not to press it when a non-target stimulus (No-Go) appeared. The mean of the number of correct responses to the non-target stimuli in the four blocks was considered the dependent variable (row scores 0–15).
- *Flanker task.* This task consisted of three blocks. The first two blocks measured interference control and the third block cognitive flexibility. The child saw on a white screen five aligned arrows that may all have the same direction (congruous condition) or the arrow in the center may have the opposite direction to the side arrows (incongruous condition). In block 1, the arrows were blue and the child had to indicate the direction of the arrow in the center (by pressing S on the keyboard when the direction was left and L when the direction was right). In block 2, the arrows were orange and the child had to indicate the direction of the side arrows. In block 3, the child had to simultaneously follow the rules of the previous blocks according to the color of the arrows. The mean number of correct responses (row scores 0–20) in the incongruous conditions of blocks 1–2 and the number of correct responses (row scores 0–32) in the incongruous conditions of block 3 were considered the dependent variables.
- *N-Back task.* This task measured visuospatial WM. Children were asked to press the spacebar when the current stimulus matched (in terms of color, shape, or letter) that of n (1 or 2) previous steps in the sequence. The mean of the number of responses to the targets plus the number of absent responses to the non-targets in the six blocks (row scores 0–52) was considered the outcome measure.

## 2.4 | Intervention

The intervention took inspiration from the training developed by García-Madruga et al. (2013) and reposed in the Italian context by Carretti et al. (2017). The activities were the same as in Carretti et al. (2017) with some changes and additions. The original materials by García-Madruga et al. (2013), adapted

into Italian by Carretti et al. (2017), were presented to the entire classroom with the aid of an electronic whiteboard. In the original procedure, texts, images, and exercises were displayed on the electronic whiteboard's screen and each child, after understanding the task, individually completed the activities on their personal paper protocol. The digitalisation therefore used and adapted these materials, to create an individual presentation displayed on the pc of each child. Specifically, a digitizing of the training using a web platform (Qualtrics XM) was implemented. Consistently, in order to make the intervention's activities as attractive as possible, images, icons, and different fonts were used (e.g., Oliver 2010). In addition, a narrative story to empower pupils' motivation and to tie the sessions together was included. On the basis of the physical metaphor of cognitive training, the story was about a boy and a girl who would like to climb a mountain, and, on the way, they made 8 stops. Each stop required some exercises empowering their skills to continue their journey. Each session began with a short video showing the two protagonists presenting the comprehension process to be trained and the underlying cognitive processes. The two animated characters accompanied the children up to the top of the mountain, reached in the last session. In comparison to the previous version, to enhance the generalization of training effects to standardized comprehension tasks, the final two sessions of the training were modified by adding exercises resembling the conventional one-page text reading task with subsequent question answering. Furthermore, in the revised version, all reading comprehension processes are concurrently honed within tasks mirroring the classic features of school texts, encompassing a specific topic, medium length, and closely related questions. Another element added to the training was that at the end of each session's block, children's performance was monitored, and an immediate real-time feedback was provided, so that they had the opportunity of repeating the exercise to the correct response. Lastly, a self-assessment questionnaire was included at the end of each session, considering the importance of favoring children's reflection on what has been trained and learned.

#### 2.4.1 | In Each Training Session, the Following EF Components Were Addressed

1. *Selective attention*: to pay attention to the information contained in the text through observation.
2. *Inhibitory control*: to stop and think before acting.
3. *WM*: making connections with what has been learned from the text and with what can be retrieved from the previous knowledge.
4. *Cognitive flexibility*: shifting attention between the various contents and parts of the text/section.

A description of each session and three detailed examples of activities extrapolated from different sessions embedding EF components with reading comprehension tasks are provided in Appendices 1 and 2, respectively.

The computerized cognitive training was composed of nine sessions, carried out twice a week for 5 weeks in 1.5-h sessions. A tenth session was used for children who missed a session as

they were absent from school. The intervention was conducted at the class level or with half a class at a time, depending on the number of digital devices provided by the school. Each child had a personal computer or tablet. Firstly, all children watched the video together introducing the session and discussed with their classmates the comprehension processes to be trained and the cognitive processes required by the task. Then, they individually carried out the proposed exercises, which were divided into blocks. None of the exercises involved verification of the answer given, except for the last exercise of each block, which required the correct answer in order to move on to the next block. In this one, if children answered correctly, they could independently proceed to the next block. If they made a mistake, they had the opportunity to discuss it with a classmate to decide together on the correct answer.

The training implementation relied heavily on teacher involvement. Specifically, tenured classroom teachers completed satisfaction questionnaires, while soon-to-be-graduated teachers conducted the intervention itself. The tenured teachers acted as observers during the sessions, whereas the trainee teachers played a hands-on role, preparing all computers with access links to the training, setting up the interactive whiteboard to display an introductory video, leading group metacognitive reflections, and assisting children with technical issues or other needs (such as restroom breaks). During the digitized activities, however, the children worked autonomously, with teachers refraining from intervening. The trainee teachers participated in two training sessions, each lasting 2 h, with project researchers to review the theoretical foundations of the training and discuss every aspect they would be managing during the implementation of the intervention.

The business-as-usual control group during the intervention period for the experimental group followed the usual teaching lessons, without any external changes.

## 2.5 | Statistical Analysis

Statistical analyses were conducted by SPSS 2023, version 28.0.1.0. For each EF task, only children who completed the task with a total accuracy higher than 60% on the go trials of the Go/No-Go task, the congruent trials of the Flanker task, and the total trials of the N-Back task were considered for the analysis (Rivella et al. 2023).

Descriptive statistics and analysis of normality assumption for pre-test and post-test data were carried out on all dependent measures.

To verify the existence of differences between the experimental and control groups at baseline considering SES, age, sex, school grade, and pre-test performances on outcome measures (DARC-Knowledge, DARC-Text Memory, DARC-Inference, DARC-Integration, MT-Reading Comprehension, WMU-Recall, WMU-Intrusion errors, and Cattell test), chi-square and t tests were run.

To study the feasibility of the intervention (RA1), the questionnaire filled out by teachers was descriptively analyzed.

To assess the effectiveness of the intervention (RA2), general linear models (ANCOVAs), with the post-test performances as dependent variable, the group and school grade as fixed factors, and pre-test performances as covariate, were used for all variables of interest. The False Discovery Rate correction method (Pastore et al. 2005) for multiple comparisons was used. Effect sizes were computed by eta squared ( $\eta^2$ ) (Lenhard and Lenhard 2016) for all measures ( $\eta^2$ : from 0.01 to 0.05 = small effect size, from 0.06 to 0.13 = medium effect size, from 0.14 = large effect size).

Lastly, to examine how the cognitive individual profile contributes to explaining improvements in the post-test (RA3), linear regression analyses were conducted. The predictors included pre-test scores, grade, and EF measures, while the outcome measure was standardized training gains (deltas calculated for each child as the difference between post-test and pre-test performance, divided by the standard deviation of pre-test performance across both groups). This analysis was performed for each measure that exhibited differences between the two groups at the post-test.

### 3 | Results

#### 3.1 | Feasibility and Fidelity

The questionnaire filled out by teachers ( $n = 10$ ) at the end of the training was descriptively analyzed, and the mean score for each question was calculated and reported in Table 1. As suggested by the mean values, which fell in the upper part of the scale, teachers positively rated their satisfaction level of the training (Q1) as well as the utility of the training (Q2) and they claimed that they noticed children's improvements in carrying out daily teaching activities after the training (Q3). Then, regarding the adaptability of training to children, activities' instructions were rated with the highest level of understandability (Q4). Teachers reported high levels of children's enjoyment in carrying out the activities (Q5) and the majority of them would recommend this training to other teachers (Q6).

With regard to the practical feasibility of the training, teachers reported a slight difficulty in fitting the weekly training sessions into the school timetable (Q7) and in obtaining a tablet/PC and headphones to carry out the activities (Q8). In line with technical difficulties, a few connection problems during the performance of activities were recorded (Q9).

Lastly, referring to the first open question (Q10. If you could change something, what changes would you suggest?) teachers suggested some changes to the training: introducing further adaptations to the activities ( $n = 1$ ), increasing the number of graphics ( $n = 2$ ), adding more sessions ( $n = 3$ ), adding non-computerized activities to the training ( $n = 3$ ), and reviewing the timings used ( $n = 1$ ). Lastly, all teachers agreed with the use of technological tools to promote reading comprehension, adding that in their opinion, the use of technological tools was very stimulating and engaging for the children, thus promoting motivation and fun during learning.

Out of 156 children who took part in the training, 112 completed all sessions. Of the remaining children, 29 missed one session, 13 missed two sessions, and 2 missed four sessions.

#### 3.2 | Specific and Transfer Effects

All the variables were normally distributed (Hair et al. 2010), except for the DARC-Knowledge variable, which was normalized with the base-10 logarithmic transformation. Possible differences between the experimental and control groups at pre-test were assessed. The experimental and control groups did not differ for SES ( $t(232) = -0.77, p = 0.44$ ), age ( $t(261) = 1.9, p = 0.06$ ), sex ( $X^2(1) = 0.12, p = 0.73$ ), or school grade ( $X^2(1) = 0.37, p = 0.54$ ). Experimental and control groups did not differ in any pre-test outcome measure, except for DARC-Inference and MT-Reading Comprehension, in which the experimental group outperformed the control group (Table 2).

Table 2 contains descriptive statistics for both pre- and post-test outcome measures in the two groups and the results of the

**TABLE 1** | Descriptive statistics of scores at the teachers' feedback questionnaire.

	<i>N</i>	<i>Min</i>	<i>Max</i>	<i>M</i>	<i>SD</i>
Q1. I am satisfied with having taken part in the intervention project	10	3	5	4.3	0.95
Q2. I think the training was useful	10	3	5	4.4	0.7
Q3. I have noticed improvements at class level in carrying out daily teaching activities after the training	10	2	5	4.	1.15
Q4. The instructions for the children included in the various stages were sufficient to understand the activities	10	5	5	5	0
Q5. Levels of pupils' enjoyment in carrying out the activities	10	4	5	4.9	0.32
Q6. I would recommend this training to other teachers	10	2	5	4.1	1.1
Q7. It was difficult to fit the weekly training sessions into the school timetable	10	1	5	2.6	1.26
Q8. It was difficult to get a tablet/PC and headphones to carry out the activities	10	1	5	2.1	1.37
Q9. There were connection problems which made it impossible to carry out the activities	10	1	5	2.2	1.48

TABLE 2 | Pre- and post-test descriptives, differences at pre-test and at post-test between the two groups.

	Group	Pre					Difference at pre-test					Post					Difference at post-test (group effect)					
		n	M (SD)	t	p	Adjusted p	n	M (SD)	F	p	Adjusted p	n	M (SD)	F	p	Adjusted p	n	M (SD)	F	p	Adjusted p	$\eta^2$
Reading comprehension (DARC)	Control	105	1.9 (0.31)	1.16	0.247	0.329	101	1.72 (0.55)	3.68	0.056	0.075	0.02										
	Experimental	153	1.84 (0.45)				156	1.83 (0.41)														
Text memory	Control	105	2.32 (0.79)	1.24	0.216	0.329	101	2.25 (0.92)	5.18	0.024	<b>0.048</b>	0.02										
	Experimental	153	2.20 (0.83)				156	2.38 (0.77)														
Inferences	Control	105	2.05 (1.15)	-2.38	0.018	<b>0.048</b>	101	2.75 (0.96)	4.13	0.043	0.069	0.02										
	Experimental	153	2.4 (1.18)				156	2.53 (1.1)														
Integration	Control	105	3.86 (1.73)	-0.39	0.696	0.696	101	3.54 (1.58)	1.64	0.202	0.23	0.01										
	Experimental	153	3.95 (1.89)				156	3.69 (1.54)														
Working memory updating (WMU)	Control	104	9.1 (2.67)	-2.38	0.018	0.048	106	9.15 (2.04)	19.1	<0.001	<b>0.004</b>	0.07										
	Experimental	156	9.81 (2.18)				149	10.58 (2.37)														
Intrusion errors	Control	104	0.75 (0.54)	2	0.047	0.094	106	0.77 (0.47)	10.71	0.001	<b>0.004</b>	0.04										
	Experimental	156	0.64 (0.37)				149	0.55 (0.45)														
Standardized reading comprehension (MT)	Control	104	-0.79 (1.19)	-3.46	<0.001	<b>0.008</b>	106	-0.54 (1.3)	0.46	0.498	0.498	0.00										
	Experimental	155	-0.27 (1.21)				149	-0.44 (1.22)														
Nonverbal reasoning (Cattell)	Control	105	27.16 (5.66)	0.54	0.591	0.675	101	26.03 (6.28)	6.25	0.013	<b>0.035</b>	0.03										
	Experimental	153	26.76 (5.93)				156	27.08 (5.55)														

Note: In bold the significant differences resulted from the False Discovery Rate correction method (Pastore et al. 2005).

differences at pre-test with *t*-test and the differences at post-test with ANCOVAs. The missing values ranged between 0 and 11 across different measures and were explained considering that all those who participated in at least one pre-test and post-test evaluation session were included in the total sample ( $n = 263$ ). Considering the standardized scores in a text comprehension test (MT), both the experimental group and the control group averaged out.

The results of the *t*-test showed differences between the experimental group and the control group at the two pre-test measures. In DARC-Inferences and MT measures, the experimental group outperformed the control group. ANCOVAs used to measure the differences between the experimental group and the control group at post-test measures, controlling for pre-test performance, showed that groups differed in DARC-Text Memory, WMU-Intrusion errors, and the Cattell test with small effect sizes. Additionally, differences between the two groups were observed in WMU-Recall with a medium effect size. In all these measures, the experimental group outperformed the control group.

The results of the ANCOVAs demonstrated that pre-test performances were a significant factor for all the post-test outcomes (adjusted  $p \leq 0.05$ ) except for DARC-Knowledge. The school grade was a significant factor only for post-test performances (adjusted  $p \leq 0.05$ ) of DARC-Text Memory and Standardized Reading Comprehension (MT).

In Table 3, descriptive statistics of EF performances in the two groups are presented. The missing values for EF tasks ranged between 0 and 24 across different measures. Both the experimental group and the control group obtained EF performances referable to the normative values collected on the typical development sample that participated in the standardization (Rivella et al. 2023).

Finally, Table 4 shows results regarding the investigation of the role of EF, pre-test performances, group, and school grades in

**TABLE 3** | Descriptive statistics of EF performances in the experimental and control groups.

		Pre	
		<i>n</i>	<i>M</i> ( <i>SD</i> )
No-Go CR	Control	103	11.12 (1.95)
	Experimental	154	11.19 (1.64)
Flanker task-single rule incongruent CR	Control	96	16.01 (4.25)
	Experimental	148	16.36 (3.62)
Flanker task-mixed rules incongruent CR	Control	96	19.75 (5.5)
	Experimental	143	19.73 (5.18)
N-Back CR	Control	102	44.52 (2.82)
	Experimental	152	44.90 (2.49)

Abbreviation: CR, correct responses.

**TABLE 4** | Linear regression analyses with pre-test performances, school grades, and EF measures as predictors and standardized training gains (deltas) as outcome measures.

Outcomes	<i>B</i>	<i>SE</i>	$\beta$	<i>t</i>	<i>p</i>
<b>Δ DARC-Text Memory</b>					
Intercept	-1.46	1.39		-1.06	0.294
Pre-test	-0.99	0.1	-0.70	-9.94	< <b>0.001</b>
School grade	0.17	0.17	0.07	1.03	0.306
No-Go CR	-0.02	0.05	-0.02	-0.32	0.751
Flanker task-single rule incongruent CR	0.04	0.02	0.13	1.66	0.099
N-Back CR	0.06	0.04	0.14	1.8	0.075
Flanker task-mixed rules incongruent CR	0.00	0.02	0.00	0.03	0.978
<b>Δ WMU-Recall</b>					
Intercept	3.24	1.41		2.29	0.024
Pre-test	-0.27	0.04	-0.54	-7.00	< <b>0.001</b>
School grade	-0.14	0.18	-0.07	-0.81	0.417
No-Go CR	-0.01	0.06	-0.02	-0.22	0.824
Flanker task-single rule incongruent CR	0.02	0.02	0.08	0.98	0.332
N-Back CR	0.00	0.04	0.01	0.13	0.901
Flanker task-mixed rules incongruent CR	-0.01	0.02	-0.06	-0.72	0.471
<b>Δ WMU-Intrusion errors</b>					
Intercept	2.79	9.69		0.29	0.774
Pre-test	0.60	0.26	0.22	2.34	<b>0.021</b>
School grade	-1.57	1.09	-0.14	-1.44	0.152
No-Go CR	-0.06	0.34	-0.02	-0.18	0.856
Flanker task-single rule incongruent CR	0.10	0.15	0.07	0.7	0.487
N-Back CR	0.03	0.22	0.01	0.13	0.894
Flanker task-mixed rules incongruent CR	-0.07	0.11	-0.06	-0.64	0.522

(Continues)

TABLE 4 | (Continued)

Outcomes	<i>B</i>	SE	$\beta$	<i>t</i>	<i>p</i>
$\Delta$ Cattell					
Intercept	-3.14	1.06		-2.97	0.004
Pre-test	-0.09	0.01	-0.65	-8.20	<0.001
School grade	0.08	0.13	0.05	0.59	0.558
No-Go CR	-0.10	0.04	-0.19	-2.54	0.012
Flanker task-single rule incongruent CR	0.04	0.02	0.16	2.08	0.039
N-Back CR	0.13	0.03	0.38	4.75	<0.001
Flanker task-mixed rules incongruent CR	0.01	0.01	0.07	0.89	0.374

Abbreviations:  $\beta$ , standardized beta estimate; *B*, beta; CR, correct responses.

explaining the standardized training gains (the third objective of the present study) using linear regression models.

As shown in Table 4, pre-test performances predicted training gains for each variable, suggesting that participants starting from a lower level of performance obtained larger gains at post-test. In addition, Cattell test gains were predicted by No-Go CR, Flanker task-Single rule incongruent CR, and N-Back CR.

To further highlight the variability in individual responses to training, we examined the differences in the pre- and post-assessment scores, EF profiles, and session performance of two participants, S1 and S2 selected as representative of improvement with training, and non-improvement with training. Details are provided in Appendix 3: Table A1. In assessment outcomes, S1, who started with a lower Cattell test score (Pre=17) than S2 (Pre=33), demonstrated a substantial improvement (Post=28,  $\Delta$ =+11) by the post-test, whereas S2 remained stable (Post=33,  $\Delta$ =0). Similarly, in the DARC-Text Memory test, S1 started lower (Pre=1) than S2 (Pre=3) but showed improvement (Post=2,  $\Delta$ =+1), while S2 showed no change (Post=3,  $\Delta$ =0). In the WMU-Recall, S1 again started lower (Pre=9) than S2 (Pre=14) and improved (Post=12,  $\Delta$ =+3), while S2 remained relatively stable (Post=13,  $\Delta$ =-1). Finally, S1 had higher initial intrusion errors in WMU (Pre=078) compared to S2 (Pre=0.29), yet showed a reduction in errors (Post=0.42,  $\Delta$ =-0.36), whereas S2 exhibited a slight increase (Post=0.38,  $\Delta$ =+0.1). Regarding children's EF profiles, S1, displayed similar but relatively lower scores compared to S2 in inhibition control (No-Go CR; S1=10.75, S2=12.25), interference control and cognitive flexibility (Flanker task-Single rule incongruent CR; S1=16, S2=20; Flanker task-Mixed rules incongruent CR; S1=22, S2=25), and in visuospatial WM (N-Back CR; S1=43.83, S2=49.33). During the training sessions, S1 attended eight sessions, while S2 completed nine. The progress in text comprehension tasks over various sessions indicates differing trajectories. S1 showed a gradual

improvement across sessions, whereas S2's performance was less variable and typically high.

#### 4 | Discussion

Acknowledging that reading comprehension skills at school age are crucial to promoting school and social success (e.g., Gray 2017; Kamil 2003; Ricketts et al. 2014) and considering the high percentage of children with reading difficulties (Carretti 2021; OECD 2019), this study proposed a computerized cognitive training designed to improve reading comprehension by boosting the main EF in third and fourth graders. Consistently, this study aimed to evaluate the feasibility and efficacy of the intervention proposed, investigating how cognitive profiles before the intervention explained the training's effects. The specific effects of the training were investigated on aligned reading comprehension and on verbal updating in WM tests, as these processes were directly trained by the intervention. Simultaneously, transfer effects were examined on a standardized reading comprehension test and a nonverbal reasoning task. Lastly, the variability in training effectiveness among different children took into consideration the pre-test performances at EF measures, specifically inhibitory control, control of interference, visuospatial WM, and cognitive flexibility, the pre-test performances on each outcome measure, and the school grades.

The implemented computerized cognitive training took inspiration from the intervention used by García-Madruga et al. (2013) and Carretti et al. (2017). They adopted two important and effective strategies to promote reading comprehension through EF exercises. Specifically, the intervention promoted training activities at school during regular school activities, and at the same time, it embedded EF exercises into reading comprehension activities. These two central features were retained in the training we implemented and extended, including the digitization of the training. The digitalization of the training falls within the framework of CAD learning. The CAD approach is often grounded in individualized methodologies, allowing for tailored instruction and support. However, adapting this approach to the school context and integrating it with the actions of teachers and classmates can enhance its effectiveness. This integration leverages the advantages of digital tools, such as personalized learning and immediate feedback, while mitigating the potential downside of social isolation often associated with purely individual digital interventions. By embedding CAD-based activities within the collaborative and interactive dynamics of the classroom, students benefit from both the personalization of digital technology and the socio-emotional support and peer learning opportunities provided by a group setting. Specifically, in this study, the computerized training made it possible to introduce standardized video tutorials to explain activities' instructions, thus making children as autonomous as possible in performing the training and reducing the effects of skills, motivation, and knowledge of the teacher conducting the training (Caprara et al. 2006). At the same time, the computerized training was used to make the intervention as graphically appealing as possible by using attractive fonts. A final important element added to the training, in comparison with the previous versions, was the

monitoring of the children's performance during the training: in case of a mistake, children could not move on to new activities until they had given the correct answer. To understand which answer was correct, children had the opportunity to compare and discuss with one of their classmates. All these features suggested that an intervention enhancing EF within reading comprehension tasks could be very promising when implemented digitally.

With regard to the feasibility of the training, the teachers' feedback on the training were analyzed qualitatively. It is important to emphasize that the teachers' role in conducting the training was kept to a minimum so as not to overload them with extra work in addition to teaching. Consistently, the activities before the training and necessary to carry it out, such as preparing the computer room, digital devices, the platform used, etc., were managed by members of the research group. However, most of the teachers had the pleasure of participating in the sessions by observing children's performances. At the end of the training, teachers answered the questionnaire giving their important feedback on the feasibility of implementing the training and possible ways to improve it. Overall, the teachers were very satisfied with the training and gave positive scores to both the training's activities and its usefulness. The majority of them noticed children's high engagement during the activities as well as their improvement in school learnings after the training. Consistently, many teachers would recommend the training to other colleagues. To this positive scenario of the pleasantness of the training, however, some slightly more critical aspects must be added. Difficult aspects were linked above all to the availability of digital devices within the school, as well as connection problems. This aspect highlights the still-present poor digitisation of primary schools in the Italian school context. In fact, Italian schools, unlike other European countries, do not have one computer per pupil but many classes share the same set of PCs or tablets that is made available to the whole school. At the same time, teachers report a medium-to high-level of difficulty in reconciling training with routine teaching activities. This was an expected result bearing in mind the considerable number of activities that teachers conduct in the classroom on a daily basis. Another important result emerged from the advice given by teachers. In addition to suggesting increasing the number of training sessions and thus its duration, they suggested supplementing the computerized intervention, which is in any case seen as a modality that teachers like, with paper-and-pencil activities. It is, therefore, possible that in the school context, a hybrid solution, involving both classical paper activities and digital exercises, is more accepted by teachers.

As far as the efficacy is concerned, the training resulted effective in the experimental group compared to the control group in enhancing the capacity to remember specific information presented in the text (DARC-Text Memory), to correctly update words in mind (WMU-Recall), to avoid remembering words that are not target words (WMU-Intrusions errors) and to reason on nonverbal stimuli (Cattell).

With regard to the specific effect of the training on reading comprehension, in line with previous studies (Carretti et al. 2017; García-Madruga et al. 2013) a significant effect of the training

was found using an aligned reading comprehension test, the DARC test. In particular, this was true when the different dimensions of the DARC were considered. The experimental group, compared to the control group, obtained a higher score in the Text Memory score of the DARC; in other words, children in the experimental group succeeded in remembering specific information from the text. However, the improvements with the training did not extend to all reading comprehension processes. In fact, there was no improvement in the ability to retrieve prior knowledge (DARC-Knowledge), to make inferences (DARC-Inferences) and integrations (DARC-Integrations) from the information in the text. These abilities reflect the capacity to go beyond the explicit information in the text and extract implicit meanings or link information together (Cain 2009). Specifically, to make inferences, readers use their prior knowledge, the context provided by the text, and logic to arrive at conclusions that are not explicitly provided in the text. At the same time, integration involves linking and combining different parts of a text to create a coherent and complete view of the information. These complex skills, which are fundamental for a deep and critical comprehension of texts, are developing at school age and may need more time to be trained (Sabatini et al. 2012). Therefore, it could be possible that training the underlying cognitive processes of text comprehension in primary graders acts firstly on the text-based components, then indirectly and in the long term on the deeper ones.

Secondly, another specific effect of the training was achieved on verbal updating WM. The experimental group outperformed the control group through the training in the capacity to constantly update the contents in memory, to compare them with new information in the text, and to retrieve the necessary and important information to perform the task (Baddeley 1992). This result is in line with the findings of García-Madruga et al. (2013) and Carretti et al. (2017) and confirms evidence in the literature on the possibility of training updating in verbal WM (Melby-Lervåg and Hulme 2013). This was an expected result as the training included exercises that specifically trained the verbal updating WM, which for this reason was considered a specific measure of effectiveness.

As far as the transfer effect concerns, the training produced a significant transfer effect, since it favored changes in nonverbal reasoning, a result that extended the evidence found in the studies by García-Madruga et al. (2013) and Carretti et al. (2017). Indeed, García-Madruga et al. (2013) had shown that although the gain in intelligence was higher for the experimental group than for the control group, it did not reach the significance level. In the study by Carretti et al. (2017), albeit an improvement in nonverbal reasoning between sessions in the same test employed in this study, no significant differences between groups were found. The result found in this study is in line with other interventions aimed at enhancing WM updating (e.g., Jaeggi et al. 2008; Klingberg et al. 2002, 2005) that demonstrated transfer effects on fluid intelligence. It is a promising result because it shows how a computerizing training using a metacognitive approach is effective in promoting the ability to think logically and solve problems in novel situations.

Regarding the second transfer effect, there was no significant effect of the training on a non-aligned reading comprehension

measure, specifically the standardized MT test (Cornoldi et al. 2017). This outcome was anticipated due to the misalignment between the standardized test's task demands and the experiences of the experimental group during training, as standardized measures lack alignment with the program's content, materials, and task demands (Clemens and Fuchs 2022). Additionally, pre-test performance differences between the two groups prevented interpreting data from this test.

In summary, the results obtained in the present study supported the efficacy of the intervention developed by García-Madruga et al. (2013) and adapted by Carretti et al. (2017) even in a digitalized version with the distinct advantage of heightened user-friendliness, as highlighted by the teachers.

As a third objective of this study, individual factors contributing to the change achieved through training were investigated. The factors considered included pre-test performances in the specific variables, executive functioning, and school grade. These factors all together were found to significantly predict the improvements achieved through the training. Specifically, in reading comprehension, verbal updating WM (correct responses and intrusions), and nonverbal reasoning, pre-training performances predicted the post-training improvements: participants starting from a lower level of performance obtained larger gains from the training.

In addition, regarding executive functioning, visuospatial WM, inhibition, and control of interference were significant predictors of improvements in nonverbal reasoning. In line with previous literature (Carretti et al. 2014, 2017; Cornoldi et al. 2015), children with lower performances in inhibition benefited more from a training with a cascade effect on skills involving more complex EF such as reasoning. On the contrary, children with starting low levels in interference control and WM obtained a lower improvement in nonverbal reasoning with the training. This contradictory result may reflect the specificity of the training program, differently stressing and requiring EF components in the various activities.

Lastly, school grades did not predict training gains, possibly due to the strong influence of other individual factors. This suggests that conventional measures like school grades may not precisely capture the nuances in cognitive development or intervention-targeted skills.

Additionally, the analysis of our two case studies highlights the variability in individual responses to training, underscoring how differences in initial scores and cognitive as well as executive functioning can influence the gain obtained. These findings suggest that participants with lower initial performance may experience more benefits from targeted training, emphasizing the importance of individualized training approaches. Consistent with the overall results of the study, the participant with lower performance in EF tasks benefited more from the training, showing progressive enhancements in their reading comprehension from session to session. This variability in response to the intervention underscores the need for further research into how specific cognitive profiles interact with educational strategies to optimize training efficacy.

## 4.1 | Practical Implications for Educators

The findings of this study have practical implications for educators. Firstly, the result about individual factors contributing to the change achieved highlights the importance of considering individual differences in EFs when designing and implementing training interventions. Specifically, initial EF levels, such as WM, inhibition, and nonverbal reasoning, appear to predict the degree of improvement following training. This suggests that EF training may be more effective if tailored to the unique cognitive profiles of students. For instance, students with lower inhibition may benefit most from activities that target inhibitory control, while those with lower WM could benefit from exercises designed to enhance memory capacity. Such a tailored approach has practical implications for educators and interventionists, who could consider a pre-assessment of EFs to design interventions that meet the specific needs of each student. This strategy could optimize training outcomes and ensure that students with varying cognitive profiles gain maximum benefit.

Additionally, there may be connections between individual differences in EFs and students' abilities to monitor their own comprehension during reading. Stronger EF skills, such as inhibition and WM, could support students' ability to recognize and resolve comprehension difficulties, a process crucial for effective learning. Therefore, future research could investigate how targeted EF training might also enhance students' self-monitoring abilities in reading, potentially leading to improvements in reading comprehension.

Another valuable implication for educators is the use of scaffolded practice, which targets multiple EF components such as selective attention, inhibitory control, WM, and cognitive flexibility. For example, students were encouraged to focus on relevant text details (selective attention), pause before responding (inhibitory control), make connections between new information and prior knowledge (WM), and shift focus between sections of the text (cognitive flexibility). These EF skills, practiced during reading activities, can improve both reading comprehension and, overall, cognitive functioning.

The final but essential elements of this training were the use of real-time feedback, peer interaction, and the self-assessment questionnaire. At the end of each training block, students received immediate feedback on their performance and had the chance to repeat exercises until they provided the correct response. If they made mistakes, they discussed the errors with classmates to reach the correct answer together, fostering collaboration and cognitive flexibility. Additionally, a self-assessment questionnaire at the end of each session encouraged students to reflect on what they had learned, supporting metacognition and self-regulation. These strategies could be incorporated into everyday reading instruction to enhance both reading skills and EF development in classroom settings.

## 4.2 | Limitations and Future Directions

It is important to recognize some limitations of the present study. Firstly, the present study does not present an assessment of the

maintenance of training's effects as no follow up was conducted. Considering the promising results coming from the follow-up assessments in the study by Carretti et al. (2017) and García-Madruga et al. (2013), it would be interesting to investigate the maintenance of training's effects over time. Another limitation is related to the sampling that took place for convenience, as classes that made their willingness to participate in the project were involved. Another limitation of the study is the use of questionnaires to obtain feedback on the training from teachers. It is indeed possible that, as with all self-report instruments, teachers were influenced by the phenomenon of social desirability. In addition, a limitation is the failure to use a counterbalance of reading comprehension texts that would have controlled for any differences in the texts used. Another limitation of this study is that some activities, particularly those in the early sessions, were too far from reading comprehension in the school context. Complex reading comprehension processes were indeed broken down to train the involved EFs. This separation may not fully reflect the complex interactions that take place in natural reading contexts. As a result, the findings may have lower ecological validity, meaning that improvements in isolated EF tasks may not easily transfer to more complex, real-world reading comprehension tasks. Future studies could address this by using EF training tasks that better represent the multifaceted demands of real-life reading situations. Furthermore, the cluster-randomized study design we adopted in this study may have limitations and should be supplemented with time series studies in future studies. A final limitation is the lack of digital measures to assess reading comprehension when implementing a digital intervention even if recent evidence showed the small digital-paper gap in reading comprehension among children (Ruffini et al. 2023). It is possible that the training had a positive effect on digital reading, more than on paper-based text comprehension, as assessed in this study. Additionally, future research could investigate children's levels of motivation in approaching digital devices within a computerized cognitive training (e.g., Ciampa 2013; Passey et al. 2004). Lastly, future studies may focus on the development and implementation of intervention activities designed to enhance core comprehension processes, including inference and integration.

## 5 | Conclusions

In sum, this study presented a feasible digitalized intervention to improve text comprehension and underlying cognitive control processes within the school setting, positively evaluated by teachers and with an effective metacognitive approach. Data support that embedding EF activities within reading comprehension tasks promotes text-based processes of reading comprehension, verbal updating WM, and nonverbal reasoning. Furthermore, inter-individual variability in pre-test performances and EF profile can affect the gains obtained by the training. Results of the present study contributed to the debate on the involvement of EF processes in reading comprehension.

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### Ethics Statement

The research was approved by the Ethic Committee of the University of Florence, reference number 0152940, date 26/05/2021. The research was carried out following the Ethical guidelines of the Italian Association of Psychology and the Declaration of Helsinki.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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## Appendix 1

### Description of Training Sessions for the Experimental Group

	Trained processes	Activities	Examples of activity
S1	P1. Selective attention; working memory; cognitive flexibility P2. Selective attention; inhibitory control; cognitive flexibility	A1. To order sequences of images A2. To understand instructions	E1. A cook putting fish in the oven; a cook putting fish on the table; a cat eating fish from the plate; a cook cutting fish E2. Write under the blackboard image the number of letters that has the name of the animal in the center
S2	Selective attention; working memory; inhibitory control	A1. To understand instructions A2. To order sequences of sentences	E1. Write the number of letters of your name below the character who is smiling, has no glasses or hair E2. I take the bottle of milk; I open the refrigerator; I close the refrigerator
S3	P1. Selective attention; working memory; inhibitory control P2. Selective attention; working memory; cognitive flexibility; inhibitory control P3. Selective attention; inhibitory control; working memory	A1. To sort sequences of sentences A2. To understand implicit information by choosing between two options A3. To decode verbal instruction requiring a verbal or motor response	E1. I put on my swimming costume; I dry myself with the towel; I dive headfirst into the pool; I swim 10 min; I get out of the pool E2. Carolina saw HER irritated by what she was saying. Who is HER referring to? 1. girl, 2. children E3. Write the name of your school, then write it below without the vowels; sit on your right hand and rest your forehead on the table
S4	P1. Selective attention; cognitive flexibility; inhibitory control; working memory P2. Selective attention; working memory P3. Selective attention; inhibitory control; working memory	A1. To understand implicit information and select the correct option A2. To identify inconsistencies in the text A3. To decode verbal instruction requiring a verbal or motor response	E1. Alberto said goodbye to her because he had to go shopping. Who is "her"? 1. aunt, 2. grandfather Marco waited for her on Sunday to go to the cinema. Who is "her"? 1. brother-in-law, 2. girlfriend Marisa activated it by the fire alarm. What is "it"? 1. sound, 2. game Rewrite the words you chose in the order they were presented E2. It was a sunny day. Elena and her family were spending the day at the lake. In the afternoon, Elena was flying in the lake when she decided to turn back. Where is the mistake? E3. Write the name of today's day by replacing vowels with the number 1 Put your right fist on the counter and your left index finger on your left foot
S5	P1. Selective attention; working memory P2. Selective attention; working memory P3. Selective attention; inhibitory control; working memory	A1. To identify inconsistencies in the text A2. To make inferences A3. To decode verbal instruction requiring a verbal or motor response	E1. Alfredo was so busy all afternoon playing that he did not realize what a mess was left in his room. All the toys were in their places. His parents warned him to come down for dinner. She knew she would be in trouble if he didn't tidy up the room before going downstairs. In a moment everything was in its place and his parents congratulated him. Which information is not coherent with the text? E2. Once upon a time there was a young pine tree living in the forest. How many trees are we talking about? 1. many; 2. few; 3. only one E3. Write your name backwards, starting with the last letter Put your right ear on the table and your left hand on your head

## Appendix 1 | (Continued)

	Trained processes	Activities	Examples of activity
S6	P1. Selective attention; working memory P2. Selective attention; working memory P3. Selective attention; inhibitory control; working memory	A1. Identify inconsistencies in the text A2. To make inferences A3. To decode verbal instruction requiring a verbal or motor response	E1. The seahorse lives in the seas and oceans. It is a very small bird, growing up to 12 cm long. When the seahorse swims, it appears to stand on its tail. It moves through the water thanks to the movement of a small, fan-shaped dorsal fin. In this way it can escape from its enemies by swimming quickly. Thus the seahorse avoids being eaten by other fish. Where is the mistake? E2. Tom knew how to make a table from a tree, but he could not read. Tom knew how to grow tomatoes, peppers and corn cobs, but he did not know letters and words “I want to learn to read”—he said to his wife Giulia. “You are wonderful as you are”—disputed Giulia, as she stroked his beard. “But I would like to learn to read”—he replied. “You can learn”—his wife told him, smiling Why does Tom want to learn to read? 1. To be able to read stories and understand magazines; 2. To become a professor; 3. Because his wife had prevented him from doing so E3. Write your name using capital letters for the first letter, adding a dot after the second and a dash after the third Point to your left eyebrow with the index finger of your right hand and stick out your tongue
S7	P1. Selective attention; inhibitory control; working memory P2. Selective attention; inhibitory control; working memory	A1. To update during reading A2. To decode verbal instruction requiring a verbal or motor response	A1. We will now read the commentary of a cyclist’s race. In each of the text fragments, you will tell how a part of the race takes place. After reading each paragraph, we will ask you what order the cyclists are in at that precise moment of the race at which we stopped the commentary E2. Select the image representing a circle below which is a square. Both figures must be enclosed in a triangle Put your left hand on the back of your head and touch the index finger of your right hand to your left ankle
S8	Selective attention; cognitive flexibility; inhibitory control; working memory	To order sequences of images To understand instructions To order sequences of sentences To understand implicit information To identify inconsistencies in the text To make inferences To update during reading	A narrative text “a stone soup” with 9 multiple choice questions requiring the EF processes linked to different reading comprehension skills trained in the previous sessions
S9	Selective attention; cognitive flexibility; inhibitory control; working memory	To order sequences of images To understand instructions To order sequences of sentences To understand implicit information To identify inconsistencies in the text To make inferences To update during reading	An expository text “Christopher Columbus” with 18 multiple choice questions requiring the EF processes linked to different reading comprehension skills trained in the previous sessions

## Appendix 2

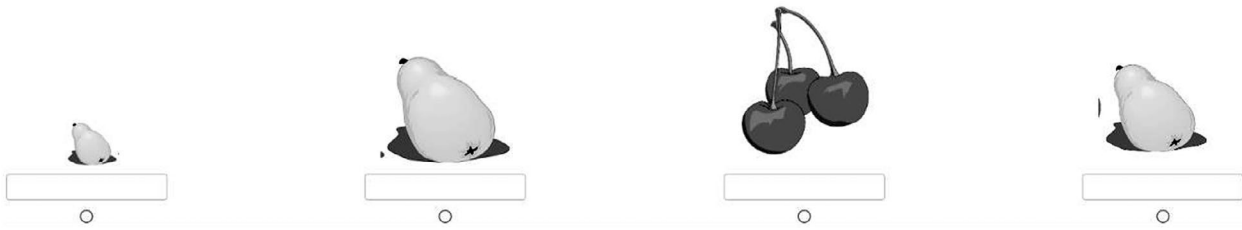
## Examples of Activities Embedding EF Components With Reading Comprehension Tasks

Children engaged in various reading activities involving EF, specifically: strategically focusing on relevant information, proficiently switching between dual tasks, establishing cognitive connections

between incoming data and existing long-term knowledge, dynamically updating content in memory, and exercising discerning control over extraneous information. Two examples of reading comprehension activities requiring EF follow:

1. Session 1. Children are asked to understand complex instructions requiring simultaneous activation of EF processes.

Write in CAPITAL LETTERS and under the SMALLEST PEAR, the NUMBER OF CHERRIES left if you eat one.



- Session 4. Children are asked to understand implicit information in the texts and select the correct option among the two provided. After choosing the answers, children are asked to rewrite the two selected words from memory in the order they were presented.

*Alberto said goodbye to her because he had to go shopping.*

Who is "her"? 1. Aunt, 2. Grandfather.

*Marco waited for her on Sunday to go to the cinema.*

Who is "her"? 1. brother-in-law, 2. girlfriend.

*Marisa activated it by the fire alarm.*

Who is "it"? 1. sound, 2. game.

- Session 10. Children are asked to carefully read the text and answer each question.

#### CHRISTOPHER COLUMBUS

Christopher Columbus was born near Genoa in 1451 and already as a young man began to develop a passion for the sea and navigation. At the age of 14, he became a sailor and began traveling to numerous European countries.

He was passionate about geography and astronomy and firmly maintained that the Earth was round. To prove this to everyone, he decided to travel to India at the end of the 15th century by sailing west. The expedition is very expensive, and Christopher Columbus decides to ask the rulers of Portugal for financial help. The king of Portugal denies him financial support, so he turns to Queen Isabella of Castile.

Having obtained money and ships, he sets sail from Palos de la Frontera on 3 August 1492 and, after months of sailing, touches land on 12 October. However, it is not India, but a new continent: America, which is called the New World.

From that moment, the great Spanish colonization of the American continent began. Christopher Columbus himself organized three more voyages to America, but continuous problems and great difficulties in finding gold made him disliked by the kings of Spain.

He died in Valladolid in 1506, poor and forgotten by all.

Some of the questions follow:

Where does Christopher Columbus arrive at the end of his first voyage?

- America
- Palos de la Frontera
- India
- Portugal

From whom does he get support for his first expedition?

- Queen Isabella of Portugal
- From the King of Castile
- From Queen Isabella of Castile
- From the King of Portugal

Rearrange the following sentences starting with what happens first.

- Christopher Columbus turns 14
- Columbus thinks the Earth is not flat
- Isabella of Castile helps Christopher Columbus set off on his journey.
- Columbus is in Palos de la Frontera
- Columbus wakes up on the morning of October 12, 1492
- Columbus organizes his third voyage to America

Isabella of Castile provided him with the financial support he needed. Who did Isabella of Castile help?

- Christopher Columbus
- The Journey

"America is called the New World. From that moment on, the great American colonization of the European continent begins."

Rewrite the sentence correctly: \_\_\_\_\_

Read the following sentence: 'Christopher Columbus was born near Genoa in 1451 and already as a young man began to be passionate about the sea and navigation.' Based on it, can you say where Genoa is located?

- Near the sea
- At high altitude
- In the hills
- From this sentence you cannot tell where Genoa is located

Read the following sentence: 'Christopher Columbus, a lover of geography and astronomy, firmly maintained that the Earth is round.' Based on what you have read, you can state that:

- Everyone believed that the Earth was round
- Some thought the Earth was flat
- Christopher Columbus did not think clearly

### Appendix 3

#### Two Example Cases of Two Children's Responses to the Training

**TABLE A1** | Differences in the pre- and post-assessment scores, EF profiles, and session performance of two participants (one who improves one who is stable at training).

Outcome	Participant S1	Participant S2
DARC-Text Memory pre	1	3
DARC-Text Memory post	2	3
DARC-Text Memory $\Delta$	1	0
WMU-Recall pre	9	14
WMU-Recall post	12	13
WMU-Recall $\Delta$	3	-1
WMU-Intrusion errors pre	0.78	0.29
WMU-Intrusion errors post	0.42	0.38
WMU-Intrusion errors $\Delta$	-0.36	0.1
Cattell pre	17	33
Cattell post	28	33
Cattell $\Delta$	11	0
No-Go CR	10.75	12.25
Flanker task-single rule incongruent CR	16	20
Flanker task-mixed rules incongruent CR	22	25
N-Back CR	43.83	49.33
Session 1 performance	1	3
Session 2 performance	2	5
Session 3 performance	2	3
Session 4 performance	5	4
Session 5 performance	4	5
Session 6 performance		5
Session 7 performance	5	2
Session 8 performance	4	4
Session 9 performance	3.75	2.5