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► To cite this version:

Sylviane Valdois, Ahmed Zaher, Svetlana Meyer, Julien Diard, Sonia Mandin, et al.. Effectiveness of Visual Attention Span Training on Learning to Read and Spell: A Digital-game-based Intervention in Classrooms. *Reading Research Quarterly*, 2024, 10.1002/rrq.576 . hal-04681829

HAL Id: hal-04681829

<https://hal.science/hal-04681829v1>

Submitted on 30 Aug 2024

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Effectiveness of Visual Attention Span Training on Learning to Read and Spell: A Digital-game-based Intervention in Classrooms

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ABSTRACT

Longitudinal studies on mainstream children and training studies in the dyslexic population suggest that visual attention span (VAS) abilities contribute to reading acquisition. We evaluated to what extent VAS training in beginning readers might enhance later literacy skills. A large cohort of 453 children was followed from the beginning to the end of Grade 1. A first group of students was trained on a custom-designed digital application—called EVASION—that targeted VAS abilities. Another group used the GraphoGame application, while the third was a “business-as-usual” group. A total training time of 10h was recommended; training was performed during the regular school day, under the sole supervision of teachers. Pre-post intervention assessment revealed higher VAS, higher reading fluency improvement, and higher postintervention spelling skills in the EVASION group. Children who spent more time playing with EVASION improved more in both VAS and literacy skills. In the whole population, VAS enhancement predicted reading fluency improvement and posttraining spelling skills, independently of other reading related skills and of the class effect. The overall findings suggest that training VAS in the classroom might prevent difficulties in learning to read and spell. Evidence for longitudinal effects of VAS training on literacy skills support a causal relationship. In improving multiletter parallel processing, training would translate into better orthographic learning, yielding higher reading fluency and spelling skills.

Introduction

Many children do not reach expected competence level in reading despite appropriate educational opportunities (OECD, 2019). Their difficulties in reading acquisition can be attributed to environmental and/or cognitive factors (Câmara Costa et al., 2013). Children who belong to socioeconomically disadvantaged neighborhoods are more prone to show delays in reading (Fluss et al., 2009). Weaknesses in the cognitive factors involved in reading development, like phonological awareness (i.e., the ability to identify and manipulate phonological units within spoken words; Melby-Lervåg et al., 2012) or visual attention span (VAS; i.e., multielement parallel-processing ability; Valdois, 2022), are other potential sources of reading difficulty. Many experimental studies have been designed to evaluate the effectiveness of intervention programs delivered in school settings to improve reading skills and prevent reading failure. Most interventions aimed at improving decoding skills, through phonics instruction (i.e., children are taught to use grapheme–phoneme correspondences to decode words) and/or phoneme awareness training (i.e., the ability to manipulate phonemes within spoken words).

There is ample evidence that decoding targeted interventions are effective to improve reading skills. Meta-analyses showed positive effects on reading outcomes in both mainstream children (Machin et al., 2016; National Reading Panel, 2000) and poor readers (Galuschka et al., 2014). The interventions that emphasized phoneme awareness training improved reading acquisition, even for low-SES children (Ehri et al., 2001). Their impact on literacy was comparable to that of direct reading interventions, but longer term positive effects were reported (Suggate, 2016). The effectiveness of computer-assisted reading instruction programs focusing on phonics training was also investigated (McTigue et al., 2020; Potier-Watkins et al., 2020; Potier-Watkins & Dehaene, 2023). Meta-analysis on the impact of the very popular GraphoGame software (Richardson & Lyytinen, 2014) did not yield evidence for intervention gains in reading outcomes (McTigue et al., 2020). However, positive effects of a French version of GraphoGame on phoneme awareness and word reading fluency have been recently reported (Lassault et al., 2022).

A few interventions were specifically designed to target reading fluency. They used repeated (word or text) reading practice (van Uittert et al., 2022; Zorman et al., 2008) or text reading acceleration training (Brenzitz et al., 2013). These interventions proved helpful to improve reading fluency in typical and poor readers (Horowitz-Kraus et al., 2014; Irausquin et al., 2005; van Uittert et al., 2022). However, previous research was more empirically founded than theoretically justified. It emphasized speed of processing and repeated exposure to print but was not informed by theoretical hypotheses on the cognitive precursors of reading fluency. Recent advances on the role of visual attention in learning to read and behavioral evidence for an impact of VAS on reading fluency open new perspectives for the development of theoretically grounded reading fluency interventions.

Theoretical Background

The development of fast reading skills relies on the capacity to process larger and larger multiletter units (Lagerge & Samuels, 1974). In their model of automaticity in reading, Lagerge and Samuels (1974) postulate that visual attention is involved in the transition from letter-by-letter fine-grained processing to more parallel coarse-grained processing. Recent behavioral findings that relate to the concept of VAS (Valdois, 2022) support an involvement of visual attention in both reading and orthographic learning. VAS is defined as the number of distinct elements that can be processed simultaneously in a visual array (Bosse et al., 2007; Frey & Bosse, 2018; Valdois, 2022). More elements can be processed in parallel when more visual attention resources are available for processing (Dubois et al., 2010; Lobier et al., 2013; Valdois, 2022). Behavioral

studies have shown that higher VAS allowed processing more letters per fixation in reading (Ginestet et al., 2020; Prado et al., 2007), leading to faster word recognition (Bosse & Valdois, 2009; Valdois, Phénix, et al., 2021), a smaller length effect (van den Boer et al., 2013), and higher reading fluency (Chan & Yeung, 2020; Huang et al., 2019; Lobier et al., 2013; van den Boer et al., 2018; Zhao et al., 2018). VAS further contributes to spelling skills (Niolaki et al., 2020; Van den Boer et al., 2015) and orthographic learning (Marinelli et al., 2020). Whether VAS causally relates to reading was widely debated (Goswami, 2015a, 2015b; Lobier & Valdois, 2015). Longitudinal and training studies support a causal relationship. They show that early VAS, measured prior to formal literacy instruction, predicts later reading fluency (Valdois et al., 2019) and that intensive VAS training results in better reading skills in dyslexic children (Valdois, Peyrin, et al., 2014; Zhao et al., 2019; Zoubrinetzky et al., 2019).

The computational models that include a visual attention component as part of the reading system provide insights on the way variations in visual attention would affect reading skills (Ans et al., 1998; Mozer & Behrmann, 1990). In BRAID models (Ginestet et al., 2019, 2022; Phénix et al., 2018; Saghiran et al., 2020; Steinhilber et al., 2023; Valdois, Phénix, et al., 2021), visual attention is implemented as a filter that modulates the flow of bottom-up sensory information on letter identity. The letters that receive more attention are identified faster and the spatial distribution of visual attention over the input letter string determines how many letters would be simultaneously processed. In the model, sensory information, modulated by visual attention, is used to build-up an internal perceptual representation of the letter string that activates word orthographic knowledge. Therefore, efficient word recognition depends on the amount of letter identity information accumulated at the perceptual level which itself depends on the amount of visual attention allocated to letter processing. Simulations carried out within the BRAID framework have demonstrated that word recognition is slowed down when the distribution of visual attention is narrowed (Ginestet et al., 2019; Valdois, Phénix, et al., 2021). This framework further predicts that the dynamics of visual attention processing during reading contributes to orthographic learning (Ginestet et al., 2022). In the model, orthographic learning occurs each time information accumulated at the perceptual level is used to create a novel word representation or update the orthographic representation of an already familiar word. Simulations showed that orthographic learning is more efficient when a higher amount of visual attention resources is available for processing (Steinhilber et al., 2023). In this case, attention is allocated to more letters simultaneously, which boosts letter identity encoding for building up the novel word representation. In turn, top-down information from the gradually acquired novel word orthographic

form enhances letter identification at the perceptual level, which improves reading fluency as learning progresses.

Overall, the BRAID theoretical framework predicts a causal relationship between visual attention and reading acquisition. This suggests that improving the ability to process multiple letters simultaneously (i.e., VAS ability) in beginning readers would improve the development of reading fluency and word-specific orthographic knowledge.

How to Improve VAS?

The concept of VAS was initially introduced to account for reading deficits in developmental dyslexia (Bosse et al., 2007). Based on evidence that a unique VAS deficit could be associated with developmental dyslexia (Bosse et al., 2007; Germano et al., 2014; Valdois, Peyrin, et al., 2014; Zoubrinetzky et al., 2014, 2016), VAS remediation programs were designed to improve reading skills in dyslexic children. The COREVA[®] paper-and-pencil remediation program (Valdois, Bosse, & Peyrin, 2014) was conceived as a battery of visual exercises that required processing targets that progressively increased in length (i.e., in number of visual elements). VAS improvement and faster word recognition were reported following intensive training with the program (Valdois, Peyrin, et al., 2014). However, the COREVA[®] program did not impose strict constraints on processing time, which was not optimal to improve VAS. Another training software called MAEVA[®] (Valdois et al., 2023) was designed to fulfill the two constraints of time and multielement processing. Across trials, the number of characters to be processed progressively increased, while presentation duration decreased to force parallel processing. Intensive training was found efficient to improve VAS in dyslexic children and positive effects were reported in irregular word and text reading fluency (Zoubrinetzky et al., 2019). These findings suggest that time constraints and gradual increase in the number of visual items to be processed are two critical ingredients to improve VAS ability.

Besides, studies showing that action video game playing enhances perception, attention and cognitive skills provide insights on additional ingredients that might contribute to improve VAS and promote reading fluency. Not only do action video games train visual processing, spatial cognition, and attentional control, but positive effects have further been reported in reading (Bavelier et al., 2013; Bavelier & Green, 2019; Bediou et al., 2018). Dyslexic children showed increased reading fluency following intensive training on action video games (Franceschini et al., 2012, 2013, 2017; Peters et al., 2019; Pucio et al., 2023). Positive effects on reading fluency were also reported in typically developing children who were trained at school under the supervision of dedicated staff (Pasqualotto et al., 2022). In Pasqualotto et al.'s (2022) study, the action video

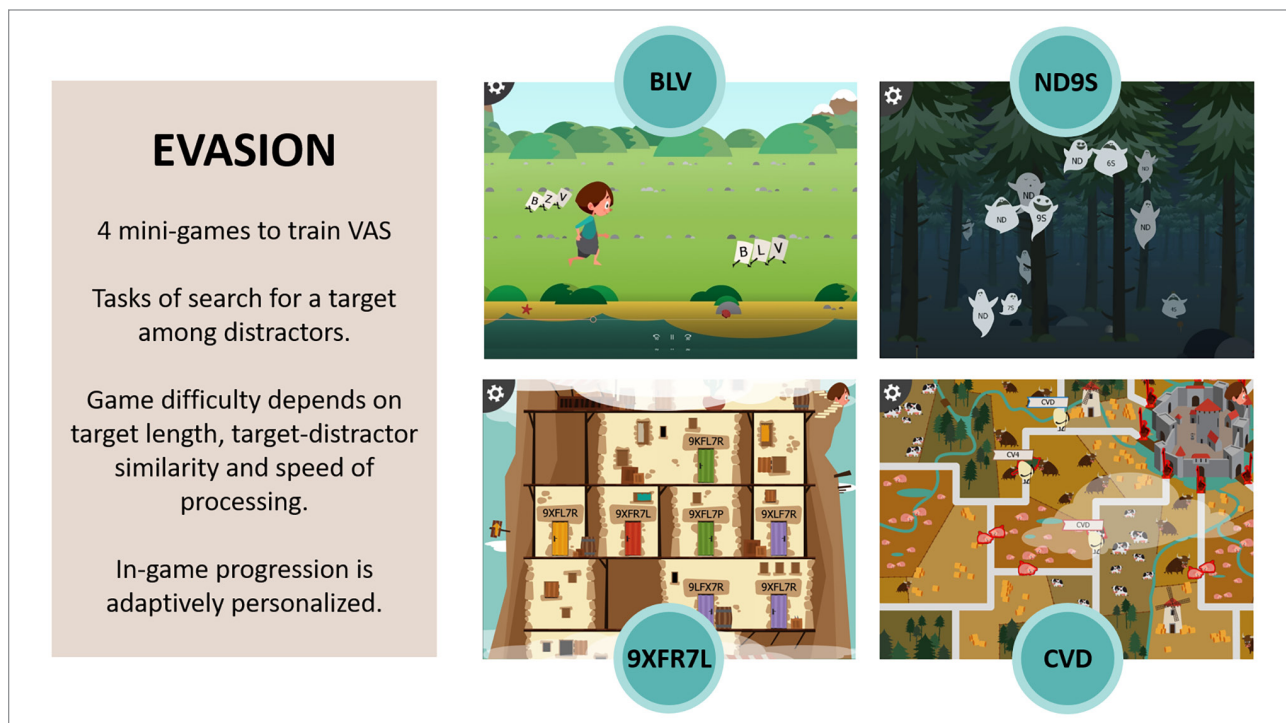
game-based intervention was designed to target various aspects of attention and executive functions. Intensive training resulted in higher performance in visual search, which was interpreted as evidence for higher attentional control, and improvement on a combined measure of word, pseudoword, and text reading fluency was also found. Given the known relationship between reading, visual search, and VAS skills (Lallier et al., 2013; Valdois, 2022), Antzaka et al. (2017) examined whether action video game playing further affected VAS. By comparison to nonplayers, they showed higher VAS and faster pseudoword reading in action video game adult players. The overall findings suggest that action video games have a beneficial effect on the attentional abilities involved in VAS. We thus anticipated that an optimal intervention for VAS enhancement should be based on the properties of action video games while requiring parallel processing of targets that gradually increased in number of visual elements.

EVASION: A New VAS Training Software to Improve Literacy Skills

EVASION is a tablet game designed to include the properties of action video games while targeting VAS. The game invited children to retrieve letters that escaped from a book in a library and spread over four islands.

The game consisted of four minigames, one minigame per island (see Figure 1). Each island proposed similar exercises, but in a different environment. All four minigames similarly involved multicharacter simultaneous processing, requiring the child to quickly retrieve target strings among distractors. The targets (and the distractors) were 2- to 6-item long, they included only consonants (like “HN” or “TBVSFD”) for half of them, or consonants and digits (like “R9” or “HK3SZT”) for the other half. In-game progression was adaptively personalized, using a learning algorithm called PARSEVAL (Probabilistic Algorithm for Real-time Subject EVALuation; Diard et al., 2011). The algorithm selected the proposed exercises based on performance on previous trials through the modulation of within-game parameters. Game difficulty was defined by three parameters known to affect VAS: the number of characters within the string, visual similarity between targets and distractors, and processing speed that was modulated by event speed and the number of strings that co-occurred on the screen. The EVASION game further shared the qualitative features of action video games (Bediou et al., 2018). In all four minigames, several target strings were displayed simultaneously, distributed among many distractors. Children had to select the targets while inhibiting responses to the distractors. They also had to ignore some unrelated events that could occur while playing (e.g., a bird crossing the screen); the spatial and temporal occurrence of targets was unpredictable,

FIGURE 1
Illustration and Brief Description of the Four EVASION Minigames. The General Principles of the Games Are Listed on the Left. An Example of the Variety of Targets is Provided (Different Lengths, Only Letters, or Letters and Digits). In the Runner Game (Top Left), the Running Character can be Shifted Across Three Horizontal Routes to Catch Target Strings While Avoiding Distractors. In the Letter Tower Game (Top Right), the Child has to Open all the Doors Wearing the Target String Before Accessing the Next Floor. The Ghost Forest Game (bottom left) Requires Clicking on the Couple of Ghosts as Soon as They Join Hands but Only if They Form the Target String. In the Castle Game (Bottom Right), the Player Helps the Knight Eggs Wearing the Target on Their Flag to Reach the Castle as Fast as Possible



requiring to monitor the whole field of view at any time (both the center of the screen and the periphery); all items (targets and distractors) were rapidly moving on the screen; several had to be tracked simultaneously; and children had to make motor responses under strong time constraints. A repetitive music accompanied the visual events but without providing any cue relevant to the task. Its main purpose was to help children concentrate on the game while ignoring auditory information from the classroom environment. Players received feedback as to the accuracy of their responses. When an incorrect response was given, negative visual feedback (i.e., a visual spray of red letters) was provided on the screen together with an auditory feedback (i.e., a low-pitch tone) through headphones. Positive responses were followed by a visual spray of green letters and a high-pitch tone. Children were systematically informed on time spent in the different islands and on remaining playtime to finish the game. After each 5-min playtime, an animal totem was displayed rising at the top of a heap of pages whose height was proportional to the player score. The animal totem was also animated in different manners depending on the player's score. Start and

end of game information was recorded and total active playtime was computed.

The Current Study

The purpose of this study was to test whether EVASION was efficient to support the development of literacy skills. Because early intervention is recommended for the prevention of learning difficulty, EVASION was proposed at the beginning of formal literacy instruction, to Grade 1 children. Students from socioeconomically disadvantaged backgrounds were more specifically targeted since they are more prone to show delays in reading. Rather than selecting children who met this criterion in classrooms, the study was carried out in an overseas French department (Mayotte) in which there is an overwhelming number of children from disadvantaged backgrounds. Our second goal was to assess the effectiveness of EVASION in the ecological context of the classroom. For this purpose, training was implemented during class hours. Game difficulty was adaptively personalized (using PARSEVAL), so that children played in a relatively independent manner

under the sole supervision of their teacher (without involvement of any dedicated staff). Teacher involvement was minimal, being limited to organizing and setting up training sessions and occasionally helping children with technical assistance.

An experimental design was adopted to assess EVASION training against two other conditions, consisting in the use of an equally engaging control intervention, called Luciole, and of the popular GraphoGame (GG) training software. The Luciole control tablet game (Loiseau et al., 2018) was designed to train oral comprehension in L2 English training while including no printed alphabetic material, none of the properties of action video games, and no requirement for multielement parallel processing. The French version of GG was used to train grapheme–phoneme correspondences (Lassault et al., 2022). Three cohorts of Grade 1 children were matched to have the same initial level on various outcome measures at the beginning of the year (Time 1, T1). The study was planned so that one cohort would receive the EVASION intervention, another one the Luciole intervention, and the last one GG training. Unfortunately, due to technical problems, Luciole was not delivered in time. As a result, the “Luciole” group ended up as a “business-as-usual” (BAU) control group. In this control group, as in the other two, the teachers’ reading lessons emphasized knowledge of grapheme–phoneme mappings and phoneme awareness development. Posttraining assessment was carried out at the end of Grade 1 (Time 2, T2). To avoid test–retest effects, different tasks were used at T1 and T2 to evaluate cognitive, reading, and spelling outcomes.

We expected greater VAS improvement between T1 and T2 in the EVASION group than in the BAU or the GG groups. We further expected that EVASION training would benefit more to children who had initially weaker VAS, which would confirm EVASION’s ability to reduce cognitive heterogeneity among pupils. Assuming that EVASION was effective to improve VAS, then positive effects of training were expected on literacy skills.

In line with the theoretical framework of the BRAID models (Ginestet et al., 2019, 2022; Phénix et al., 2018; Saghiran et al., 2020; Steinhilber et al., 2023; Valdois, Phénix, et al., 2021), greater VAS would result in more efficient orthographic learning and enhanced capacity to process multiple letters in parallel, which would affect reading fluency. Thus, an increase of VAS following EVASION training was expected to translate in greater improvements in word, pseudoword, and text reading fluency. Better orthographic learning following higher VAS would further predict intervention gains in spelling, in particular for real words. However, higher VAS might further enhance pseudoword spelling, in particular when spelling requires the use of long or context-dependent graphemes. An effective effect of EVASION training on literacy skills would further result in stronger effects on literacy in the EVASION group

than in the BAU group. More subtle differences were expected by comparison to the GG group. Because GG allows intensive training for automation of grapheme–phoneme correspondence knowledge (Potier-Watkins et al., 2020), EVASION and GG might have either similar effects on pseudoword reading fluency or the effect might be lower in the EVASION group. With respect to word and text reading fluency, positive effects of GG have been reported (Lassault et al., 2022), but EVASION was expected to more directly impact reading fluency, which would result in higher word and text reading fluency in the EVASION group. Higher VAS improvement for children with initially weaker performance, if observed, would also yield higher reading improvement. Finally, assuming that VAS and phoneme awareness are independent cognitive processes (Valdois, 2022), we expected no effect of EVASION training on phoneme awareness as compared to the BAU group.

A preliminary analysis of total playtime duration during EVASION training revealed strong interindividual differences in effective playtime, showing that, most of the time, recommendation for a 10-h playtime duration had not been followed. This gave us the opportunity to examine the link between outcome measures at T2 and total time played. We further designed two subgroups of EVASION players with either an effective longer playtime (more than 5 h) or an effective shorter playtime (less than 5 h). As further evidence that improvement on T2 outcome variables would relate to EVASION training, we expected greater gains for children who had longer than shorter total effective playtime.

Finally, as further evidence for generalization of the relationship between VAS and literacy skills, we examined whether T1–T2 VAS improvement contributed to both T1–T2 reading fluency improvement and T2 spelling performance independently of the child’s cognitive skills at T1 and independently of class effect.

Method

Participants

A total of 749 children (53% females; 6;0 to 7;2 years old) were initially recruited from 52 classes of first grade belonging to 35 different schools that were located in the Mayotte Academy. Mayotte is a French overseas department. French is the official language but, most of the time, it is not the children’s mother tongue. Although children may have some degree of exposure to French in their familial or social environment, they are mainly exposed to French at school. French is the language of instruction so that children learn to read in a language most of them are not familiar with. It was impossible to get information on the socioeconomic status (SES) of the participants’ family through a questionnaire to be completed by the parents,

since many of them were not readers and/or not French speakers. It is, however, well documented that SES is particularly low in Mayotte. A great share (67%) of the population has no diploma or the BEPC (Official school achievement test conducted at the end of secondary education) at the best; 30.1% are unemployed (Couleaud et al., 2021). The schools and classrooms of the participants were a priori selected to be representative of the diversity of the island population, so that these general SES statistics should apply to the present sample.

The participants were administered a first battery of test at the beginning of Grade 1 (T1). Due to data collection issues, the sample was reduced to 671 children. The classes of the participants were then matched to design three groups of participants that did not differ on any of the T1 measures. The unmatched classes were not considered further. The selected classes were then randomly assigned to either the EVASION ($N=190$), the BAU ($N=184$), or the GG ($N=201$) group. A second battery of tests was proposed at the end of Grade 1 (T2). Actually, 492 children participated to the two assessment sessions. Twenty-eight students were a priori excluded from the sample due to their incapacity to perform any task at T2 (score of 0 on all tasks at T2, suggesting they did not understand French; they also scored 0 on all or most tasks at T1). Eleven further students were identified as outliers. This study focuses on the 453 participants who completed the different phases of the project (pretest, training, and posttest) and belonged to either the EVASION ($N=144$), the BAU ($N=159$), or the GG ($N=150$) group.

Ethics

In accordance with the Declaration of Helsinki, the parents (or legal guardians) gave written informed consent for the participation of their child to the research. The teachers were informed on the ethical aspects of the project. When required, they read aloud the written document that provided information on the project to make it accessible to the parents; they were trained to provide explanations and additional information on request. The ethics committee (CERGA) of the Grenoble-Alpes University approved the research protocol (IRB00010290-2017-07-04-22). An agreement of the “Commission Nationale de l’informatique et des libertés” (CNIL, agreement number: 0979176) was obtained that guarantees the protection of personal data and respect of the participants’ rights in terms of privacy and anonymity. The study was carried out in close collaboration with the “Rectorat de Mayotte” (i.e., the local education authority). The teachers volunteered for the participation of their class to the study.

Study Design

The initial assessment was proposed to Grade 1 children in November 2018 (after 2–3 months of formal literacy

instruction). The whole population was first trained on the French version of the GG software (Lassault et al., 2022). This was done for two main reasons. First, GG was already available while there were delays in the development of the new experimental (EVASION and Luciole) software. Second, the use of GG prior to the experimental phase provided the opportunity to solve technical problems and familiarized the pupils with the tablets and the teachers with the training schedule. Our purpose was not to measure the impact of this first phase of training on reading acquisition, so that no assessment was scheduled at the end of these first 8 weeks. Then, a first group was attributed the EVASION software for the following 10 weeks (three sessions of 20 min a week), while a second group went on using GG at the same frequency (three sessions of 20 min a week during 10 weeks). Due to technical problems, Luciole was not delivered in time so that the control group ended up as a BAU group. Within the classes that used EVASION or GG training, teachers organized small groups of students depending to the number of tablets dedicated to training (typically around 6). Children took turns using the tablet. To ensure that an equivalent amount of time was dedicated to learning to read in the three groups, teachers were asked to carry out EVASION and GG training outside the time slots initially planned for reading lessons. Posttraining assessment was carried out at the end of Grade 1 (in May–June), from 1 to 4 weeks after the end of the intervention.

Pre and Posttraining Assessment

Different test materials that were adapted to the class level were used at the two testing phases (T1 and T2). Some of the tasks were administered in collective sessions by the teachers. A 2-day teacher training was scheduled before assessment during which the teachers were familiarized with the collective assessment material and trained on how to conduct it. Other tasks were administered individually in a quiet room of the school by a research staff member. National education staff members in charge of digital technologies at school participated for the administration of the computerized tasks. All the tasks were designed for the need of the study. In the following, we recap the tasks that were administered. A detailed description of each task is provided in the Supplementary Material.

Pretraining Assessment (T1)

The T1 assessment battery included an evaluation of oral language, reading, and reading related skills. To evaluate oral language, tasks of vocabulary knowledge and syntactic comprehension were administered collectively; a pseudoword repetition task was individually administered. Two tasks of word and pseudoword reading fluency were designed and administered individually to estimate early

reading skills. The words were very frequent and short, adapted for reading assessment at the beginning of literacy instruction. The pseudowords included the simple grapheme–phoneme correspondences that are the first to be taught at the beginning of Grade 1. Additional tasks were administered to assess skills that are known as reliable longitudinal predictors of learning to read, namely, phonological awareness (PA), rapid automatized naming (RAN), and VAS. Seven PA tasks were used: the four tasks of rhyme judgment, syllable count, oddball detection, and phoneme position detection were administered collectively; three other PA tasks of rhyme judgment, phoneme blending, and phoneme deletion were administered individually. RAN was evaluated individually through the naming of an array of digits. Two computerized tasks of whole and partial digit report were used to estimate VAS abilities along with a single-digit identification threshold control task (individual testing). Additional tasks of letter name knowledge and verbal short-term memory (namely forward and backward digit-span, pseudoword repetition) were individually administered. The assessment further included a task of oral comprehension in English that was initially designed to evaluate the effect of the Luciole intervention. The whole collective assessment lasted around 1.5h. The collective tasks were administered in two sessions with a 20-min break in between. In each session, additional short breaks were scheduled between the tasks. The collective and individual assessments were administered on different days. The individual assessment required a further 1-h and a half testing. The computerized tasks were all administered one after the other. Their order was systematically switched and they were scheduled before the noncomputerized individual tasks for half of the children, or after for the other half.

Posttraining Assessment (T2)

Test materials at T2 were adapted for assessment at the end of Grade 1; they thus differed from the tests used at pretest. Tasks of word, pseudoword, and text reading were administered individually to estimate reading fluency. The words and pseudowords were designed to include multiletter and/or contextual graphemes. The children were asked to read the different lists and text as fast and as accurately as they could within the 1-min limit. The score was the number of items accurately read within this time limit. Spelling was assessed through tasks of word and pseudoword spelling that were administered collectively. For word spelling, the spoken word was first presented followed by a sentence incorporating the target for disambiguation. The dictated words included inconsistent graphemes; multiletter or contextual graphemes were required to spell the dictated pseudowords. The scores were the number of words accurately spelled and the number of spellings having the same pronunciation as the spoken pseudoword, respectively.

Tasks of phoneme awareness and VAS were further administered. Two tasks of phoneme deletion and phoneme segmentation were used to measure phoneme awareness skills. VAS was assessed using letter report tasks in which five consonant strings were briefly presented for 200 ms and the children were asked to report either all the letters (global report) or a single letter (partial report) whose position was indicated by a cue displayed at the offset of the letter string. Single-letter identification threshold was further measured.

Analysis Plan

Data were analyzed using R (R Core Team, 2020). One-way ANOVA test were first computed to compare performance of the three EVASION, GG, and BAU groups on T1 (pretest) and T2 (posttest) measures. Given that different tasks were used at each assessment, *z* scores were systematically computed by reference to the whole population performance ($N=453$). Training effect on VAS was examined by means of analyses of covariance with Time as within-subject factor, Group as between-subject factor, and single-digit processing time (e.g., digit identification threshold) as covariate. Pairwise analyses were used to assess the significance of local interactions. Linear regression models were performed to evaluate the influence of T1 VAS on T2 VAS for the three groups. T2 VAS measure was expected to be less dependent on T1 VAS skills following EVASION training. We then examined whether initial (T1) VAS performance interacted with the intervention using the same regression models. To examine whether EVASION training differently affected reading fluency and phoneme awareness, ANCOVAs were computed on the different outcome measures, using the same factors and covariate as previously for VAS. Significant interactions were expected for the reading fluency measures, but not for phoneme awareness. As previously for VAS, we examined the relationship between T1 and T2 reading fluency and expected a lower relationship following EVASION training using linear regression models. Spelling skills were only assessed at T2, ANOVA's were computed, and a group effect expected on the two T2 outcome measures of word and pseudoword spelling. For all the analyses, effect sizes were presented as partial η^2 's.

A second series of analyses was restricted to the EVASION group to focus on playtime duration effect on T2 performance. Information on playtime was only collected for around half of the EVASION group children. We first examined whether performance on the different outcome variables at T2 correlated with playtime duration. Additional analyses were performed considering two subgroups with longer ($N=49$) and shorter ($N=28$) playtime duration on the EVASION game. Time-by-group interactions were rerun considering the three following groups: the EVASION subgroup with either long or short playtime

and the two control groups (BAU and GG). Higher improvement was expected on the variables of interest for the subgroup with longer EVASION playtime (but not for the shorter EVASION playtime subgroup) than for the GG and BAU groups.

Finally, hierarchical linear mixed (HLM, Bates et al., 2015) models were computed on the whole population of 453 participants, taking class as random effect. We first evaluated to what extent T1 variables predicted pre-posttest reading fluency improvement and spelling skills at T2. We then evaluated the proposal that VAS enhancement related to reading fluency improvement and spelling skills. Separate analyses were run for reading fluency ($\Delta T2-T1$ word reading fluency) and spelling (composite T2 word and pseudoword skills) outcomes. The model was used to evaluate the contribution of VAS improvement between T1 and T2 on these two outcomes after control of the class effect and of all the other reading related skills measured at T1.

Results

Raw data and detailed analyses are available as supplementary material files (https://osf.io/6xm73/?view_only=326d542cebe14496a59d205b651dc28f). Descriptive statistics (with Omega's estimates of reliability) for all T1 and T2 variables are provided in the Appendix. Correlation coefficients between all the variables are provided in the supplementary material. Composite scores of oral language (vocabulary, sentence comprehension, pseudoword repetition), letter knowledge (letter name and letter sound), PA (rhyme judgment, phoneme position, phoneme blending, and phoneme deletion), VAS (global and partial report), and reading fluency (word and pseudoword) were computed at T1, based on significant correlations between the measures of the same construct. The analyses reported

below were computed on z scores. However, all the analyses were rerun using raw data to ensure no bias was introduced when using z scores built on the population of interest. Very similar results were obtained when using raw scores (results are available as supplementary material, cf. the OSF file).

Descriptive Statistics

Table 1 provides the baseline balance scores on the whole T1 tasks for the three, EVASION, GG, and BAU groups. Results of one-way ANOVA test with unequal variances show that the three groups were matched on all the T1 measures (all p values $>.05$). As further evidence of good matching at T1, cross-group pairwise comparisons (using Welch's t test) showed no significant differences.

Table 2 shows the scores of the three groups for all measurements at T2. One-way ANOVA tests were computed, showing significant differences between the groups. Children from the EVASION group performed better than children from the two other BAU and GG groups on VAS abilities, reading, and spelling skills. They further showed faster single-letter recognition skills. In contrast, the three groups did not differ in either PA skills or reading comprehension at posttest.

The Effect of EVASION on VAS

The evolution of VAS performance between pretest (T1) and posttest (T2) is illustrated in Figure 2a for the EVASION, GG, and BAU groups. A 2×3 ANCOVA with Time (T1 and T2) as within-subject factor, Group (EVASION, GG and BAU) as between-subject factor, and T1 digit identification threshold as covariate was carried out for the VAS composite z score as the outcome measure. The Time-by-Group interaction was significant, $F(2, 356) = 5.62$, $p = .004$, partial $\eta^2 = 0.031$. Pairwise comparisons showed that VAS improvement was higher for the

TABLE 1
Baseline Balance of the Composite Scores (Mean and SD) at T1 between the Three EVASION, GraphoGame (GG), and "Business-as-Usual" (BAU) Groups

Time 1 (pretest, G1)	EVASION (N = 144)	GG (N = 150)	BAU (N = 159)	F (df1, df2)	p
Oral language	0.68 (0.15)	0.66 (0.18)	0.65 (0.14)	1.487 (2, 293)	0.228
Phonological awareness (PA)	0.53 (0.22)	0.50 (0.21)	0.49 (0.22)	1.097 (2, 299)	0.335
Verbal short-term memory	0.68 (0.14)	0.67 (0.16)	0.67 (0.16)	0.263 (2, 299)	0.769
Letter knowledge	0.87 (0.22)	0.86 (0.26)	0.85 (0.27)	0.361 (2, 299)	0.697
Reading fluency (wpm)	3.85 (4.77)	3.68 (4.46)	3.44 (4.32)	0.314 (2, 297)	0.731
Rapid automatized naming (RAN)	40.83 (21.63)	37.32 (26.05)	38.62 (17.71)	0.861 (2, 288)	0.424
Visual attention span (VAS)	69.41 (23.57)	72.48 (18.18)	71.28 (18.54)	0.773 (2, 293)	0.462
Digit identification threshold	71.44 (14.10)	69.44 (7.27)	69.83 (8.57)	1.151 (2, 281)	0.318

EVASION group than for either the BAU group, $F(1, 246)=9.52, p=.002$, partial $\eta^2=0.037$, or the GG group, $F(1, 277)=6.14, p=.014$, partial $\eta^2=0.026$, while these two latter groups evolved similarly between pre- and posttest ($F<1$, ns).

To investigate to what extent posttest T2-VAS performance was influenced by pretest T1-VAS performance in the three groups, we computed linear regression models. Results showed that T1-VAS explained a lesser amount of variance in T2-VAS for the EVASION group, $R^2=0.15$; $F(1, 127)=22.49, p<.001$, than for the BAU, $R^2=0.40$; $F(1, 120)=53.01, p<.001$, or the GG, $R^2=0.31$; $F(1, 132)=87.33, p<.001$, group. These findings suggest a positive EVASION training effect yielding VAS performance at the end of Grade 1 to be less dependent on earlier VAS skills than in the two other groups. Furthermore, as illustrated on Figure 2b and by comparison with the control group, EVASION training (but not GG training; $ES=-0.16, p=.2$) was more beneficial for the children who initially had weaker VAS skills than for those who showed higher VAS scores at pretest ($ES=-0.34$; 95% CI $[-0.52, -0.16]$; $p<.001$).

The Effect of EVASION on Reading Skills

The effect of EVASION training on improvement in reading fluency was evaluated for each reading outcome variable using 2×3 ANCOVAs with Time (T1 and T2) as within-subject factor, Group (EVASION, GG, and BAU) as between-subject factor, and T1 digit identification threshold as covariate. The main Time-by-Group interaction was significant for all the reading fluency measures, except text reading: for words, $F(2, 364)=6.58, p=.002$, partial $\eta^2=0.035$, for pseudowords, $F(2, 374)=5.78, p=.003$, partial $\eta^2=0.030$, and for the composite measure of W and PW reading fluency, $F(2, 365)=5.06, p=.007$, partial $\eta^2=0.027$.

Results are illustrated on Figure 3 for word and pseudoword reading fluency. As shown on Figure 3a, pre-posttest reading enhancement was higher in the EVASION group than in the GG group (for words: $F(1, 235)=10.19, p=.002$, partial $\eta^2=0.042$; for pseudowords: $F(1, 240)=5.82, p=.017$, partial $\eta^2=0.024$) and higher in the BAU group than in the GG group (for words: $F(1, 238)=9.68, p=.002$, partial $\eta^2=0.039$; for pseudowords: $F(1, 243)=11.12, p<.001$, partial $\eta^2=0.044$). However, results revealed similar T1-T2 word and pseudoword reading fluency progression for the EVASION and the BAU control group ($F<1$, ns). As previously for VAS, linear regression models were computed to assess the intervention effect on word and pseudoword reading fluency at posttest depending on the child reading level at pretest. Results showed that the amount of variance in reading fluency at T2 that was explained by T1 reading performance was lower for the EVASION group ($R^2=0.31$; $F(1,$

$132)=58.82, p<.001$ and $R^2=0.23$; $F(1, 139)=42.13, p<.001$ for words and pseudowords, respectively) than for the BAU ($R^2=0.46$; $F(1, 133)=102.8, p<.001$ and $R^2=0.39$; $F(1, 133)=64.33, p<.001$) or the GG ($R^2=0.44$; $F(1, 144)=123.7, p<.001$ and $R^2=0.33$; $F(1, 150)=96.34, p<.001$) group. As illustrated on Figure 3b, the children who initially had lower word reading fluency (T1) performance did not benefit more from EVASION training ($ES=-0.05$, 95%CI $[-0.24, 0.15]$, $p=.7$). However, the gains in pseudoword reading fluency tended to be higher for the children who initially had lower pseudoword reading skills ($ES=-0.20$, 95% CI $[-0.40, 0.00]$, $p=.054$).

The Effect of EVASION Training on Spelling Skills

Spelling performance was only assessed at T2. As shown on Table 2, performance was higher in the EVASION group than in the two other groups for the two measures of word and pseudoword spelling and the corresponding composite score. The main training effect was significant for both the composite spelling score, $F(2, 356)=5.88, p=.003$, partial $\eta^2=0.032$, and each of the word, $F(2, 376)=4.37, p=.013$, partial $\eta^2=0.023$, and pseudoword, $F(2, 356)=6.10, p=.002$, partial $\eta^2=0.033$, spelling scores. Pairwise comparisons showed significantly higher composite spelling score in the EVASION group than in either the GG, $F(1, 223)=10.14, p=.002$, partial $\eta^2=0.043$, or the BAU, $F(1, 240)=6.91, p=.009$, partial $\eta^2=0.028$, group. Higher performance was observed for the EVASION group as compared to the GG and BAU groups on both word, $F(1, 243)=7.23, p=.007$, partial $\eta^2=0.029$, and $F(1, 260)=5.37, p=.02$, partial $\eta^2=0.020$, and pseudoword, $F(1, 223)=10.44, p<.002$, partial $\eta^2=0.045$, and $F(1, 240)=6.91, p=.009$, partial $\eta^2=0.028$, respectively, spelling scores. Performance of the BAU and GG groups did not differ on any of the spelling measures at T2 (all $F_s<1$).

Is There Some EVASION Training Effect on Phoneme Awareness?

The ANCOVA computed on PA composite score with Time (pre- and posttest) as within-subject variable, Group (EVASION, GG, BAU) as between-subject variable, and T1 digit identification threshold as covariate showed no significant Time \times Group interactions ($F<1$, ns) and no significant pairwise interactions (all $F_s<1$). PA skills improved from T1 to T2, but similarly for the three groups.

The Effect of EVASION Playtime Duration on VAS, Reading, and Spelling Improvement

The EVASION software was used by 144 children whose performance enhancement between pre- and posttest in

TABLE 2
Posttest (2) Performance (Mean, SD) of the Three EVASION (a), GG (b), and BAU (c) Groups

Time 2 (posttest, G1)	EVASION (N = 144)	GG (b) (N = 150)	BAU (c) (N = 159)	F (df1, df2)	p
PW reading fluency (wpm)	20.36 (10.94) ^b	15.32 (10.82) ^c	18.45 (12.36)	7.49 (2, 283.16)	0.001
Word reading fluency (wpm)	20.15 (16.46) ^{b,c}	13.95 (14.16)	15.85 (13.79)	5.58 (2, 271.43)	0.004
Text reading fluency (wpm)	27.16 (22.32) ^b	21.07 (21.78)	22.98 (21.18)	2.68 (2, 275.10)	0.071
Word and PW reading fluency	20.29 (14.17) ^{b,c}	14.45 (12.78)	16.76 (12.91)	6.29 (2, 272.72)	0.002
Phoneme segmentation (max = 10)	8.16 (3.29)	7.54 (3.72)	7.72 (3.19)	1.14 (2, 264.26)	0.321
Phoneme deletion (max = 8)	5.16 (3.16)	4.59 (3.47)	4.67 (3.26)	1.26 (2, 265.98)	0.286
PA composite score (max = 18)	13.32 (5.91)	12.19 (6.36)	12.39 (5.66)	1.37 (2, 264.54)	0.255
VAS whole report (max = 100)	53.03 (14.09) ^{b,c}	47.14 (18.56)	48.44 (19.16)	5.11 (2, 268.04)	0.007
VAS partial report (max = 50)	32.11 (8.99) ^c	30.39 (10.79) ^c	24.35 (12.70)	18.35 (2, 267.26)	<0.001
VAS composite score (max = 150)	85.27 (19.51) ^{b,c}	77.53 (27.07)	72.57 (26.95)	10.85 (2, 264.62)	<0.001
Letter identification threshold (ms)	67.25 (24.59) ^{b,c}	77.29 (35.03)	77.23 (31.60)	5.81 (2, 257.28)	0.003
Word spelling (max = 10)	4.14 (2.73) ^{b,c}	3.30 (2.77)	3.30 (2.72)	4.42 (2, 278.89)	0.013
PW spelling (max = 12)	6.56 (3.57) ^{b,c}	4.97 (3.52)	5.17 (3.50)	7.22 (2, 257.21)	0.001
Composite spelling score	10.70 (6.01) ^{b,c}	8.27 (5.90)	8.46 (5.86)	6.26 (2, 257.10)	0.002
Word comprehension (max = 10)	6.55 (2.59) ^b	5.81 (2.96)	6.32 (2.38)	2.48 (2, 273.92)	0.085
Sentence comprehension (max = 11)	6.67 (2.65) ^b	5.83 (2.79) ^c	6.75 (2.34)	4.98 (2, 274.62)	0.007
Text comprehension (max = 5)	2.50 (1.52)	2.12 (1.64)	2.30 (1.65)	1.95 (2, 278.71)	0.144

Note: The superscripts indicate significant pairwise differences between the EVASION group and the GG or BAU groups and between the two control groups.

VAS, reading, and spelling was examined earlier. However, playtime duration information was only available for a subset of 77 participants. In this population, we investigated the effect of playtime duration on gains in VAS and reading skills between T1 and T2, as further evidence of EVASION training efficacy. We further split the subset of EVASION players into two groups with longer (more than 5 h) or shorter (less than 5 h) playtime duration and examined the effect of playtime duration on their VAS and literacy skills.

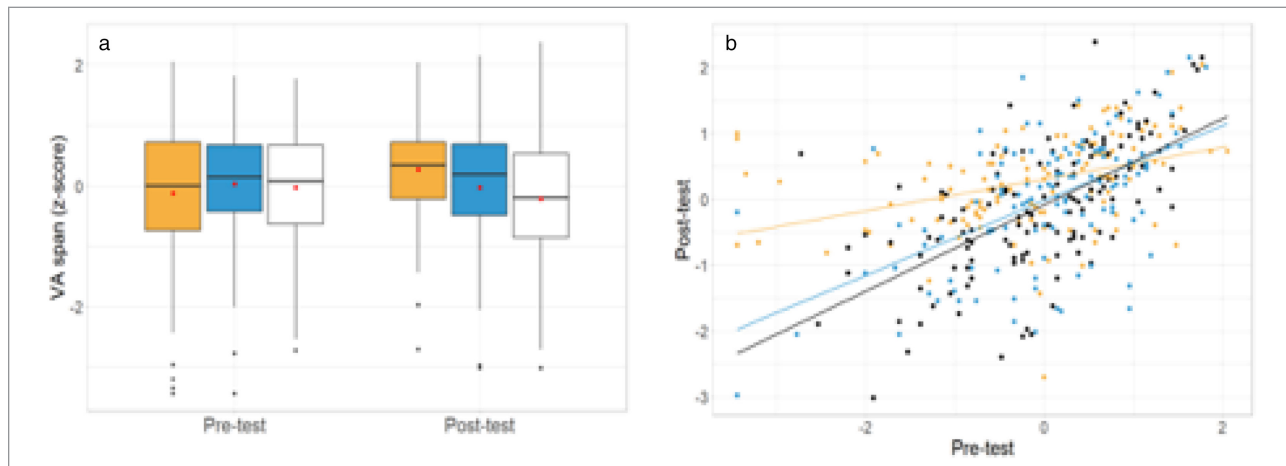
The Pearson's correlation between playtime duration and T2–T1 gain in VAS performance for the whole population of 77 participants was significant ($r=0.28$, $p=.02$). ANCOVAs were rerun to estimate whether VAS differently improved for the two EVASION playtime subgroups (see Supplementary Material). Results showed significant interactions when the analysis focused on the EVASION subgroup with longer playtime, by comparison to the BAU group, $F(1, 165)=16.23$, $p<.001$, partial $\eta^2=0.090$, and by comparison to the GG group, $F(1, 147)=11.30$, $p<.001$, partial $\eta^2=0.071$. None of the interactions were significant when considering the EVASION subgroup with shorter playtime (all $F_s<1$).

The correlation between playtime duration and T2–T1 gain in reading performance was significant for words ($r=0.32$, $p=.01$), but not for pseudowords ($r=0.03$, ns). ANCOVAs showed significant Time \times Group interactions on word reading fluency (but not pseudoword reading fluency) when the analysis focused on the EVASION subgroup with longer playtime (by comparison to the BAU group, $F(1, 168)=4.66$, $p=.030$, partial $\eta^2=0.027$, and by comparison with the GG group, $F(1, 152)=20.95$, $p<.001$, partial $\eta^2=0.121$). None of the interactions were significant when considering the EVASION subgroup with shorter playtime (all $F_s<1$).

We lack information on the gains in spelling performance between T2 and T1, since spelling was only assessed at T2. However, T2 spelling performance differed depending on the training Group (EVASION long playtime, EVASION short playtime, GG, BAU). For both words and pseudowords, spelling performance was always higher for the longer playtime subgroup than for the two control groups (GG and BAU; all $p_s<.01$ for word spelling and all $p_s<.001$ for pseudoword spelling). Performance of the shorter playtime subgroup did not differ from that of the

FIGURE 2

Evolution of VAS Performance Following Intervention: (a) VAS Performance (in z Scores) at Time 1 and Time 2 in the EVASION (Orange), GG (Dark Blue), and BAU (White) Groups. The Red Point in the Scatterplots is for the Mean. (b) Regression Plots of the Effect of Pretest VAS Performance (z Scores at T1 on x-Axis) on Posttest VAS Performance (z Scores at T2 on y-Axis) for the Three Groups. Note that Only Children Without Missing Data (i.e., VAS Performance Available at Pre- and Posttest) Are Plotted on (b) Thus, Corresponding to a Sample of 139 Participants in the EVASION Group, 132 in the GG Group, and 140 in the BAU Group



two control groups, except for pseudoword spelling performance that was higher in the EVASION group with shorter playtime duration than in the GG group, $F(1, 137) = 4.30, p = .039$.

No significant playtime effect was found on PA ($F < 1$).

Does VAS Improvement Predicts Later Reading and Spelling Skills after Controlling for the Class Effect?

Stepwise multiple regression models were run on the entire population while controlling for the class effect. The dependent variables in the models were reading fluency improvement (word and pseudoword composite measure) between T1 and T2 and performance on spelling skills (word and pseudoword) at T2. The two models were computed with Class as a random effect. The first model included all T1 variables as early predictors of literacy skills, namely oral language, letter knowledge identification, RAN, PA, and VAS. The second model included the same T1 variables except VAS, but further considered the predictive effect of changes in VAS skills between T1 and T2 on the outcome variables.

Independently of the class effect, early VAS performance (at T1) was a significant and unique predictor of both reading fluency improvement between pre- and post-test, and later spelling skills (Table 3, Model 1). PA was another significant and independent predictor of the two measures, but none was predicted by RAN. More interestingly for the present purpose, the results of Model 2 (Table 3) showed that gains in VAS performance between

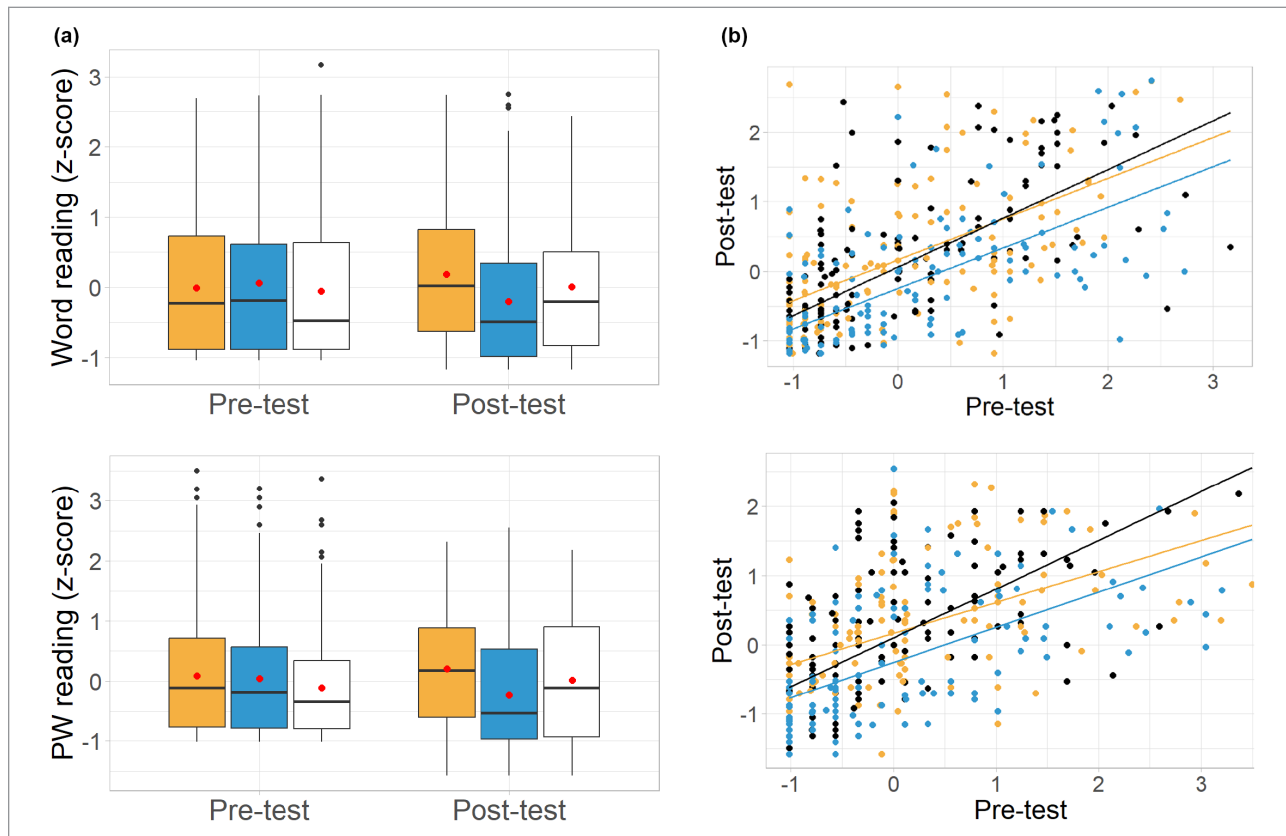
T1 and T2 predicted reading fluency improvement over the same period, independently of the class effect and after controlling for the influence of all other T1 predictors.

Discussion

This study presented a training software—called EVASION—that was designed to target visual attention and improve VAS. Our main goal was to determine whether intensive visual attention training with EVASION would enhance reading and spelling skills in beginning readers. The originality of the study was threefold. First, most previous training studies targeted phonological awareness and phonics (Lassault et al., 2022; Potier-Watkins & Dehaene, 2023) as a way to improve literacy, while only a few focused on attentional skills (Franceschini et al., 2013, 2017; Pasqualotto et al., 2022). Second, the studies that focused on attention skills either used commercially available action video games that were not informed by theories on the role of visual attention in reading (Franceschini et al., 2013, 2017) or used custom-designed software that targeted a diversity of cognitive and attention skills, some of which were not specific to the visual modality (Pasqualotto et al., 2022). Third, in most studies, trainings were implemented under the supervision of dedicated staff, while, in this study, intervention was carried out in the ecological context of the classroom, only based on teacher instructional support (McTigue et al., 2020). Our main purpose was to examine whether the intervention was efficient to prevent literacy acquisition difficulties. Thus,

FIGURE 3

Effect of EVASION Training on Word (Top) and Pseudoword (Bottom) Reading Fluency. (a) Improvement of Word/Pseudoword Reading Fluency Between Pretest (T1) and Posttest (T2) for the EVASION (Orange), GG (Blue), and BAU (White) Groups. (b) Linear Regressions Showing T2 Word/Pseudoword Reading Fluency Enhancement Depending on Pretest Performance for the Three Groups. Note that Only Children Without Missing Data (i.e., Reading Performance Available at Pre- and Posttest) Are Plotted on (b). There Were no Missing Data in the EVASION and GG Groups and Only Three Missing Data for Words ($N = 156$) in the BAU Group



EVASION training was implemented in a large sample of Grade 1 children who, for most of them, were from socio-economically disadvantaged backgrounds.

Our first goal was to examine whether EVASION was effective to improve VAS. Results revealed this was indeed the case. Children in the experimental EVASION group showed greater VAS improvement as compared to the two GG and BAU control groups. Interestingly, we found that children who started with weaker VAS abilities benefitted more from EVASION training than children who had higher VAS at the beginning of Grade 1. This later finding suggests that cognitive heterogeneity was reduced at the end of the year in the EVASION group. The effects of EVASION playtime duration were further examined, but on the reduced subgroup of EVASION players for which information was available. As further evidence that the gains on VAS were specifically related to the intervention, VAS improvement was higher when time using the EVASION game increased. Comparison of the two subgroups of short- and long-time players revealed that only the

subgroup of children who spent more than 5 h using EVASION training showed higher gains in VAS than the two control groups, with effect sizes that were larger than in the whole population of EVASION players. Evidence that EVASION training was efficient to improve VAS is well in line with previous findings showing that the processing of multielement strings that progressively increased in length affected VAS in dyslexic readers (Zoubinetzky et al., 2019) and that the practice of action video games improved VAS in typical readers (Antzaka et al., 2017).

Second, we examined the effects of EVASION training on reading fluency. Children in the experimental group showed higher word and pseudoword reading fluency improvement than children from the GG group. However, their reading fluency did not improve more than in the BAU group. This result was doubly unexpected. First, higher VAS enhancement in the EVASION group than in the two other groups was expected to translate into higher reading fluency, as compared to both the GG and the BAU control groups. Second, the systematic introduction of

TABLE 3
Summary of Stepwise Multiple Regression Analyses after Controlling for the Class Effect

Model 1 dependent variables	Reading fluency delta (T2-T1)			Spelling skills at T2		
	N = 384; Marginal R ² = 0.196; Conditional R ² = 0.384; ICC = 0.19			N = 370; Marginal R ² = 0.427; Conditional R ² = 0.586; ICC = 0.28		
Equation results	β	<i>t</i>	ΔR^2	β	<i>t</i>	ΔR^2
Predictors						
(Constant)	0.035	0.423	-	0.026	0.321	-
Oral language at T1	-0.083	-1.255	0.006	0.003	0.059	0.001
Letter knowledge at T1	0.085	1.374	0.006	0.172	3.545	0.038***
RAN at T1	0.019	0.372	0.001	0.024	0.594	0.001
PA at T1	0.270	4.127	0.058***	0.398	7.511	0.172***
VAS at T1	0.244	4.486	0.063***	0.264	5.721	0.092***
Model 2 dependent variables	Reading fluency delta (T2-T1)			Spelling skills at T2		
	N = 390; Marginal R ² = 0.204; Conditional R ² = 0.284; ICC = 0.10			N = 377; Marginal R ² = 0.432; Conditional R ² = 0.551; ICC = 0.21		
Predictors model 2	β	<i>t</i>	ΔR^2	β	<i>t</i>	ΔR^2
(Constant)	0.019	0.285	-	0.046	0.494	-
Oral language at T1	-0.043	-0.687	0.002	0.008	0.149	<0.0001
Letter knowledge at T1	0.142	2.411	0.019*	0.193	4.031	0.051***
RAN at T1	0.064	1.246	0.005	0.069	1.613	0.009
PA at T1	0.312	5.048	0.083***	0.488	9.127	0.237***
VAS delta T2-T1	0.163	3.414	0.040***	0.148	3.305	0.037**

Note: Model 1 includes all T1 variables as predictors of reading fluency improvement between T1 and T2, and spelling performance at T2. Model 2 considers all T1 variables, except VAS, as early predictors but includes T2-T1 VAS improvement as an additional predictive variable. * $p < .05$, ** $p < .01$, *** $p < .001$.

grapheme-phoneme mappings and explicit training of word reading in GG were expected to improve reading skills, so that the EVASION group's reading performance was expected to differ more from that of the BAU than of the GG group. A questionnaire given to the teachers at the end of the project helps understanding why reading fluency improved similarly in the EVASION and BAU groups and more in these two groups than in the GG group. Against our recommendations, most teachers actually scheduled EVASION and GG training during reading slots. This suggests that students of the EVASION and GG groups probably benefited from fewer hours of reading instruction by their teachers than students of the BAU group.

A more coherent picture emerged when focusing on the effect of EVASION playtime duration on reading fluency, but only for words. As expected, the correlation between playtime duration and word reading fluency improvement was significant, showing that the gain in word reading fluency increased with playtime duration in the whole population of EVASION players. Interestingly, the group of children who used EVASION for a longer

playtime duration showed higher gains in word reading fluency as compared not only to the GG group but further to the BAU group. The effect of the intervention was less robust for pseudoword reading fluency. Despite higher pseudoword reading fluency improvement in the EVASION group than in the GG group, there was no significant effect of playtime duration on pseudoword reading fluency.

Overall, the current findings suggest that EVASION training was efficient to improve word reading fluency, but without evidence for transfer to pseudoword or text reading fluency. This is consistent with previous findings that VAS relates to word processing (de Jong & van den Boer, 2021; Valdois et al., 2019; Valdois, Phénix, et al., 2021; van den Boer et al., 2013). However, the improvements that were reported in developmental dyslexia following VAS training were not specific to word reading fluency (Valdois, Peyrin, et al., 2014; Zhao et al., 2019; Zoubinetzky et al., 2019). In the same way, VAS was found to be a concurrent and longitudinal predictor of reading fluency in general, not just for words (Bosse et al., 2007; Bosse & Valdois, 2009; Chan & Yeung, 2020; Huang et al., 2019; Lobier

et al., 2013; Valdois et al., 2019; Valdois, Reilhac, et al., 2021). A positive effect of VAS training on pseudoword reading fluency was indeed expected, assuming that higher VAS would allow parallel, thus faster, processing of larger chunks within pseudowords (Lallier & Carreiras, 2018; Valdois et al., 2004; Van den Boer & de Jong, 2015). The current findings do not support this prediction. Note, however, that it is premature to conclude that EVASION training has no effect on pseudoword processing. First, positive EVASION training effects on pseudoword fluency were found compared to the GG group. Second, an absence of robust intervention effect on pseudoword reading fluency in the EVASION group could well follow from lack of assessment sensitivity. Contrary to the word list in which words of different length were mixed, the pseudowords were ordered by length. The participants only read the first items within the 1-min time constraint, so that processing was limited to short monosyllabic pseudowords (from 2- to 4-letter long). We speculate that the processing of these very short items was not demanding enough on visual attention to be sensitive to VAS improvements following the intervention.

Current findings further highlight benefits of VAS training on spelling skills. At posttest, the spelling performance of the children who trained with EVASION outperformed that of the two other groups, for both words and pseudowords. No significant correlation with playtime duration was found in the whole group of EVASION players, but the effect was specific to the subgroup of children who spent longer time playing with EVASION. This suggests that significant effects on spelling only occurred after sufficient exposure to the intervention. This finding is first evidence that VAS training improves spelling, in addition to reading, thus suggesting a more general effect of the intervention on literacy acquisition. There is already some evidence that VAS contributes to both lexical orthographic knowledge and orthographic learning in typical readers (Ginestet et al., 2020; Marinelli et al., 2020; Niolaki et al., 2020; van den Boer et al., 2015), but very few studies have explored whether reading and spelling skills were both predicted by VAS in the same participants (van den Boer et al., 2015). The stepwise regression analyses carried out on the whole participants in this study support a significant and unique contribution of VAS to literacy skills.

Finally, evidence for positive effects on reading and spelling skills in the absence of PA improvement shows how specific was the impact of EVASION training. The absence of transfer to PA was expected considering that VAS and PA tap different cognitive skills (Valdois, 2022), correspond to different brain networks (Peyrin et al., 2012; Liu et al., 2022), and independently contribute to literacy acquisition (Bosse & Valdois, 2009; Marinelli et al., 2020; Niolaki et al., 2020; Valdois, Phenix, et al., 2021). Our findings also agree with evidence from action video games. Although positive effects of action video games on word and pseudoword reading fluency is well established

(Antzaka et al., 2017; Bertoni et al., 2021; Franceschini et al., 2017; Franceschini & Bertoni, 2019; Mancarella et al., 2022; Pasqualotto et al., 2022; Peters et al., 2019, 2021), transfer to PA was occasionally (Franceschini et al., 2017) but not systematically (Luniewska et al., 2018; Mancarella et al., 2022) reported.

To sum up, the current findings show that EVASION training significantly improved VAS and translated into better reading fluency and spelling skills. VAS enhancement further contributed uniquely and significantly to reading fluency improvement and spelling skills in the whole sample of participants. These overall findings have strong theoretical and educational implications.

At the theoretical level, evidence that pupils with longer playtime showed higher gains in both VAS and literacy skills supports a causal relationship. Causality is also supported by evidence that changes in VAS uniquely accounted for reading fluency enhancement and higher T2 spelling skills in the whole population. Despite the difficulty to firmly conclude in support of causality (Goswami, 2015a, 2015b), other longitudinal and training studies also suggest that differences in VAS yield differences in literacy skills. Research with pre-readers showed that weaker VAS prior to literacy instruction predicted lower reading skills 1 year later at the end of Grade 1 (Valdois et al., 2019). Longitudinal studies carried out in primary school showed that early VAS predicted later literacy skills, both reading fluency and spelling, beyond PA and other reading related skills (Valdois et al., submitted). Finally, training studies carried out to remediate developmental dyslexia report reading improvements following VAS-targeted interventions (Valdois, Peyrin, et al., 2014; Zhao et al., 2019; Zoubrinetzky et al., 2019).

Recent computational models can help better understanding how and why visual attention, in modulating multiletter parallel processing (i.e., VAS), yields better reading fluency and spelling acquisition through more efficient orthographic learning (Ginestet et al., 2022; Steinhilber et al., 2023). These models simulate faster and more accurate word processing when visual attentional quantity and dispersion is larger, thus allowing the identification of a higher number of letters in parallel within words (Ginestet et al., 2019; Valdois, Phénix, et al., 2021). They further show that the efficiency with which letters are identified within novel words (depending on visual attention) contributes to orthographic learning (Ginestet et al., 2022) and reading fluency improvement (Steinhilber et al., 2023). Assuming that more efficient orthographic learning results in good lexical orthographic knowledge for both reading and spelling, these models predict an effect of visual attention and VAS on literacy acquisition in general.

At the educational level, the current findings suggest that EVASION training and more generally, intervention programs that explicitly focus on VAS, can contribute to the prevention of reading fluency and spelling difficulties.

Furthermore, the intervention benefitted more to those students who started with lower VAS, suggesting it might reduce interindividual cognitive heterogeneity within classrooms.

However, despite a very coherent picture showing significant improvements in both VAS and literacy skills, the reported effect sizes were always very small. This might be interpreted negatively, suggesting only marginal impact on literacy. However, even minimal impact was beyond our expectations considering effective playtime duration with the game. It is well documented that training duration is a significant moderator of intervention efficiency (Ehri et al., 2001; McTigue et al., 2020). At the start of this study, teachers were requested to provide a 10-h training, assuming that this playtime duration was required to expect any transfer to literacy. The effective playtime was of only 6 h on average, thus decreasing the likelihood of any intervention effect. The analysis of playtime duration effects revealed that the impact of intervention on literacy was higher in the subgroup of children who spent more time playing. We thus speculate that longer playtime duration than here observed would yield greater learning and, thus, larger effects on performance measures. Also, individual children are likely to differ in how much intervention time they need to train and improve their VAS skills enough. Further studies are needed to determine how long the intervention should be to get stronger effects on literacy. Further studies are required to provide teachers with clear feedback on the students' progress that can help them deciding who should continue the intervention and who should move on to additional reading activities.

This training study was specifically designed to focus on visual attention. Our purpose was to demonstrate the involvement of visual attention and VAS in learning to read and spell, and promote the EVASION software as a way to favor literacy acquisition and prevent reading difficulties. VAS intervention appears as an important target for instruction in initial grades to complement the range of tools that teachers can use to promote learning to read (Schiff & Malatesha Joshi, 2016). While phoneme awareness instruction and intervention mainly affect phonological decoding and reading accuracy (Ehri et al., 2001), VAS is critical to improve reading fluency. Thus, the combination of trainings in phoneme awareness and VAS should be encouraged (Zoubinetzky et al., 2019). Previous studies have emphasized repeated exposure to words (or texts) as a way to improve reading fluency (van Uittert et al., 2022; Zorman et al., 2008). However, recent data suggest that children with higher VAS benefit more from repeated exposure to words (Ginestet et al., 2022; Marinelli et al., 2020; Steinhilber et al., 2023). We thus anticipate that VAS training prior to repeated (word or text) reading should be particularly helpful to improve orthographic knowledge and literacy acquisition.

Acknowledgments

We warmly thank the teachers for their participation and the administrative authorities of the “Rectorat de Mayotte” for their active support of this study. We are particularly indebted to Sandrine Ingremeau (DRANE at the Mayotte Academy) for her logistical support and strong involvement in the project. We further thank the parents for allowing their children to participate and the children for their enthusiasm.

Funding Information

This work has been supported by the French Government through the e-FRAN program (“e-FRAN Fluence” project, 2017–2022); PI: SV), funded by the “Programme d'Investissement d'Avenir” (PIA2) handled by the “Caisse des Dépôts et Consignations.” It also benefited from a grant from the French government (France 2030) to the TRANS3 project (2023–2025; PI: MLB) operated by the Agence Nationale de la Recherche (ANR), with the reference ANR-22-FRAN-0008.

Conflict of Interest Statement

No conflict of interest.

Data Availability Statement

The raw data and statistical analyses are available at: https://osf.io/6xm73/?view_only=326d542cebe14496a59d205b651dc28f.

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Submitted June 14, 2023

Final revision received November 21, 2023

Accepted March 9, 2024

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Supporting Information

Additional supporting information may be found in the online version of this article on the publisher's website: [10.1002/rrq.576/supinfo](https://doi.org/10.1002/rrq.576/supinfo)

Data S1.

Data S2.

Data S3.

APPENDIX A

Descriptive Statistics and Omega Values for All T1 and T2 Measures

Time	Measure	Mean	SD	Median	Min	Max	Omega
Time 1 (pretest, yr1)	Oral language						
	Vocabulary (max = 20)	14.67	4.27	16.00	0.00	20.00	0.90
	Syntactic comprehension (max = 10)	4.33	2.12	4.00	0.00	9.00	0.70
	Composite score (max = 1)	0.67	0.16	0.69	0.05	0.97	-
	Letter knowledge						
	Letter name (max = 20)	17.63	4.64	20.00	0.00	20.00	0.97
	Letter sound (max = 12)	10.00	3.53	12.00	0.00	12.00	0.97
	Composite score (max = 1)	0.86	0.25	0.98	0.00	1.00	-
	Phonological awareness						
	Rhyme judgment (max = 5)	2.28	1.55	2.00	0.00	5.00	0.69
	Phoneme position (max = 10)	6.77	2.66	7.00	0.00	10.00	0.83
	Phoneme blending (max = 8)	4.63	2.51	5.00	0.00	8.00	0.93
	Phoneme deletion (max = 4)	1.23	1.32	1.00	0.00	4.00	0.81
	Composite score (max = 1)	0.50	0.22	0.50	0.00	1.00	-
	Reading						
	Word reading fluency (wpm)	4.15	5.21	2.00	0.00	32.73	0.97
	Pseudoword reading fluency (pwwpm)	3.10	4.16	1.50	0.00	28.00	0.95
	Composite score (score per min)	3.65	4.51	2.17	0.00	36.19	-
	STM and nonword repetition						
	Short-term memory (max = 8)	4.17	0.88	4.00	1.00	5.00	-
	Pseudoword repetition (max = 12)	9.98	2.79	11.00	0.00	12.00	0.90
	Composite score (max = 1)	0.68	0.15	0.73	0.06	0.81	-
	Visual attention span (digits)						
	VAS whole report (max = 80)	46.94	14.80	49.00	0.00	77.00	-
	VAS partial report (max = 40)	24.14	8.96	26.00	0.00	36.00	-
	Composite score (max = 120)	71.08	20.16	71.08	0.00	115.00	-
	Identification threshold (in ms)	70.21	10.33	67.00	0.00	150.00	-
	RAN digits (score per min)	38.89	21.99	35.00	0.00	210.00	-
	English oral comprehension (max = 20)	5.97	5.10	5.00	0.00	19.00	-

APPENDIX A (Continued)

Time	Measure	Mean	SD	Median	Min	Max	Omega
Time 2 (posttest, yr1)	Phonological awareness						
	Phoneme segmentation (max = 10)	7.82	3.39	9.00	0.00	10.00	0.99
	Phoneme deletion (max = 8)	4.81	3.29	6.00	0.00	8.00	0.96
	Composite score (max = 1)	0.50	0.22	0.50	0.00	1.00	-
	Reading fluency						
	Short word reading (wpm)	19.46	17.08	15.80	0.00	100.00	-
	Long word reading (wpm)	13.51	13.85	10.00	0.00	70.59	-
	Word reading score (wpm)	16.62	15.00	13.65	0.00	81.58	-
	Pseudoword reading (pwpm)	18.09	11.58	16.23	0.00	60.00	-
	Text reading (wpm)	23.70	21.83	17.57	0.00	107.00	-
	Spelling						
	Orthographic choice (max = 15)	7.71	3.64	7.00	0.00	15.00	0.84
	Word spelling (max = 10)	3.58	2.76	3.00	0.00	10.00	0.86
	Pseudoword spelling (max = 12)	5.50	3.58	6.00	0.00	12.00	0.89
	Spelling score (max = 22)	9.04	6.00	9.00	0.00	22.00	-
	Comprehension						
	Word comprehension (max = 10)	6.23	2.65	7.00	0.00	10.00	0.83
	Sentence comprehension (max = 11)	6.43	2.62	7.00	0.00	11.00	0.81
	Text comprehension (max = 5)	2.30	1.61	2.00	0.00	5.00	0.73
	Visual attention span (letters)						
VAS whole report (max = 100)	49.53	17.60	51.00	0.00	91.00	-	
VAS partial report (max = 80)	28.67	11.73	31.00	0.00	50.00	-	
Composite score (max = 180)	87.24	25.34	81.00	0.00	140.00	-	
Identification threshold (in ms)	73.92	30.93	67.00	50.05	150.00	-	
English oral comprehension (max = 20)	7.68	4.61	8.00	0.00	19.00	-	