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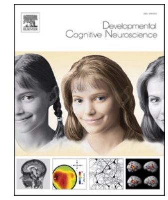

Error-monitoring: A predictor of future reading skills? A 3-year longitudinal study in children

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ABSTRACT

Investigation of the factors explaining individual differences in the acquisition of expert reading skills has become of particular interest these last decades. Non-verbal abilities, such as visual attention and executive functions play an important role in reading acquisition. Among those non-verbal factors, error-monitoring, which allows one to detect one's own errors and to avoid repeating them in the future, has been reported to be impaired in dyslexic readers. The present three-year longitudinal study aims at determining whether error-monitoring efficiency evaluated before and during reading instruction could improve the explanation of reading skills. To do so, 85 children will be followed from the last year of kindergarten to the second grade. The classic predictors of reading will be assessed at each grade level. Error-monitoring indices in domain-general and reading-related contexts will be derived from EMG data recorded during a Simon task in kindergarten and during both a Simon and a lexical decision tasks in the first and second grades. Findings concerning the role of error-monitoring on reading skills are expected to have an important impact on reading instruction to prevent reading difficulties in at-risk children and improve remediation to help children with reading difficulties.

1. Introduction

Learning to read is considered as a fundamental human right by the United Nations Educational, Scientific, and Cultural Organization (UNESCO; Bhola, 1995) and as one of the most important achievements during primary education. Years of academic training are necessary to reach expert reading skills but are not sufficient for all children. Indeed, despite adequate schooling, 5 to 17% of the children present developmental dyslexia (Gabrieli, 2009), with reading impairments that persist until adulthood and negative consequences for academic achievement and socio-professional integration. Investigation of the factors likely to explain individual differences in the acquisition of expert reading skills has thus become of particular interest these last decades. Phonological abilities such as phonological awareness, verbal short-term memory, and rapid automatized naming (RAN) measured before reading acquisition have been repetitively reported to be strong predictors of future reading skills in children (Ehri et al., 2001; Kirby et al., 2003, 2010; Melby-Lervåg et al., 2012; Scarborough, 1998). Moreover, the specialisation of brain areas involved in the rapid processing of written words would depend on the adequate acquisition of letter-to-sound mapping (Brem et al., 2010; McCandliss and Noble, 2003). Indeed, the practice of letter-by-letter decoding allows children to constitute an orthographic lexicon and then automatize reading. Deficits have been reported in print-to-sound mapping in developmental dyslexia (Blau et al., 2009, 2010; Froyen et al., 2011). Impairments in the expert processing of print in dyslexia have also been reported to be related to their phonological deficits (Mahé et al., 2013). Besides phonological abilities, it should be noted that non-verbal abilities would also play an important role in the acquisition of expert reading skills and are described in the next subsection.

1.1. Reading acquisition and non-verbal abilities

Previous findings have revealed that visuo-attentional abilities (i.e., rapid attention orienting and serial search) measured in pre-reading children are strong predictors of future reading skills in the first and second grades (Franceschini et al., 2012). Indeed, it has been postulated that during reading, before letter-to-sound mapping, an adequate

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selection of the relevant letter clusters to be processed is necessary. This relevant graphemic parsing would depend on the rapid orienting of visual attention into relevant letter clusters and on the inhibition of irrelevant and neighbouring letters (Vidyasagar and Pammer, 2010). In support, brain imaging studies have suggested that written strings processing would depend on an interplay between a ventral stream (i.e., left fusiform gyrus) involved in the rapid recognition of visual word forms and a dorsal stream (i.e., posterior parietal cortex) involved in the rapid orienting of attention on the relevant letter clusters to be processed (Cohen et al., 2008; Cohen and Dehaene, 2009). Of importance, impairments in rapid attention orienting (Dhar et al., 2008; Facoetti et al., 2010; Mahé et al., 2014) have been reported in dyslexic readers and could in part explain their reading deficits. Finally, even if most cognitive models of visual word recognition and reading aloud have so far not included visuo-spatial attention, an exception concerns visual attention span (Ans et al., 1998).

Other non-verbal abilities which have been related to reading acquisition are executive functions (Farah et al., 2021). Executive functions support cognitive control mechanisms allowing individuals to self-regulate their own thoughts and actions. Miyake and Friedman (2012) have proposed a model composed of three key executive functions: a) inhibition, corresponding to the ability to suppress irrelevant stimuli or responses leading to the focus on relevant information; b) updating, corresponding to the constant updating of information in working memory; and c) switching, corresponding to the ability to adapt rapidly to task demand changes. Previous studies have reported deficits in inhibition and updating (Doyle et al., 2018) or switching (Poljac et al., 2010) in dyslexic readers. Furthermore, both inhibition and updating measured in kindergarten have been related to reading skills in the first and second grades (Michel et al., 2019). Concerning the relationship between working memory and reading, Peng and colleagues (2018) reported only a moderate relationship in a meta-analysis, suggesting the role of both domain-general and domain-specific working memory (i.e., verbal working memory). They revealed stronger relationships between reading and domain-general central executive of working memory in the early stages of reading acquisition while stronger links have been found between reading and verbal working memory in more skilled readers. Apart from this rich work concerning the links between working memory and reading (see Peng et al., 2018 for a meta-analysis), only a few hypotheses have been proposed to try to explain the relationship between executive functions and reading skills (e.g., Doyle et al., 2018). It should be noted that links have been recently made in the context of the simple view of reading model (Hoover and Gough, 1990), which divides reading into two components: decoding and language comprehension. It has been postulated that efficient decoding depends on the adequate integration between phonological, visual attention, and executive function abilities (Taran et al., 2022). Becoming an expert reader would thus depend on the interaction of various factors. Among those factors, the specific role of executive functions remains to be explored. A specific executive function, error-monitoring, could play an important role in expert reading acquisition, as described in the next section.

1.2. Expert reading skills and error-monitoring

Error-monitoring, also called performance-monitoring, is crucial in a variety of situations to remain adapted to the environment. Indeed, error-monitoring enables individuals to detect their errors online, triggering corrective mechanisms and behavioural adjustments so that similar errors are not repeated in the future (Botvinick et al., 2001). In this context, error-monitoring would play an important role in learning (Astolfi, 1997). Considering error-monitoring as a potentially important factor in reading acquisition is new. Due to the novelty of this research field, the nature of the links between error-monitoring and reading acquisition can only be speculative. During reading, one can imagine a child making a mistake (e.g., pronouncing the "p" in the French word "sept" which means "seven" in English) and being corrected by an adult. This external feedback from the parents or educators creates representations of what is an erroneous and the correct reading of the word. The next time this child will encounter the word, he/she will read it either correctly or incorrectly. If he/she reads it incorrectly and his/her monitoring system is effective, then the monitoring system (acting as an internal feedback) will detect the mismatch between his/her erroneous answer and the representation of the correct reading of the word. The efficiency of error-monitoring would allow this child to try to correct his/her reading himself. On the contrary, if the monitoring system is not efficient enough, no (or weak) corrective mechanisms will be recruited and the child will persevere in the error.

The hypothesised role of error-monitoring during reading can be extended to cognitive models of reading, such as the dual route model (Coltheart et al., 2001). In this model, children first read words via a phonological route involving grapheme-to-phoneme correspondences. After multiple exposures to the word, they are able to recognise it automatically via the lexical route, which directly associates the global orthographic form of the word to its phonological form and semantics. We can hypothesise that an efficient monitoring system would act on both reading routes by: 1) reducing overt errors during grapheme-to-phoneme conversions due to better corrective mechanisms; and 2) enhancing the acquisition of orthographic forms of written words (this second point being suggested by Horowitz-Kraus and Breznitz, 2013). In the context of connectionist triangle models (e.g., Seidenberg and McClelland, 1989), reading is the result of a pattern of activation of orthographic, phonological, and semantic codes. During reading learning, when a word is encountered for the first time, a first pattern of activation leads to the production of a first reading of the written word. This produced reading of the word is then compared to the target reading (the correct one), leading to an error score. The target reading can be provided by external feedback (e.g., a teacher) or internal feedback if the child has already been exposed to the word. Reading acquisition would depend on statistical learning based on repeated exposures to words on which feedback (external or internal) seems crucial. After learning, the error score, which represents the difference between the correct reading of a word and the actual one, is lower for the correct reading compared to any other pronunciation. Error score is the result of the monitoring of reading and thus, error-monitoring efficiency could play an active part during reading acquisition. Interestingly, some studies already reported relationships between error-monitoring efficiency and some other general abilities, such as working memory (Miller et al., 2012), or with global academic performances (Hirsh and Inzlicht, 2010). Therefore, it seems important to assess differences in error-monitoring efficiency in children to determine whether they can explain some variability in reading skills.

1.3. Error-monitoring assessment

Error-monitoring is assessed through different indices, mainly collected during the completion of a compatibility stimulus-response manipulation task that promotes error commission, such as the Simon task. In the standard version of the Simon task, a red or green circle is displayed either to the right or left of the centre of a screen (Craft and Simon, 1970). Participants are asked to discriminate the colour of the circle and respond as fast and accurately as possible as a function of the learned stimulus-response mapping (e.g., red circle → press right; green circle → press left; instructions counterbalanced across participants). Importantly, although irrelevant to the task, the position of the stimulus can hence be presented on the same or opposite side as the requested response, leading to compatible and incompatible trials, respectively. Reaction times (RTs) and error rates reported in these tasks are typically degraded in incompatible trials compared to compatible ones.

In addition to behavioural data, electromyographic (EMG) measures, obtained by recording the electrical activity of the muscles involved in the required responses (e.g., the *flexor pollicis brevis* for a thumb response), are very useful to assess error-monitoring efficiency. In particular, in about 15 to 20% of the correct trials, EMG measurements enable to uncover the presence of a small incorrect activation preceding the correct response. These incorrect activities, called "partial-errors", indicate an efficient detection and correction of an erroneous response before the correct response execution (Hasbroucq et al., 1999). Indeed, they supposed that the engaged error was detected, stopped, and corrected in time to provide the correct response. Analyses of the occurrence of these partial-errors relative to the total number of errors and the speed at which they are corrected are well suited to assess the efficiency of the error-monitoring system (Roger et al., 2014). Also, EMG studies showed that the motor time (MT), which is the time between the onset of muscle activity and the mechanical response, is longer for errors compared to correct responses. Furthermore, the amplitude of the electrical muscular activity leading to the response is lower for errors than for correct responses (Allain et al., 2004). Both of these results suggest that even in overt error trials, the error is detected and the system tries to catch it. Finally, EMG recordings enable a precise analysis of participants' performance, mostly to assess how efficient the error-monitoring system is.

In addition to EMG data, electroencephalographic (EEG) recordings can also be used to evaluate error-monitoring. Indeed, an event-related potential (ERP) component, originally observed rapidly after errors, named "Error(-Related) Negativity" (ERN or Ne), has been discovered in frontocentral sites around the time of response onset, reaching its maximum around 50 to 150 ms later (Falkenstein et al., 1991; Gehring et al., 1993). The ERN/Ne component has firstly been interpreted as reflecting the mismatch between the representations of the actual and the required responses (Falkenstein et al., 2000). Nearly ten years after the discovery of the ERN/Ne, an ERN/Ne-like activation after a correct response has been discovered (Vidal et al., 2000). This component, named "Correct(-Related) Negativity" (CRN or Nc), shows a lower amplitude than the ERN/Ne observed in error trials. The ERN/Ne and the CRN/Nc share the same spatio-temporal dynamics and the same source, which leads to the conclusion of the existence of a general performance monitoring system that enables to self-evaluate the performance of ongoing actions (Roger et al., 2010).

1.4. Error-monitoring and dyslexia

To our knowledge, the only studies investigating the relationships between error-monitoring and reading skills have been performed in dyslexia using the recording of EEG. Horowitz-Kraus and Breznitz (2008) were the first to investigate the error-monitoring mechanism in dyslexic adults during the processing of written words and pseudowords in a lexical decision task. During this task, participants were presented with written words and pseudowords and had to indicate as fast and as accurately as possible whether the stimulus displayed was a real word (e.g., "candle") or not (i.e., a pseudoword, e.g. "gantle"). Compared with expert readers, dyslexic readers have: a) smaller ERN/Ne and CRN/Nc amplitudes; and b) reduced amplitude difference between the ERN/Ne and CRN/Nc. The authors concluded that error-monitoring could be altered in dyslexia because of a limited experience with correct word patterns stored in the mental lexicon. This limitation would impair the distinction between patterns of correct and erroneous processing. Lower activation of the performance monitoring mechanism during print processing in dyslexia could prevent them from both being aware of their reading errors and learning from them. Other experiments have revealed variations of the error-monitoring deficit in dyslexia according to both age (Horowitz-Kraus, 2011) and compensation (i.e., reduced error-monitoring impairment in compensated compared to non-compensated dyslexic adolescents, Horowitz-Kraus and Breznitz, 2013). This last finding suggests a continuum of error-monitoring deficits according to the magnitude of reading impairments. The authors proposed that the amplitude difference between ERN/Ne and CRN/Nc might serve as a marker for the lack of compensation of reading deficits in dyslexia. Intending to improve error-monitoring efficiency and thus reading skills, Horowitz-Kraus and Breznitz (2009, 2014) have proposed training programs targeting working memory or reading fluency. Following these trainings, behavioural and EEG data showed improvement in both reading and error-monitoring in dyslexic readers. Finally, it should be noted that reduced ERN/Ne amplitudes have also been reported in dyslexic compared to good reading children using a Go/No-Go task with non-verbal material (Van De Voorde et al., 2010). This suggests that the observed deficits in error-monitoring in dyslexic readers are not only due to the difficulty in processing written strings, but may also be due to an inefficient error-monitoring system that would be an independent factor contributing to the acquisition of expert reading skills. If so, the error-monitoring efficiency evaluated in kindergarten could potentially predict future reading skills, as other reading predictors, in children with varying reading skills (with or without dyslexia). It is thus crucial to determine whether error-monitoring abilities explain variability in reading acquisition.

1.5. Aims and hypotheses

Taken together, results from Horowitz-Kraus and Breztniz (2008) and Van De Voorde and colleagues (2010) suggest that poor error-monitoring efficiency could explain a significant part of the reading deficits in developmental dyslexia. Indeed, not being able to detect one's reading errors could seriously impair the acquisition of expert reading skills. A solid understanding of the role played by error-monitoring in reading acquisition difficulties is necessary to be able to develop more effective remediation training to help at-risk children during their school learning as well as dyslexic readers. To date, experiments investigating error-monitoring in relation to reading abilities have been performed only in dyslexic populations (e.g., Horowitz-Kraus and Breznitz, 2008). To our knowledge, relationships between error-monitoring efficiency and reading skills have never been investigated in non-dyslexic poor readers or in the typical population. The current study aims to better characterise the relationships between error-monitoring and the acquisition of expert reading skills in the typical population. To do so, a longitudinal study is planned from the last year of kindergarten, before reading instruction at school, to the first and second grades, after the beginning of reading instruction.

In a first step, we will test the hypothesis that error-monitoring efficiency evaluated before reading instruction improves the prediction of future reading skills compared to known reading predictors alone (Hypothesis 1; H1). Classic reading predictors, as well as domain-general error-monitoring efficiency measured during a Simon task, will be evaluated in kindergarten. Reading abilities will be assessed in the same population in the first and second grades. As experiments will be run in a school context with young children (from 5 years old), the present study will not include EEG measurements to assess error-monitoring for practical reasons. Instead, a methodological approach using EMG indices of error-monitoring efficiency is proposed. It should be noted that EMG measures have been successfully used in young children (i.e., from 6 years old) to assess error-monitoring efficiency (Śmigasiewicz et al., 2020, 2021, 2022).

In a second exploratory step aimed at improving our understanding of the links between error-monitoring and reading, we will explore these relationships in two distinct contexts at two different moments from the beginning of reading acquisition (Grade 1 and Grade 2). Error-monitoring will be assessed in both a domain-general and a reading-related tasks, namely the Simon and the lexical decision tasks, in both grades to investigate whether the relationship between error-monitoring and reading skills differs as a function of the type of stimuli (i.e., verbal vs. non-verbal stimuli, Hypothesis 2; H2). Nevertheless, we are unable to make any strong predictions about the direction of this effect, or whether a difference even exists. Indeed, to our knowledge, no previous experiment has undertaken a simultaneous comparison of error-monitoring in these two contexts and especially not in a typical population with varying reading levels. These findings will help in identifying the materials for which error-monitoring remediation would be beneficial.

2. Method

2.1. Population

2.1.1. Sample size

The longitudinal study will follow the same children from the last year of kindergarten to second grade. Each child will participate in three experimental sessions: the first in autumn/winter during the last year of kindergarten (5–6 years), the second in winter/spring during first grade (6–7 years), and the third in winter/spring during second grade (7–8 years). Power analyses were computed in G*Power 3 (Faul et al., 2007). To reach an effect power of.80 in the statistical analyses described below, $\alpha = 0.05$, and an expected medium effect size, the required sample size is 85 participants. It should be noted, however, that longitudinal studies following children over several years are at significant risk of attrition. Based on the previous literature, we estimate an attrition rate of 25%. Table 1 describes the attrition rates of previous studies with protocols similar to the current study. With an attrition rate of 25% (taken from the maximal attrition rates compared to the duration of the studies described in the table below), we will need to recruit 107 participants in kindergarten, with an expected loss of 22 participants, to have 85 children in Grade 2.

2.1.2. Inclusion and exclusion criteria

Only children with a French native language will be included in the study. In the case of bilingualism, French will need to be at least spoken with one of the parents at home. Exclusion criteria will be: neurodevelopmental disorders (e.g., primarily intellectual disability, autism spectrum disorders, developmental language disorders, motor disorders such as developmental coordination disorder, attention deficit hyperactivity disorder), not normal or not corrected-to-normal vision or audition, a psychiatric or neurological disorder (e.g. epilepsy). Both inclusion and exclusion criteria will be checked through a questionnaire addressed to the parents who agreed to have their child participate in the study (see Annex 3). For ethical reasons, it will be proposed to children who will not respect those criteria to take part in the reading-related and reading tests of the study and see the EMG material. In the case of a child repeating a class or skipping a year during the longitudinal study, his/her data will not be retained in the analyses. Each child will receive a small gift after his/her participation in each phase of the study. In addition, to thank the school directors and teachers for opening the doors of their schools, educational kits and books will be provided to classes and teachers and science popularisation workshops will be organised in the participating schools.

2.2. Ethics and general procedures

The study protocol has been approved by the ethics committee of the University of Lille (reference 2021–553-S100). A declaration to the French Data Protection Property has also been made (reference 2021–288).

The study will be conducted in the schools of Lille Metropole. Experiments will be run in both public and under-contract private schools. For public schools, authorization will be first asked from the school inspectors who will then indicate to the main investigator of the study the schools with which experiments can be conducted. Contact will then be established with directors and teachers. For under-contract private schools, authorization will be asked directly from the head of the school and then the teachers.

At the beginning of the kindergarten study, the documents addressed to the parents (i.e., a letter of information, a consent form, and a general questionnaire; see Annexes 1 to 3) will be given by the teachers to the children. Only the children who will give back the signed consent form with the consent of at least one parent will participate in the study. The consent form will cover the three years longitudinal study. In the first and second grades, an additional letter of information will be provided to the parents to remind them of the study and their right to refuse their children to pursue participation (see Annex 4). The organisation of the experiments will be discussed with the teachers. At the beginning of the experiment, a letter of information will be read to the children (see Annex 5) and the experiment will only take place if the children agree to participate.

2.3. Reading-related and reading capacities assessment

2.3.1. Kindergarten

The general questionnaire addressed to the parents (see Annex 3) will allow to control inclusion and exclusion criteria in addition to general information (i.e., gender and age) and variables known to predict future reading skills (i.e., languages spoken at home and socioeconomic level). The socioeconomic level will be assessed by parental years of education, known to be representative of the socioeconomic level (e.g., Smith and Graham, 1995).

Children will complete a 30-minute, one-on-one assessment session on reading-related abilities (i.e., phonological awareness, verbal short-term memory, RAN, letter name knowledge) in addition to nonverbal intelligence and laterality. Laterality will be determined by the Edinburgh Handedness Scales (Oldfield, 1971). Nonverbal intelligence will be assessed as a control measure by the matrix of the WNV ("Echelle non-verbale d'intelligence"; Wechsler and Naglieri, 2009) on which children will have to complete matrices with geometric figures. Norms are established from 4 to 20 years and are thus adapted to our population. Children will perform the practice trials A, B, C, and then items 1 to 41 except if they perform four erroneous responses over 5 consecutive trials after which the task will be stopped. An accuracy score on 41 will then be calculated and transformed into a *T* score.

Phonological awareness will be assessed with the child version of the Evalec (Sprenger-Charolles et al., 2005). Children will delete the first syllable of trisyllabic pseudowords. Children will also perform a task of deleting the first phoneme of pseudowords of CVC (consonant-vowel-consonant) and CCV (consonant-consonant-vowel) types. For the three tasks, two practice trials will be performed before 10 to 12 experimental items. The time to perform each task will be measured in

Table 1
Summary of characteristics and attrition rates of previous longitudinal studies run on children.

Study	Duration of the study	Grades or ages of the children	Measures	Attrition rate
Franceschini et al. (2012)	3 years	Prereaders, Grades 1 and 2	3 behavioural measures	15%
De Vos et al. (2017)	4 years	62, 85, 100, and 109 months	2 behavioural and EEG measures	22%
Maurer et al. (2009)	5 years	Kindergarten (6.6 years), Grade 2 8.3 years), Grade 3 (9.5 years), Grade 5 (11.4 years)	1 EEG and 4 behavioural measures	28%
Myers et al. (2014)	3 years	Kindergarten (5-6 years), Grade 3 (8.2 years)	2 fMRI	25%
Piquard-Kipffer and Sprenger-Charolles (2013)	3 years	Prereaders, Grade 2	3 behavioural measures	32%

addition to an accuracy score of 10 or 12. In order to avoid floor effects in kindergarten (Anthony and Francis, 2005; Liberman, 1973), children will also be asked to judge if 20 pairs of words rhyme or not (N-EEL subtest, Chevrie-Muller and Plaza, 2001). An accuracy score out of 20 is used as an additional index of phonological awareness.

Verbal short-term memory will be assessed with the pseudoword repetition task from the NEPSY II Battery (Korkman et al., 2012) with norms established from 5 to 12 years. Children will perform 13 items unless they fail four consecutive items. Pseudowords are two to five syllables long. One point is given for each syllable correctly repeated, with a maximum raw accuracy score of 46.

RAN will be assessed with the child version of the DRA (Plaza et al., 2007), with norms established from the last year of kindergarten to Grade 5. Each child will perform picture and letter naming, each containing 48 stimuli. Time to compute each task and the accuracy score will be measured.

Letter name knowledge will be assessed through a designation task in which children will be asked to designate each of the 26 letters of the alphabet. Each correct answer will be assigned one point.

Finally, vocabulary and oral comprehension will be assessed in the context of the class. A vocabulary test will be proposed using a part of the Peabody test (Dunn et al., 1993). We will assess the level of vocabulary in reception, corresponding to the ability to associate a word pronounced by the experimenter with the correct image among the four represented. An accuracy score will be calculated. An oral comprehension test will be proposed using a part of a standardised French test (E.CO.S.SE.) developed by Lecocq (1996), which corresponds to the French version of the Test for Reception Of Grammar (TROG, Bishop, 1983). In this test, a spoken sentence will be given to the children, who must select the corresponding image among four possibilities, two of which contain lexical or grammatical traps. The test is designed to use a variety of syntactic structures, the complexity of which increases during the test. The accuracy scores out of 35 and 18 for the vocabulary and oral comprehension tests, respectively, will be collected.

2.3.2. First and second grades

In the first and second grades, children will perform a 30-minute individual assessment session evaluating reading-related abilities described in the previous subsection (i.e., phonological awareness, verbal short-term memory, RAN, letter name knowledge) in addition to measures of vocabulary and oral comprehension in the context of the class. Reading skills will also be measured during the individual assessment.

Reading will be assessed through meaningless and meaningful text reading. Meaningless text reading will be assessed with the Alouette reading test (Lefavrais, 1965, 2005) on which children will be asked to read aloud a text with no meaning in a maximum of three minutes. The reading time and the number of words correctly read on 265 will be taken. An efficiency score (CTL) will also be calculated as follows: (number of words correctly read*180)/reading time (see Cavalli et al., 2018). Norms are provided for first and second grades on reading time, the number of words correctly read, and the efficiency score (CTL). Meaningful text reading will be assessed with the “Mouette” test from EVALéo (Maeder et al., 2018) in which children will be asked to read aloud a text with meaning in a maximum of two minutes. The number of correctly read words in two minutes will be measured. Norms are provided for first and second grades.

Isolated word and pseudoword reading will be assessed with one-minute reading tasks from Gentaz, Sprenger-Charolles and Theurel (2015). In these tasks, the child has to read aloud as many words (or pseudowords) as he/she can in a maximum of one minute. The number of correctly read words (or pseudowords) in one minute on 60 is calculated.

Finally, a written comprehension test will also be proposed in Grade 2 in the context of the class, using a part of a standardised French test (E.CO.S.SE.) developed by Lecocq (1996), which corresponds to the French version of the TROG (Bishop, 1983). An accuracy score out of 18 will be collected.

2.4. Experimental tasks

2.4.1. Kindergarten

2.4.1.1. Simon task. Children will perform a domain-general error-monitoring task with a child version of the Simon task (Craft and Simon, 1970; Ambrosi, Śmigasiewicz et al., 2020, 2020, 2021, 2022) during which EMG activities will be recorded. In this task, each stimulus will combine two attributes. The coloured stimulus will be the relevant attribute and its position the irrelevant attribute (i.e., stimuli will be displayed on the left or the right of a central fixation point). Two possible kinds of trials will be displayed: compatible trials (i.e., when the position of the stimulus corresponds to the side of the correct answer), and incompatible trials (i.e., when the position of the stimulus does not correspond to the side of the correct answer). Three sets of stimuli will be used as in Śmigasiewicz et al., (2020, 2021, 2022): 1) images of a yellow banana and an orange carrot; 2) images of a brown nut and a red strawberry; and 3) images of a green frog and a pink pig. For each set, each child will be asked to associate each coloured stimulus with a response side. For example, half of the children will be requested to press as fast and accurately as possible a left button with the left hand when the stimulus is a green frog and a right button press with the right hand when the stimulus is a pink pig. The other half of the children will have the reverse rule. The different kinds of trials will have equal probability and will be displayed in random order.

At the beginning of each trial, a fixation point will be displayed in the centre of the computer screen for 500 ms. Then, a coloured stimulus will be displayed on the left or the right of the fixation point until a response is given. The next trial will begin one second after the child’s response. Before the beginning of the task, a two-minute training will be proposed. It will consist of 20 trials (i.e., five times each of the four possible stimuli). Feedback on response accuracy will be provided only during the training through smiling or not smiling emoticons. If a criterion of 80% of correct answers is reached at the end of the training, the experimental task will begin. If not, the child will perform another training. The experimental task will consist of three blocks of 129 trials each. Short breaks will be proposed after every 25 trials and longer breaks will be proposed at the end of each block. The duration of the experimental task (with training and breaks) is estimated to be about 20 min.

2.4.1.2. Behavioural measures. Mean RTs and error rates will be calculated relative to the type of trial (i.e., compatible, incompatible). For each child, trials with RTs larger than three standard deviations from the child’s mean RT for each trial type and trials excessively short (RTs $<$ 300 ms) will be excluded.

The compatibility effect (i.e., the difference in RTs and error rates between incompatible and compatible trials) and the post-error slowing will be measured (i.e., longer RTs on correct trials following an error, Rabbitt, 1966).

2.4.2. First and second grades

2.4.2.1. Simon task. First and second grade children will perform the child version of the Simon task, as described in the previous section.

2.4.2.2. Lexical decision task. Error-monitoring efficiency in a reading-related task is only measured in first and second grade children as it requires reading abilities. A visual lexical decision task will be proposed in addition to the Simon task, during which EMG activities will be also recorded. A total of 160 words have been selected from the French lexical database Manulex (Lété et al., 2004) and divided into four conditions: short with low frequency, long with low frequency, short with high frequency, long with high frequency. Words are mono- or bisyllabic. Short words comprise four to five letters and long words comprise six to seven letters. They were selected based on the estimated frequencies per million in the first and second grades (i.e., corresponding to the U index in the Manulex database). The selected words do not contain any word with an estimated frequency lower than one per million considering the average values of first and second grade. Words of low frequency are lower than 25 per million (average lexical frequency of 8.3) and words of high frequency are higher than 50 per million (average lexical frequency of 218.5). Conditions of short and long words are matched on lexical frequency, bigram frequency, first syllable frequency and grapheme-to-phoneme consistency ($p > .10$). Conditions of words of low and high frequency are matched on the number of letters and syllables, number of orthographic and phonological neighbours, bigram frequency, first syllable frequency and grapheme-to-phoneme consistency ($p > .10$). Letter, bigram, and syllable frequencies, and grapheme-to-phoneme consistency were calculated based on the French database Manulex-infra (Peereman et al., 2007). A total of 160 pseudowords were created by changing letters for the previously selected words. Words and pseudowords have a similar number of letters and syllables and are matched on bigram and first syllable frequencies ($p > .10$).

At the beginning of each trial, a fixation cross will be displayed in the centre of the computer screen for 400 ms followed by a blank screen for 100 ms. Then, a word or a pseudoword will be displayed until a response is given. The next trial will begin one second after the child answer. Children will be asked to indicate as fast and accurately as possible whether the stimulus displayed corresponds to a word or a pseudoword with two buttons. Before the beginning of the task, a two-minute training will be proposed. It will consist of 10 trials (i.e., 5 words and 5 pseudowords). Feedback concerning response accuracy will be provided during the training only through smiling or not smiling emoticons. If a criterion of 80% of correct answers is reached at the end of the training, the experimental task will begin. If not, the child will perform another training. The experimental task will consist of four blocks of 80 trials each. Short breaks will be proposed after every 40 trials and longer breaks will be proposed at the end of each block. The duration of the experimental task (with training and breaks) is estimated to be about 20 min.

2.4.2.3. Behavioural measures of the lexical decision task. RTs and error rates will be measured relative to the type of trial (i.e., word, pseudoword). For each child, trials with RTs larger than three standard deviations from the child's mean RT for each trial type and trials excessively short (RTs < 300 ms) will be excluded. The lexicality effect will be measured (i.e., the difference in RTs and error rates between words and pseudowords).

2.5. EMG data acquisition and pre-processing

The EMG recordings will concern the computerised tasks, namely during the Simon task performed by children in kindergarten, first and second grades, and during the lexical decision task performed by children in first and second grades. These recordings will be made by placing two flat active Ag/AgCl electrodes above the thumb-*flexor pollicis brevis* of both hands using the BioSemi Active-Two system (Biosemi Inc., Amsterdam, The Netherlands). The sampling rate will be set at 1024 Hz.

The EMG signal will be observed throughout the tasks by the experimenter to check its quality and to correct any excessive muscle tension that may mask the muscular activities related to the responses by asking the child to relax his/her muscles. The EMG data will be filtered with a 10 Hz high-pass filter to remove low-frequency activities that are not associated with a muscular response. Onsets of EMG activities will be manually marked after visual inspection. Experimenters will not be aware of the nature of the trial being inspected. Trials with a low signal-to-noise ratio and thus on which EMG-burst onsets will be undetectable by visual inspection will be excluded from analysis (estimated to represent 2% of all trials, see Śmigasiewicz et al., 2020).

2.6. EMG indices

Based on the manual markers of EMG onsets, trials will be classified (see Fig. 1) as (1) pure-correct trials (i.e., trials with only one muscular burst on the correct side), (2) full-error trials (i.e., trials with only one muscular burst on the incorrect side), and (3) partial-error trials (i.e., trials containing two EMG activations, one on the incorrect side preceding the correct response; see Grisetto et al., 2019). Trials with EMG activations that cannot be classified according to these three trial types (e.g., more than two muscular bursts) will be excluded from the analyses.

Trials classified as partial-errors (see Fig. 1C) will be accounted for to assess the efficiency of online suppression of incorrect responses through two indices. First, the correction ratio will be calculated as the

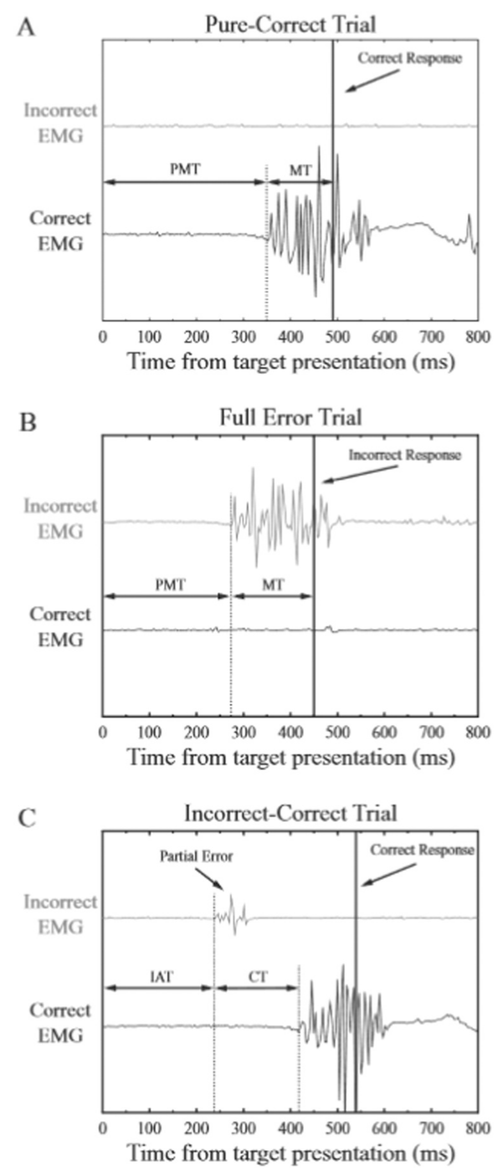

Fig. 1. Type of trials based on EMG measures.
(From Roger et al., 2014)

proportion of partial-errors among all incorrect activations (i.e., the sum of partial-errors and full-error trials, Burle et al., 2002). It will be used to determine how often erroneous responses are successfully detected, suppressed and corrected. A higher correction ratio thus indicates a more efficient error-monitoring mechanism. Second, the correction time (CT) will be measured as the time between the onset of the partial-error to the onset of the correct EMG burst (see Fig. 1C). The CT will provide a measure of the time necessary to detect and correct the initial incorrect response activation (Burle et al., 2002). A smaller CT thus indicates a more efficient error-monitoring mechanism.

The manual markers will also allow us to precisely compare erroneous and correct trials to derive other error-monitoring indices. Firstly, reaction times in full-error and pure-correct trials will be broken down into premotor time (PMT; i.e., the time between stimulus onset and the marked onset of the EMG burst) and motor time (MT; i.e., the time between the marked EMG onset and button press; Roger et al., 2014, see Figs. 1A and 1B). Interestingly for the study of error-monitoring efficiency, the MTs in full-error trials are longer than the MTs in pure-correct trials (Allain et al., 2004; Roger et al., 2014), indicating that the successful detection of the error led to an unsuccessful attempt to prevent its execution. Secondly, the amplitude of the EMG burst will be measured by rectifying the EMG signal on individual trials by taking the absolute value of the signal. The rectified signal will then be averaged time-locked to the burst onset for pure-correct and full-error trials. Then, the surface under the curve will be calculated separately for full-errors and pure-correct trials (Allain et al., 2004). Interestingly for the study of error-monitoring, the amplitude of the EMG burst in full-error trials is smaller than in pure-correct trials (Allain et al., 2004), indicating that the successful detection of the error led to an unsuccessful attempt to prevent its execution.

2.7. Statistical analyses

Table 2 describes the different variables used for the statistical analyses described below. The first section concerns classical findings which we expect to replicate. The following two concern statistics allowing us to test our hypotheses.

2.7.1. Expected classical findings

Global performances (i.e., RTs and error rates) in both the Simon task and the lexical decision task will be analysed to ensure that their classic behavioural effects (i.e., compatibility effect and lexicality effect, respectively) are observed. To investigate performances in the Simon task, two mixed effect linear models will be used to analyse mean RTs in correct trials and error rates as a function of compatibility (i.e., compatible and incompatible trials) as fixed effect and subjects and sets, as random effects. To investigate performances in the lexical decision task, two mixed effect linear models will be used to analyse mean RTs in correct trials and error rates as a function of lexicality (i.e., word and pseudoword trials) as fixed effect and subjects and items, as random effects. Mixed model analyses will be performed with the *lme4* and *lmertest* packages on RStudio (Bates et al., 2015; Kuznetsova et al., 2017).

The expected development of (1) performances in reading-related tests from kindergarten to Grade 2, and (2) reading skills between Grade 1 and Grade 2 will also be checked. To do so, two one-way

Table 2
Summary table of the different variables used in the statistical analyses planned in the longitudinal study and the periods in which these measurements will be carried out.

	Materials	Measures	Variables	Periods
Classic predictors of reading abilities	General questionnaire	Socio-economic status	Parental years of education	K
	N-EEL (Chevrie-Muller and Plaza, 2001)	Phonological awareness	Correct rhyme judgement (/20)	K
	Evalec (Sprenger-Charolles et al., 2005)	Phonological awareness	Score divided by the time	K, G1, G2
	NEPSY II Battery (Korkman et al., 2012)	Verbal short-term memory	Number of correct responses (/48)	K, G1, G2
	DRA (Plaza et al., 2007)	Rapid automatized naming	Score divided by the time	K, G1, G2
	Simple designation task	Letter name knowledge	Number of correct responses (/26)	K, G1, G2
	Peabody test (Dunn et al., 1993)	Vocabulary	Number of correct responses (/35)	K, G1, G2
	E.CO.S.SE. test (Lecocq, 1996)	Oral comprehension	Number of correct responses (/18)	K, G1, G2
Error-monitoring in a domain-general context	Simon task (Simon, 1990)	Chronometric	MT in errors and correct trials	K, G1, G2
			Correction time in partial-error trials	K, G1, G2
		Physiological	EMG burst amplitudes in error and correct trials	K, G1, G2
		Behavioural	Correction ratio	K, G1, G2
Error-monitoring in a reading-related context	Lexical decision task	Chronometric	MT in errors and correct trials	G1, G2
			Correction time in partial-error trials	G1, G2
		Physiological	EMG burst amplitudes in error and correct trials	G1, G2
		Behavioural	Correction ratio	G1, G2
Reading abilities	"L'Alouette" (Lefavrais, 1965, 2005)	Meaningless text reading	CTL score or percentage of correctly read words	G1, G2
	"La Mouette" (Evaléo,Maeder et al., 2018)	Meaningful text reading	Number or percentage of correctly read words	G1, G2
	One-minute tests (Gentaz et al., 2015)	Isolated word and pseudoword reading	Number of correctly read words and pseudowords (/60)	G1, G2
	E.CO.S.SE. test (Lecocq, 1996)	Written comprehension	Number of correct responses (/18)	G2

Note. K: kindergarten, G1: first grade, G2: second grade, DRA: Dénomination Rapide Automatisée (Rapid Automatized Naming), E.CO.S.SE.: Epreuve de COmpréhension Syntaxico-SEmantique (Syntactic-Semantic Comprehension Test), EMG: electromyography, MT: motor time, N-EEL: Nouvelles Epreuves pour l'Examen du Langage (New Tests for the Examination of Langage), NEPSY II: Bilan neuropsychologique de l'enfant - 2ème édition (Child neuropsychological assessment - 2nd edition), CTL: number of correctly read words divided by the reading time.

MANOVAs will be performed. All classical predictors of reading abilities (except for socioeconomic status and non-verbal intelligence, see Table 2) will be analysed as a function of Grades as a within-subject factor (Kindergarten, Grade 1, Grade 2). All the measures of reading abilities (except for written comprehension, see Table 2) will be analysed as a function of Grades as a within-subject factor (Grade 1, Grade 2).

Hypothesis 1. Error-monitoring efficiency as a predictor of future reading skills.

The first aim of the present study was to investigate whether domain-general error-monitoring evaluated before reading instruction improved the prediction of future reading skills compared to known reading predictors only (H1). In order to do so, we will compare two multiple linear regression models for both Grade 1 and Grade 2 (i.e., four regression models will be performed). In each of these models, the reading level to be predicted will be modelled as the first principal component obtained through a principal component analysis (PCA) on the four reading measures collected in Grade 1, and on the five reading measures taken in Grade 2 (see Reading abilities in Table 2), hereafter described as "Reading PC" in the equations of the models m1 and m2.

In the first model (i.e., the classical model, hereafter named "m1"), the predictors will be the classic predictors of reading abilities listed in Table 2, measured in kindergarten. To reduce the number of factors in the model and their potential overlap, a PCA will be performed on the set of classical predictors of reading measured. To catch the diversity in these predictors (e.g. phonology, vocabulary, socio-economic status), the three first principal components will be used as predictors in the regression model (hereafter described as "Classical Predictors PCs" in the model equations). Therefore, 77 participants are needed for this analysis to reach a statistical power of.80 with $\alpha = 0.05$ and for an expected effect size $f^2 = 0.15$ (Faul et al., 2007).

m1: Reading PC ~ Classical predictors PCs

In the second model (i.e., the enlarged model, hereafter named m2), the classical predictors will be enriched with domain-general error-monitoring measures collected in kindergarten (see Table 2). As for the previous analysis, a PCA will be performed to reduce the overlap of the measures. A single principal component summarising the error-monitoring efficiency is expected (hereafter described as "Error-monitoring PC" in the model equation). Thus, the enlarged model will be composed of four predictive factors, requiring 85 participants with the same parameters as the above sample size estimation (Faul et al., 2007).

m2: Reading PC ~ Classical predictors PCs + Error-monitoring PC

Finally, to address our first hypothesis, the two regression models (i.e., m1, m2) will be compared with a likelihood ratio test with the R function *anova*, for both Grade 1 and Grade 2. Our prediction is that m2 will better explain the variability in reading skills than m1, both for Grades 1 and 2 children.

Hypothesis 2. Error-monitoring/reading skills relationships as a function of stimuli types.

Regardless of the predictive value of error-monitoring measured in kindergarten on future reading skills one year or two years later (H1), we seek to explore whether the relationship between error-monitoring efficiency and reading skills measured at the same time is modulated by the type of stimuli on which error-monitoring is assessed. To do so, two regression models will be performed separately for both Grade 1 and Grade 2. In each of these models, the reading level to be predicted will be modelled as the same first principal component obtained through PCA on the four reading measures collected in Grade 1, and on the five reading measures taken in Grade 2 (see Table 2), described as "Reading PC" in the equations of the models m3 and m4.

In both models, predictors will be the four error-monitoring measures (see Table 2): the difference in motor time between error and correct response (MT), the correction time (CT), the correction ratio (CR) and the difference in the EMG amplitude burst between error and correct responses (Amp). For these analyses, 85 participants are needed to reach a statistical power of.80 with $\alpha = 0.05$ and an expected effect size $f^2 = 0.15$ (|Faul et al., 2007). In the first model (hereafter named "m3"), these predictors will be measured in the Simon task (i.e., a non-verbal task, "nv") while in the second model (hereafter named "m4"), predictors will be measured in the lexical decision task (i.e., a verbal task, "v"):

m3: Reading PC ~ nvMT + nvCT + nvCR + nvAmp

m4: Reading PC ~ vMT + vCT + vCR + vAmp

Finally, to address our second hypothesis, the two regression models (i.e., m3, m4) will be compared with a likelihood ratio test with the R function *anova*, for both Grade 1 and Grade 2.

2.8. Timeline for completion of the study

Table 3 below described the timeline for the completion of the experiments with children and the analyses of the data. The complete version of the paper is planned to be finished by 2026.

2.9. Financial support of the project

This work will be funded by the French National Research Agency (ANR) young researcher grant READER obtained by Gwendoline Mahé and Clémence Roger (ANR-21-CE28-0006-01). The grant has begun in January 2022 and will be finished in December 2025, covering thus all the duration of the longitudinal study. This research will also be funded by the "Maison Européenne des Sciences Humaines et Sociales" (MESHS; project ECOLE) obtained by Clémence Roger, Gwendoline Mahé , Fanny Grisetto, Lucie Macchi and Ludivine Javourey-Drevet, and their non-academic partner represented by Sébastien Courbot, head of the private school Saint-Sauveur et Saint-Eubert in Lille. A funding from the "Institut National Supérieur du Professorat et de l'Education" (INSPE, project MonitoRead) has also been obtained by Gwendoline Mahé and Clémence Roger. Finally, this research will be supported by the Equipex Continuum +, supported by the "Programme d'Investissement Avenir" grants (PIA).

Data statement

In line with the registered report format, data collection was not initiated at the time of the initial submission of the manuscript (May 6, 2022), nor at the time of the submission of the first manuscript revision (October 11, 2022). Due to the extended duration of the review process (11 months), at the time where the feedback on the first revision was received the data from 120 kindergarten children had already been collected as originally scheduled (November 2022 to April 2023). Importantly, we declare not having performed any analyses on the data.

Table 3
Timeline for the completion of the study.

	Experiments with children	Analyses of the data
Kindergarten	From November 2022 to April 2023 in kindergarten, considering that some children are already readers by the end of kindergarten	From May 2023 to August 2023
Grade 1	From January to June 2024 in first grade, allowing several months of reading instruction for the children	From July to October 2024
Grade 2	From January to June 2025 in second grade, a year after Grade 1 measures	From July to November 2025

However, it is essential to highlight that, to address our research hypothesis, we still require data from Grade 1 and Grade 2 children. Data collection for Grade 1 and Grade 2 children is respectively planned from January to June 2024 and 2025.

Furthermore, the authors declare their agreement to share the raw data of the study, along with all relevant materials and code, once the final manuscript is accepted for publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dcn.2024.101350.

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