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Electrophysiological signatures of spelling sensitivity development from primary school age to adulthood

Ekaterina Larionova[1]✉, Anna Rebreikina[1] & Olga Martynova[1,2]

Recognizing spelling errors is important for correct writing and reading, and develops over an extended period. The neural bases of the development of orthographic sensitivity remain poorly understood. We investigated event-related potentials (ERPs) associated with spelling error recognition when performing the orthographic decision task with correctly spelled and misspelled words in children aged 8–10 years old, early adolescents aged 11–14 years old, and adults. Spelling processing in adults included an early stage associated with the initial recognition of conflict between orthography and phonology (reflected in the N400 time window) and a later stage (reflected in the P600 time window) related to re-checking the spelling. In children 8–10 years old, there were no differences in ERPs to correct and misspelled words; in addition, their behavioral scores were worse than those of early adolescents, implying that the ability to quickly recognize the correct spelling is just beginning to develop at this age. In early adolescents, spelling recognition was reflected only at the later stage, corresponding to the P600 component. At the behavioral level, they were worse than adults at recognizing misspelled words. Our data suggest that orthographic sensitivity can develop beyond 14 years.

One aspect of literacy is the ability to recognize errors in text. We check texts after writing or notice errors in words while reading. The search for mistakes in written words is closely related to the lexical representations of words stored in memory. Lexical representations of words can be divided into orthographic, phonological, and semantic components[1]. In addition to lexical processing, reading and spelling also involve sublexical processes responsible for spelling-to-sound mappings[2,3]. The event-related potential (ERP) method has good temporal resolution and makes it possible to evaluate various stages of processing verbal information at the millisecond level. When conducting ERP studies, multiple characteristics of words are manipulated to investigate the various temporal stages of processing visual-verbal information and the underlying cognitive processes. The sensitivity of ERP components to the phonological, lexical, and semantic characteristics of words varies at different stages of ontogenesis[4]. The process of recognizing the correct spelling can be associated with several stages of information processing – from sublexical processing to understanding the meaning of a word, which may differ in various age groups. However, this issue has not been sufficiently studied.

Many studies on the perception of orthographic violations examined evoked brain activity to pseudowords and non-words, i.e., letter strings that do not exist in the language. A word can turn into a non-word as a result of accidental typos. Previous ERP studies showed that brain responses to non-words differ from words at the sublexical processing stage by about 100–150 ms in fluently reading adults; the P1 component of ERPs was larger for atypical letter combinations than for typical ones[5–7]. Differences between words and non-words were also identified for components peaking at about 200 ms in adults (e.g., N170 or N1)[6,8]. Also, the N1 differed between words and pseudowords, which may be associated with the lack of visual representations for pseudowords in memory[5,7,9–11]. In adults, specific features in the processing of words, non-words, and pseudowords have also been found later, at the lexical-semantic processing stages corresponding to the N400 component[6,12–14]. Thus, ERP data on the processing of words, pseudowords, and nonwords in adults seem to exhibit a consistent pattern in alphabetic languages, irrespective of the transparency of the writing system—that is, how closely the spelling of a word corresponds to its pronunciation.

[1]Institute of Higher Nervous Activity and Neurophysiology, Russian Academy of Sciences, Moscow, Russian Federation. [2]Centre for Cognition and Decision Making, Institute for Cognitive Neuroscience, Higher School of Economics, Moscow, Russian Federation. ✉email: larionova.ekaterin@gmail.com

Sensitivity to orthographic structure in children develops in the early school grades as familiarity with letter sequences and words, and their spelling increases. Behavioral research demonstrates that this process is not universal across languages, even when decoding simple orthographic units such as high-frequency words. In a comprehensive cross-linguistic study of early reading, Seymour and colleagues[15] discovered that by the end of the 1st school year, most children across 14 nations achieve 87% accuracy in decoding familiar high-frequency words. Notably, the English word-reading result, at 34%, deviated significantly from the 14-nation mean, indicating substantial differences across languages. Thus, on the one hand, decoding skills progress more rapidly in transparent orthographies compared to less transparent ones, and this accelerated development is attributed to the consistent mapping between graphemes and phonemes in languages with transparent orthographies. On the other hand, this shows that English should be regarded as a special case, and that insights from studies conducted in non-Anglophone contexts are more likely to yield a more accurate representation of the global norm[16].

Considering that repetitive decoding is essential for constructing word-specific orthographic representations, the establishment of these representations may also be contingent on the transparency of the orthography[17,18]. In alphabetic orthographies with high transparency, most children can successfully decode almost any monosyllabic word by the conclusion of the first year of schooling. However, in English, the intricacies of spelling-sound relationships result in a significant delay in acquiring this proficiency, spanning approximately three years of schooling[15,16]. At ages 7, 8, and 9, English-speaking children make more errors than their German-speaking peers in reading nonwords and low-frequency words despite matching word-recognition abilities. Although both groups achieve comparable speed in nonword recognition by age 12, native English speakers still displayed lower accuracy in decoding lengthy and complex nonwords[19]. This is consistent with the results of other work for transparent orthography: children 8–10 years old are already able to distinguish between valid and invalid combinations of letters in pseudowords with almost 100% accuracy if they have the opportunity to choose between two alternatives (for example, sinnum or ssinum)[17]. This is because the development of reading and spelling in transparent orthography is faster than in opaque orthography.

Nevertheless, Share[16] posits that the initial and final stages of reading are consistent across all alphabetic orthographies: phonological decoding plays a crucial role in the initial development of literacy skills in all alphabetic systems, while the essence of proficient reading lies in the automatic and effortless recognition of words. Indeed, behavioral studies demonstrate that, by about 4th grade, when reading high-frequency words is already automated, children, regardless of the transparency of the writing system, can reliably distinguish words, pseudowords, and nonwords and even use strategies similar to adults[20–25]. However, it is essential to understand that the duration of the development of orthographic sensitivity varies across different orthographies. For example, in parts of the English-speaking world, formal reading instruction starts at 5 years old instead of 6 (e.g., in Britain and certain U.S. states), with some even beginning at 4 years old[26]. Contrastingly, in countries with transparent orthographies, reading instruction typically begins at 6 years old and, in certain Scandinavian nations, at 7 years old[16]. Considering this heterogeneity and the different durations of recognition processes for simple orthographic units in various writing systems, even behavioral data of children similar to adults may not always reflect a shift to automatic word recognition. ERPs provide direct neural correlates, offering an objective measure of brain activity associated with reading automation.

However, at the neural level, not much is known about the development of orthographic processing. Using the ERP in children aged 6–9 years old, in both transparent and opaque orthographies, differences in the N170 component were revealed between words and strings of symbols similar to the letters of the alphabet, but consisting of completely new characters[10,27–30], however, there were no early differences between words, pseudowords, and non-words[24,27]. The few findings regarding the differentiation of words, pseudowords, and non-words in children relate mainly to languages with transparent orthography (mainly German). So, in the 11-year-old group, differences were found for the P150 and N400 components between pseudowords and non-words, and differences in 7-year-old children were revealed only at a later stage of information processing: the N400 was larger for non-words than words[24]. According to the authors, these results reflect lexical mechanisms of word superiority effects in younger children but both sublexical and lexical mechanisms in older children[24]. ERP differences for words, non-words, and pseudowords were also observed in children of different ages at later time intervals of word processing. In children aged 8–9 years, the amplitude of the late positive complex was significantly reduced for pseudowords compared to words[28,31]. The same patterns for a similar P600 wave were also obtained in children aged 12–14[32]. English-speaking adolescents (ages 15.4–19.3) show ERP patterns similar to adults at up to 110 ms in distinguishing between words and pseudowords that are earlier than in children[33].

The development of specialized processing of lexical units and the differentiation of words from non-words, pseudowords, and more complex units—pseudohomophones reflect the automation of reading processes[34,35]. Unlike non-words and pseudowords, pseudohomophones, i.e., words with orthographic violations but pronounced like an existing word, are words with commonly occurring spelling errors. Therefore, using such stimuli can shed light on the mechanisms underlying one of the aspects of literacy—recognition of the correct and incorrect spelling of words. In various languages, many misspelled words tend to be phonologically similar to correctly spelled words. For example, Russian is a transparent language, but each vowel phoneme [i, e, a, ɔ] in unstressed syllables can be translated into two graphemes resulting in spelling errors. Thus, the pronunciation of the correctly spelled word "волна" ("wave") with an unstressed first syllable, and the misspelled word "вална" (an incorrect spelling of a word "волна") is the same [vɐɫˈna]. Similar phenomena can be observed in other languages. For example, in Spanish, there are several phonemes that can be translated into two or more graphemes (e.g., phoneme /b/ can be translated into b and v); these conflicting phonemes would produce an error in spelling[36,37]. For example, Spanish "baca" vs. "vaca" ("cow") may be a frequent spelling error.

However, data from neurophysiological studies on the ERP components associated with the processing of pseudohomophones in adults are still inconsistent, and there is limited data available for children. The findings discussed below concern languages with transparent orthographies. In adults, some studies have identified early perceptual effects of pseudohomophones at up to 200–250 ms[5,11,38–40], but they were also detected later for the N400 and P600 components[28,29,38,39,41]. Notably, in the study conducted by González-Garrido and colleagues, only late adolescents (16–18 years) exhibiting high performance on a 5-test battery of orthographic knowledge demonstrated significant differences in P450 amplitude between correctly and incorrectly written words during the execution of an orthographic decision task. Additionally, differences were noted for the amplitude of the P150 component. In contrast, adolescents with lower levels of orthographic knowledge showed no difference between the conditions for any of the studied components P150, N170, P200, P450, and P600[42]. That is, adolescents with a high literacy level showed results similar to adults.

In the subsequent sections, we delve into the available ERP data related to pseudohomophone processing in children. There is evidence that the P600 component is higher for words and pseudohomophones than for pseudowords in 8-year-old children; however, there were no significant effects observed for the earlier N170 and N400 components[31]. No differences were found between words and pseudohomophones in 8-year-old children[31]. Remarkably, in 9-year-old children without spelling disorders, differentiation of pseudowords from words and pseudohomophones occurs at an earlier stage: the amplitude of the N400 component was higher for pseudowords than for words and pseudohomophones[28]. Although the effect of P600 is observed in both children with and without spelling disorders[28]. Unfortunately, this study did not compare words and pseudohomophones in children of this age. In contrast to 8-year-old children, those aged 9–10 exhibited distinctions between words and pseudohomophones: the amplitude of the late positive component was higher for words than for pseudohomophones. However, children did not show differences for components N170 and N400[29].

Heldmann and co-authors[43] compared the development of spelling sensitivity in elementary school in children of the 2nd (6.8–8.7 years) and 4th grades (9.6–10.8 years) during presentation of a line drawing (black lines on white background) representing a common object or an animal along with its proper correct or misspelled but phonologically correct name (e.g., a picture of a donkey with the correct German word for donkey "Esel", or with a misspelled but phonologically correct version "Ehsel"). The difference between correct and misspelled words was reflected by a more pronounced positive shift to misspelled words at about 600 ms, which was observed only in children in the 4th grade (9.6–10.8 years), which is consistent with the results of Bakos and colleagues[29]. However, differences in ERP between correct and misspelled words in Heldmann's study were also identified for 2nd graders but were observed at later stages, between 1300–1400 ms. The authors consider this effect a marker of orthographic sensitivity and conclude that there is a distinct shift from the 2nd (age range 6.8–8.7) to the 4th (age range 9.6–10.8) grade with regard to orthographic sensitivity[43]. The authors also assessed earlier ERP components in successive time-windows of 100 ms length after the stimulus presentation but found no significant effects.

Gómez-Velasquez and colleagues examined the detection of spelling errors in 8-year-old children with varying performance on four naming tasks (drawings, letters, numbers, and colors)[44], and their results partially agree with the results of Heldmann and colleagues[43]. Their study found enhanced amplitude for negativity peaking at 380 ms (N380) and also enhancement of the subsequent positive component (600–700 ms) for pseudohomophones in children with average naming performance that was not found in children with slow naming performance[44]. Thus, ERPs in children of the 2nd grade with good reading skills in Gomes-Velaskes's study[44] were similar to ERPs in children of the 4th grade in Heldmann's study[43]. In addition, as in Heldmann's study, the statistical analysis showed no significant effect for the first examined time window 165–265 ms.

It is important to note that in the experiment of Gomes-Velaskes[44] and in the Heldmann study[43], the presentation of verbal stimuli was associated with the presentation of the corresponding picture. This means that such paradigms differ from those used in studies with adults, which makes it difficult to compare the results obtained in different age groups. At the same time, using corresponding pictures could facilitate the recognition of the correct spelling of words in children. As far as we know, a comparative study of orthographic sensitivity that includes both groups of children and adults has not been previously conducted. Therefore, one of the objectives of our study was to use the same paradigm to study different age groups and not to use corresponding pictures that could potentially lead to improved spelling recognition.

Another significant gap in the knowledge of the neural underpinnings of literacy is the lack of ERP data in processing pseudohomophones in adolescents. Most studies of the neurophysiology of reading in children reported ERP findings for children in grades 1–5, that is, during the reading development period[28,29,31,43–45]. Behavioral data show that automatic word recognition develops gradually, starting in early school age, and reaches the adult level, at least for simple words, by grade 4[23,45–48]. At the same time, there are neurophysiological data that demonstrate that 5th-grade children still differ in ERP word processing patterns from adults, and the path to fluent reading continues beyond 5th grade[24]. In addition, even in good readers aged 10–11 years the functional lateralization of linguistic neural networks involved in automatic word recognition and phonological processing is still not developed[49,50]. Although neurophysiological evidence suggests that early adolescents use similar strategies to adults in processing and learning new words and can effectively use context to anticipate incoming information[51,52], the visual word processing system continues to develop[53].

Moreover, ERP studies have shown non-linear complex dynamics in the development of processing of various characteristics (spelling, lexical, semantic) of verbal stimuli; for example, in a study by Coch and Benoit[45], 4th-grade students showed smaller differences in ERPs between words, pseudowords, nonpronounceble letter strings, and false font strings than 3rd and 5th-grade students. Changes in the nature of errors in written language as children grow older are also noted: shifts in the proportion of spelling and morphological errors were observed between grades 4 and 5, and the relative frequency of morphological errors increased in older school students[54]. The authors hypothesized that the normal development of spelling reflects non-linear growth and that it takes a long time to develop a robust spelling vocabulary that coordinates phonology, spelling, and morphology and supports word-specific, regular spelling. In addition, the complexity and bi-directionality of this process imply that engaging in reading activities enhances word-reading skills and contributes to a deeper understanding of print, encompassing aspects such as spelling, phonology, and morphology[55]. Therefore, studies in various age groups are needed to form a complete picture of the age dynamics of the formation of literacy.

In this study, we investigated the process of spelling error recognition when presented with correctly spelled words and words with real spelling errors in the orthographic decision task and features of spelling recognition in different age groups. This study aimed to compare ERP patterns associated with spelling recognition in three age groups: primary (8–10 years old) and middle-school-aged children (early adolescence, 11–14 years old) and adult native speakers. An important feature of this study is the use of words with real misspellings rather than artificially constructed pseudo-homophones that do not occur in natural written speech. We assume that as the processes of spelling and reading are automated, earlier neurophysiological markers of recognition of spelling errors will be revealed. If the formation of spelling sensitivity is completed by early adolescence, then middle-school-aged children will have similar spelling recognition ERP patterns to adults.

Methods

Participants

We investigated three age groups: primary and middle-school-aged children (early adolescence) and adult native speakers. Twenty-seven healthy children aged 8 to 10 years old (20 female, 7 males; mean age 8.8, SD 0.9; educational level 2.8, SD 0.8 years), twenty-five healthy children aged 11 to 14 years old (9 female, 16 males; mean age 12.7, SD 0.9; educational level 6.6, SD 0.8 years) and thirty-six adult healthy volunteers aged 18 to 39 years old (22 female, 14 males; mean age 24.5, SD 5.0; educational level 13.9, SD 1.8 years) participated in the study. All participants were right-handed, native speakers of Russian, without speech disorders, neurological, or psychiatric diseases. They had normal or adjusted to normal vision. All children aged 11 to 14 years old, with the exception of one, had good academic performance in the Russian language (they had a score of 4–5 points, where 5 is the maximum score). Children aged 8–10 were not assessed in Russian language at school, so we relied on parental reports that children did not experience spelling difficulties. All participants or their legal representatives in the case of children gave written informed consent to participate in the study. The study was carried out in compliance with the Declaration of Helsinki and was approved by the Ethics Committee of the Institute of Higher Nervous Activity and Neurophysiology of the Russian Academy of Sciences (protocol #03 from 15.07.2019).

Stimuli material

The stimuli were 99 singular and plural nouns spelled correctly and incorrectly. Each misspelled word contained only one error. To neutralize the influence of the word length factor on processing, all selected words were 5–6 letters long. Two types of stimuli were presented: words with unstressed vowels in the word root written correctly (correct root [CR], 50 words; for example, “волна” [vɐɫˈna] [“wave”]) and incorrectly (misspelled root [MR], 49 words; for example, “блоха” [bɫɐˈxa] [“flea”]). An important feature of these stimuli is that the correctly spelled words and the misspelled words sound the same. For this reason, errors often occur in words with an unstressed vowel. A complete list of the stimuli and their characteristics is provided in Appendix A.

The frequency of words was determined using the Frequency Dictionary of the Modern Russian Language[56]. The mean frequency of CR words was 110.77 (range 0.7–926), while that of MR words was 81.98 (range 1.5–709). The CR and MR words were equalized in frequency ($T = 555.0$, $p = 0.57$, level of significance: 0.05). We also compared the orthographic neighborhood size using the StimulStat database[57]; this parameter did not differ statistically for correct and misspelled conditions ($T = 151.5$, $p = 0.54$). The mean orthographic neighborhood size of CR words was 1.0 (SD 1.0), MR 1.0 (SD 1.0). The frequency of bigrams containing an error for misspelled words, or bigrams containing an unstressed vowel, which could have been misspelled for a correctly spelled word was equalized for correct and misspelled words ($T = 579.0$, $p = 0.74$): the mean bigram frequency of CR words was 3,061,677 (SD 1,554,942), MR 2,975,152 (SD 1,574,369) (determined according to Frequency Dictionary of Modern Russian Language[56]).

Experimental procedure

During the EEG recording, the participants sat in a comfortable chair in a darkened room at a distance of about 1 m from the computer screen. The subjects were instructed to silently read the words presented on the screen and determine whether the word on the screen was spelled correctly or misspelled by pressing the left or right buttons of a Logitech F310 gamepad. The allocation of right and left buttons for correct and misspelled words were balanced across subjects.

The words were presented in the center of the screen in a white font (lower case Liberation Sans (an analog of Arial), 125 pt) on a black background. Stimuli were presented in a random order on a 19 " LG FLATRON L1952T monitor using PsychoPy Experiment Builder v3.0.7 software[58]. Stimulus presentation began with a fixation cross; stimuli were presented on the screen until the subject responded, the time interval after the response until the next stimulus varied from 1300 to 2300 ms. The total time for completing the task did not exceed 40 min for children aged 8 to 10 years old, 15 min for children aged 11 to 14 years old and 10 min for adults.

EEG recording and data processing

EEG was recorded from 19 electrodes Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, T5, T6, P3, P4, O1, O2, Fz, Cz, Pz, according to the International 10–20 system guidelines, referenced to the mastoids. Data were sampled at 250 Hz; electrode impedances were below 10 kΩ.

Offline processing was carried out using Brain Vision Analyzer 2.0.4 software (Brain Products, GmbH, Munich, Germany). Offline filtering was performed using a band-pass filter (0.5–30 Hz), followed by fast ICA for removing eye-blink artifacts. Data were segmented into epochs starting 300 ms before the word onset and lasting until 1500 ms after the onset. Only correct trials were segmented. Semi-automatic artifact rejection (± 100 μV threshold) was performed on each epoch section (– 300–1500 ms). Data were corrected relative to a 300 ms prestimulus baseline.

Data were averaged per subject and per condition. Five children aged 8 to 10 years were excluded due to an insufficient number of averagings (less than 28 realizations) and excessive noise or artifacts. Three adult participants were excluded due to excessive noise or artifacts. In Section "Participants", data are provided only for those volunteers whose data were ultimately analyzed.

The reaction time and error rate were analyzed using ANOVAs with repeated measures (RM) for three groups of participants. One participant whose average reaction time exceeded three standard deviations (from the group of children aged 8–10 years old) was excluded from the analysis of behavioral data. The reaction time was only evaluated for correct answers. All significant ($p < 0.05$) main and interaction effects were followed by post hoc Bonferroni-corrected contrasts. To correct violations of sphericity and homogeneity, the Greenhouse–Geisser correction was applied as well. Statistical analysis was performed using the STATISTICA software (Statsoft, Tulsa, OK, USA).

Statistical analyses of the ERPs were carried out using the Matlab FieldTrip toolbox. A permutation t-test was performed to explore significant differences between CR and MR conditions in the window between 0 and 900 ms after the stimulus for the adult group and in the window between 0 and 1500 ms after the stimulus for the two groups of children, whose response time was longer compared to adults (Fieldtrip, Monte Carlo method, 500 permutations at 19 electrodes). The differences between CR and MR words were considered significant if maintained for a minimum of 5 consecutive samples (i.e., over 20 ms) in at least 2 neighboring electrodes and with an alpha level of 0.025.

Results

Behavioral data

The RM ANOVA results are shown in Fig. 1. The analysis of error rate indicated a significant main effect for Group $F(2,84) = 28.46$, $p < 0.0001$, $\eta^2p = 0.40$: the total percentage of errors for CR and MR differed in all three groups (adults vs. early adolescents vs. children, 2.65 vs. 8.68 vs. 13.91%). A significant Spelling × Group interaction was also found $F(2,84) = 10.69$, $p < 0.0001$, $\eta^2p = 0.20$: the percentage of errors for MR differed between the adult and early adolescent groups (adults vs. early adolescents, 3.97 vs. 13.68%), the percentage of errors for both CR and MR differed between the adult and children groups (CR: adults vs. children, 1.33 vs. 9.54%; MR: adults vs. children, 3.97 vs. 18.29%), the percentage of errors for CR differed between the early adolescent and children groups (early adolescents vs. children, 3.68 vs. 9.54%).

Dependent post-hoc t-tests within each group revealed that adults, early adolescents and children gave more correct answers to CR than MR (adults: CR vs. MR, 1.33 vs. 3.97%; early adolescents: CR vs. MR, 3.68 vs. 13.68%; children: CR vs. MR, 9.54 vs. 18.29%).

The analysis of reaction time indicated a significant main effect for Group $F(2,84) = 71.70$, $p < 0.0001$, $\eta^2p = 0.63$: the total reaction time for CR and MR differed between adults and children (1.17 vs. 4.55 s), and between early adolescents and children (1.80 vs. 4.55 s). Significant Spelling × Group interaction was also found $F(2,84) = 7.24$, $p < 0.001$, $\eta^2p = 0.15$: the reaction time for both CR and MR differed between adult and children groups (CR: adults vs. children, 1.09 vs. 4.68 s; MR: adults vs. children, 1.25 vs. 4.41 s), the reaction time for both CR and MR differed between the early adolescent and children groups (CR: early adolescents vs. children, 1.70 vs. 4.68 s; MR: early adolescents vs. children, 1.89 vs. 4.41 s).

Post-hoc t-tests within each group revealed that only adults and early adolescents had longer reaction times for MR than CR (adults: CR vs. MR, 1.09 vs. 1.25 s; early adolescents: CR vs. MR, 1.70 vs. 1.89 s).

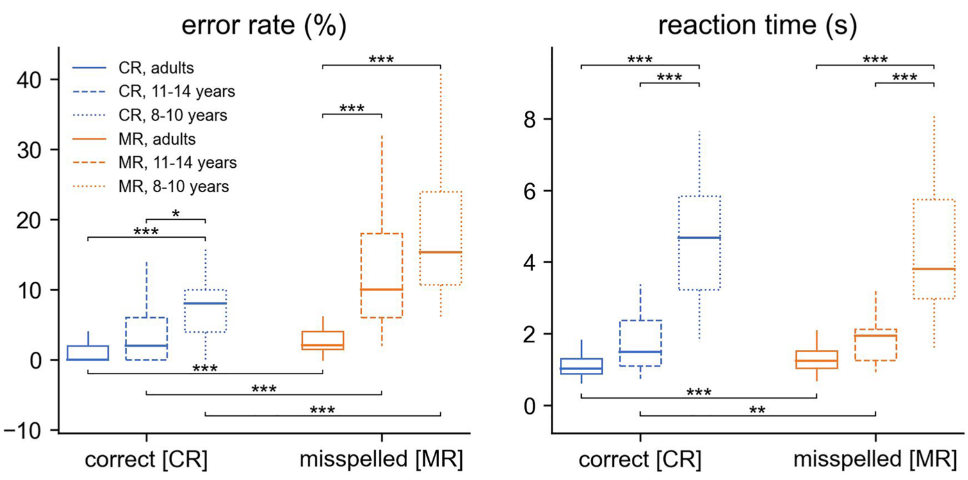

Figure 1. RM ANOVA results and post-hoc t-tests within each group for error rate and response time. $^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$.

ERP analysis

We found differences between ERPs to CR and MR conditions in adult participants in two time windows (Fig. 2). More negative activity distributed across the frontal and posterior scalp sites was found for misspelled than for correctly spelled words around 400 ms that is compatible with N400 (300–520 ms, p = 0.002). More positive activity distributed across the frontal, central and posterior scalp sites was found for misspelled words than for correctly spelled words around 700 ms that is compatible with P600, (592–868 ms, p = 0.002).

We found differences between ERPs to CR and MR conditions in children aged 11 to 14 years in the period from 768 to 1192 ms (p = 0.002). In this group, more positive activity, predominantly distributed across the central scalp sites was found for misspelled words than for correctly spelled words that is compatible with P600, (Fig. 3). However, we did not find any difference between ERPs to CR and MR conditions in children aged 8 to 10 years (Fig. 3).

Discussion

We investigated the neural processes that underlie recognizing the correct spelling of words and the features of spelling processing in different age periods (adults, 11–14 years old children, and 8–10 years old children). At the behavioral level, all the studied groups successfully identified correctly spelled words and misspelled words, the average percentage of errors even in the group of children aged 8–10 did not exceed 14%. Children had more incorrect answers and longer reaction times than early adolescents and adults. Early adolescents and adults showed similar, but not identical, behavioral results. The response time to both types of stimuli and the percentage of erroneous answers to correctly spelled words did not differ between these groups, at the same time early adolescents were worse than adults at recognizing misspelled words. At the ERP level, it has been shown that adults demonstrate earlier spelling error recognition patterns compared with early adolescents 11–14 years old, corresponding to the N400 (300–520 ms) and P600 (592–868 ms) components. In the early adolescents, the recognition of spelling errors was associated only with the late positive wave (768–1192 ms). In children of 8–10 years old, no differences were found in ERPs for correctly and incorrectly spelled words. Thus, our results show that orthographic sensitivity can develop until at least 14 years of age.

A higher percentage of errors was observed for misspelled words compared to correct ones, which is consistent with many previous studies[9,59–61]. It has previously been shown that correctly spelled words are recognized better and faster than misspelled words in adult native speakers and in late adolescents[39,42,62]. It is important to note that in our study adults and early adolescents did not differ in response time to either type of stimuli: they equally quickly recognized correctly spelled and misspelled words, that is, they probably used similar reading and spelling

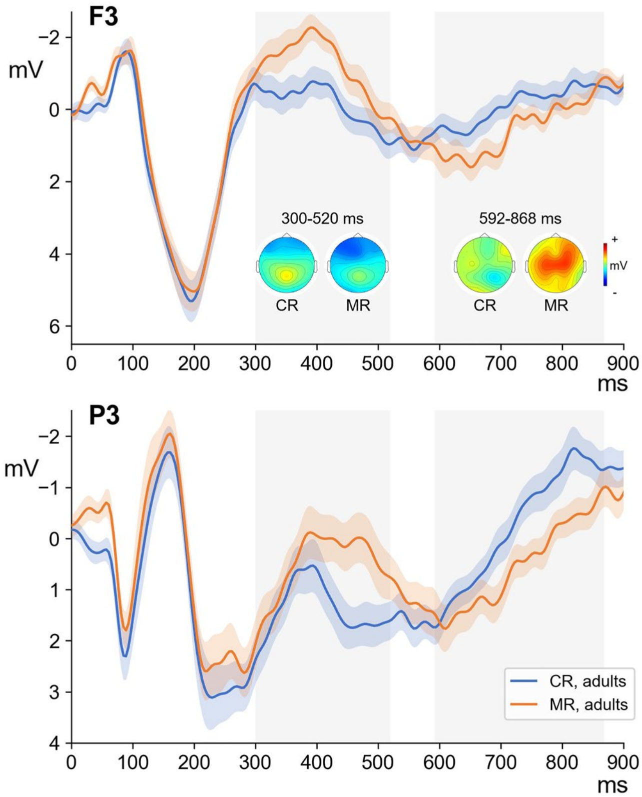

Figure 2. Averaged ERPs and topographic maps for correct (CR) and misspelled (MR) words in adult subjects for P3 and F3.

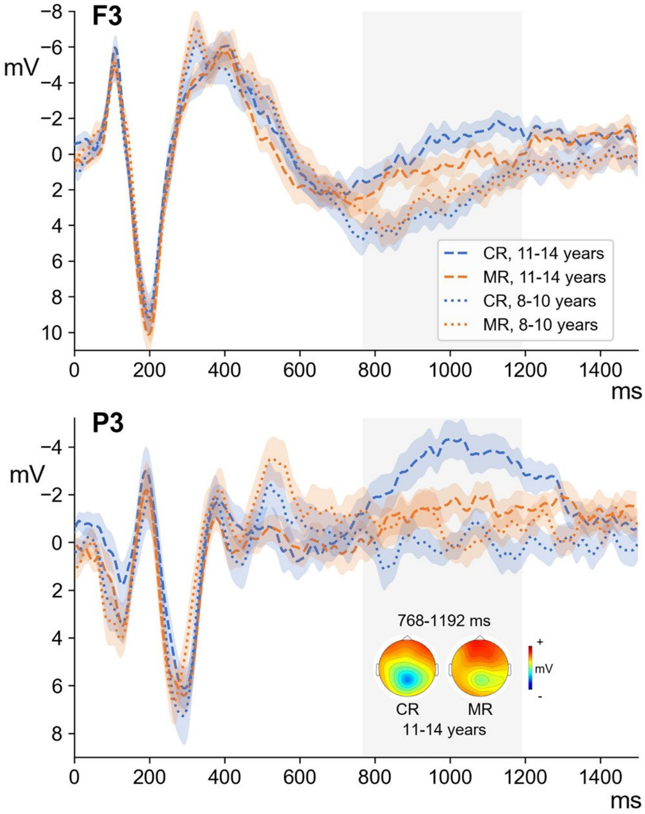

Figure 3. Averaged ERPs and topographic maps for correct (CR) and misspelled (MR) words in children for P3 and F3.

recognition strategies. However, the percentage of misidentified misspelled words was higher in early adolescents than adults, which may indicate that spelling sensitivity is still developing at this age.

Interestingly, in our work, the reaction time for misspelled words and correctly spelled words differed only in the groups of adults and early adolescents but not in children aged 8–10 years. The dual-route model of reading supports either an indirect phonological route or a direct orthographic route for semantic access[2,63]. Misspelled words do not have orthographic representations and are therefore likely to activate an indirect route, which slows down recognition, while correctly spelled words activate a direct route in experienced readers[64], which is consistent with our findings in adults and early adolescents. At the same time, phonological skills are primary in reading acquisition when an orthographic representation is not fully specified, and novice readers predominantly use an indirect phonological route for lexical access to correctly spelled words[65–67]. Behavioral evidence demonstrates that 3rd grade readers typically rely predominantly on a direct lexical strategy to read familiar words silently, unlike grade 2 children[68–70]. In addition, children at the end of grade 3 (mean age 9.5) may already show faster reaction times for words compared to pseudo-homophones in the phonological decision task[29]. Thus, in our study, the sample of children aged 8–10 years (mainly pupils in grades 2 and 3) corresponds to the period of transition from the indirect phonological route to the direct orthographic route for semantic access, and the obtained behavioral results may reflect the dominance of the phonological route in children aged 8–10 years. Our behavioral data is broadly consistent with the electrophysiological evidence we received.

For the N400 component, we found differences between correctly spelled and misspelled words only in adults: the N400 amplitude across the frontal and posterior scalp sites was more negative for misspelled words. The N400 component is associated primarily with lexical-semantic information processing and reflects the integration of orthographic and phonological information with lexico-semantic representations[6,12–14]. Furthermore, the frontal N400 is associated with familiarity memory: its amplitude decreases for familiar stimuli[71,72]. Pseudohomophones evoked an increase in the amplitude of N400 compared to words in adult native speakers and late adolescents[38,39,41,73] that is probably associated with lexical-semantic conflict and difficulty in semantic access. Gonzalez-Garrido and colleagues[38], suggested that recognizing an error causes a conflict, which can be resolved by visually re-comparing the word with its stored visual representation. So, the enhanced N400 for misspelled words may reflect conflict in the integration of the visual and phonological forms and meaning-based representations. On the other hand, N400 (FN400) has been associated with familiarity memory, and even implicit memory[74–76]. So our findings may also reflect inconsistency in incoming visual information and visual word forms stored in memory.

The revealed absence of the N400 effect in early adolescents may indicate that orthographic representations for correctly spelled words are not strong enough therefore there is no conflict between orthographic and phonological word form or between sensory input and memory when processing misspelled words. As there is some evidence that FN400 can be related to implicit memory, we hypothesized that in adults the more prominent N400 for misspelled word may reflect an implicit process, while recognizing spelling in early adolescents is less automated and related only to explicit analysis in the time window of 768–1192 ms, corresponding to the P600 wave. Nonetheless, the process of spelling recognition in adults is not limited to the time window of 300–520 ms; they demonstrate neural patterns similar to early adolescents for the late wave corresponding to the P600 component.

The functional role of the P600 component is still a matter of debate. P600 refers to access to the phonological lexicon and knowledge of word spelling[31]. Moreover, P600 reflects re-processing to check for possible processing errors[77,78]. González-Garrido and colleagues[38] suggested that P600 could be related to parsing, which finally made it possible to distinguish between words and pseudo homophones. Several studies have found that recollection is associated with a 500–700 ms parietal effect termed the late-positive complex (LPC or P600)[72,79]. Recollection involves the explicit retrieval of specific details about something recognized[80]. Consequently, in our study, the incomplete coincidence of "memory traces" for the visual word forms and the later explicit "rechecking" of the presence of errors (or recollection of details of word spelling) can explain the larger P600 amplitude for misspelled words in adults. We assume that the P600 component in early adolescents has a different functional meaning than P600 in adults and is not associated with re-processing to check for possible processing errors, but reflects only primary explicit analysis (without rechecking), so at the behavioral level, early adolescents recognize misspelled words worse than adults do.

Thus, the adult spelling recognition process involves at least two steps: implicit detection of conflict between orthography and phonology associated with the N400 component and subsequent explicit rechecking for errors related to the late positive component. In the early adolescence, recognizing misspellings is associated only with explicit analysis of words reflected in the late positive wave. Somewhat consistent data were obtained by González-Garrido and colleagues: the N400 component differed between correctly and incorrectly spelled words only in adults with good spelling skills, while the P600 component differed between correctly and incorrectly spelled words in both good and poor spellers[38]. In our study, early adolescents, who are less experienced in reading and spelling, had differences between responses to MR and CR in the P600 component, and more experienced adult readers had differences in both N400 and P600.

Children 8–10 years old demonstrate similar neural processes for correctly spelled words and words spelled incorrectly, at least up to 1500 ms, as well as a longer process of recognizing spelling and finding the correct answer at the behavioral level. Comparable reading processes can explain this for correctly spelled and misspelled words, while it is likely that children need more time to determine the correct spelling (longer than the 1500 ms epoch we analyzed), which is consistent with the long response time to both types of stimuli. Similar results were found in the phonological decision task: neither N400 nor LPC (similar to P600 wave in our study) differed between words and pseudohomophones in children of 8 years old (although at the behavioral level children recognized words better than pseudohomophones)[31]. However, in the other study, older children aged 9–10 in the phonological decision task already showed higher average LPC amplitudes (600–976 ms) for words compared to pseudohomophones[29]. It could be assumed that the spelling task, unlike the phonological task, modulates the differences between words and pseudo-homophones, but our data showed that the spelling task did not modulate the differences in ERP in children. At the same time, as we already noted in the introduction, in the few studies with the spelling task in which differences between words and pseudohomophones were observed, images were used that were presented before a verbal stimulus and probably, facilitated the detection of conflict between orthography and phonology in children 8–10 years old[43,44]. The division of children aged 8–10 years into narrower age groups may be useful in further research since, during this period, the initial patterns of recognition of correct spelling at the neural level might be formed. However, dividing our sample into subgroups of children aged 8, 9, and 10 did not show significant differences in ERPs between correctly spelled and misspelled words (see Appendix B). The absence of differences could be due to the small number of children in the subgroups.

Conclusion

The present ERP study provides electrophysiological data showing age-related differences in spelling error recognition. In adult native speakers, ERP analysis of brain responses to correctly spelled and misspelled words revealed two stages of error processing: an earlier one associated with the initial recognition of conflict between orthography and phonology (reflected in the N400 time window) and a later one (reflected in the P600 time window), probably related to re-checking for errors in the spelling of the word. In early adolescents aged 11–14 years, spelling recognition is reflected only at a late stage, corresponding to the P600 component. We did not find differences in the ERP in the time window up to 1500 ms in children aged 8–10 years old. Our results imply that orthographic sensitivity begins to develop in primary school and does not allow preattentive recognition of the correct spelling (without attentive rechecking of the correctness of spelling). Thus, our results confirm previous adult findings and provide new data on the neurophysiological underpinnings of spelling processing in children and adolescents. It is important to note that we have shown that orthographic sensitivity can develop until at least 14 years of age. However, additional longitudinal research is required to ascertain when the shift to automatic word recognition resembling at least two-stage recognition of the correctness of spelling, similar to adult native speakers, is realized.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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References

1. Perfetti, C. A. The representation problem in reading acquisition. *Read. Acquis.* **1**, 145–174. https://doi.org/10.4324/9781351236904-6 (2017).
2. Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychol. Rev.* **108**, 204–256 (2001).
3. Hepner, C., McCloskey, M. & Rapp, B. Do reading and spelling share orthographic representations? Evidence from developmental dysgraphia. *Cogn. Neuropsychol.* **34**, 119–143 (2017).
4. Rebreikina, A. B., Larionova, E. V. & Martynova, O. V. Event-related potentials during literacy acquisition. *J. Mod. Foreign Psychol.* **9**, 21–33 (2020).
5. Araújo, S., Faísca, L., Bramão, I., Reis, A. & Petersson, K. M. Lexical and sublexical orthographic processing: An ERP study with skilled and dyslexic adult readers. *Brain Lang.* **141**, 16–27 (2015).
6. Coch, D. & Mitra, P. Word and pseudoword superiority effects reflected in the ERP waveform. *Brain Res.* **1329**, 159–174 (2010).
7. Hauk, O. *et al.* [Q:] When would you prefer a SOSSAGE to a SAUSAGE? [A:] At about 100 msec: ERP correlates of orthographic typicality and lexicality in written word recognition. *J. Cogn. Neurosci.* **18**, 818–832 (2006).
8. Mahé, G., Bonnefond, A., Gavens, N., Dufour, A. & Doignon-Camus, N. Impaired visual expertise for print in French adults with dyslexia as shown by N170 tuning. *Neuropsychologia* **50**, 3200–3206 (2012).
9. Braun, M., Hutzler, F., Ziegler, J. C., Dambacher, M. & Jacobs, A. M. Pseudohomophone effects provide evidence of early lexico-phonological processing in visual word recognition. *Hum. Brain Mapp.* **30**, 1977 (2009).
10. Maurer, U., Brandeis, D. & McCandliss, B. D. Fast, visual specialization for reading in English revealed by the topography of the N170 ERP response. *Behav. Brain Funct.* **1**, 13 (2005).
11. Sauseng, P., Bergmann, J. & Wimmer, H. When does the brain register deviances from standard word spellings? An ERP study. *Cogn. Brain Res.* **20**, 529–532 (2004).
12. Kutas, M. & Federmeier, K. D. Thirty years and counting: Finding meaning in the N400 component of the event related brain potential (ERP). *Annu. Rev. Psychol.* **62**, 621 (2011).
13. Ziegler, J. C., Besson, M., Jacobs, A. M., Nazir, T. A. & Carr, T. H. Word, pseudoword, and nonword processing: A multitask comparison using event-related brain potentials. *J. Cogn. Neurosci.* **9**, 758–775 (1997).
14. Bermúdez-Margaretto, B., Shtyrov, Y., Beltrán, D., Cuetos, F. & Domínguez, A. Rapid acquisition of novel written word-forms: ERP evidence. *Behav. Brain Funct.* **16**, 1–17 (2020).
15. Seymour, P. H. K., Aro, M. & Erskine, J. M. Foundation literacy acquisition in European orthographies. *Br. J. Psychol.* **94**, 143–174 (2003).
16. Share, D. L. On the Anglocentricities of current reading research and practice: The perils of overreliance on an 'outlier' orthography. *Psychol. Bull.* **134**, 584–615 (2008).
17. Rothe, J., Cornell, S., Ise, E. & Schulte-Körne, G. A comparison of orthographic processing in children with and without reading and spelling disorder in a regular orthography. *Res. Gate* **28**, 1307–1332 (2015).
18. Share, D. L. Phonological recoding and orthographic learning: A direct test of the self-teaching hypothesis. *J. Exp. Child Psychol.* **72**, 95–129 (1999).
19. Frith, U., Wimmer, H. & Landerl, K. Differences in phonological recoding in German- and English-speaking children. *Sci. Stud. Read.* **2**, 31–54 (1998).
20. Barron, R. W. *Reading Research: Advances in Theory and Practice* (Academic Press, 1981).
21. Henderson, L. & Chard, J. *The Reader's Implicit Knowledge of Orthographic Structure* (Academic Press, 1980).
22. Rosinski, R. R. & Wheeler, K. E. Children's use of orthographic structure in word discrimination. *Psychon. Sci.* **26**, 97–98 (1972).
23. Adams, M. *Beginning to Read*. (1990).
24. Coch, D., Mitra, P. & George, E. Behavioral and ERP evidence of word and pseudoword superiority effects in 7- and 11-year-olds. *Brain Res.* **1486**, 68–81 (2012).
25. Hasenäcker, J. & Schroeder, S. Syllables and morphemes in German reading development: Evidence from second graders, fourth graders, and adults. *Appl. Psycholinguist.* **38**, 733–753 (2017).
26. Caravolas, M. The nature and causes of dyslexia in different languages. in *The Science of Reading: A Handbook*, 336–355 (Blackwell Publishing Ltd, 2005). https://doi.org/10.1002/9780470757642.ch18.
27. Eberhard-Moscicka, A. K., Jost, L. B., Raith, M. & Maurer, U. Neurocognitive mechanisms of learning to read: Print tuning in beginning readers related to word-reading fluency and semantics but not phonology. *Dev. Sci.* **18**, 106–118 (2015).
28. Kemény, F. *et al.* Print-, sublexical and lexical processing in children with reading and/or spelling deficits: An ERP study. *Int. J. Psychophysiol.* **130**, 53–62 (2018).
29. Bakos, S., Landerl, K., Bartling, J., Schulte-Körne, G. & Moll, K. Neurophysiological correlates of word processing deficits in isolated reading and isolated spelling disorders. *Clin. Neurophysiol.* **129**, 526–540 (2018).
30. González, G. F. *et al.* Brain-potential analysis of visual word recognition in dyslexics and typically reading children. *Front. Hum. Neurosci.* **8**, 474 (2014).
31. Hasko, S., Groth, K., Bruder, J., Bartling, J. & Schulte-Körne, G. The time course of reading processes in children with and without dyslexia: An ERP study. *Front. Hum. Neurosci.* **7**, 570 (2013).
32. Wang, E. *et al.* N400 and P600 effect of chinese words recognition. *Interdiscip. J. Neurosci. Quant. Phys.* **15**, 76–83 (2017).
33. Taroyan, N. A. & Nicolson, R. I. Reading words and pseudowords in dyslexia: ERP and behavioural tests in English-speaking adolescents. *Int. J. Psychophysiol.* **74**, 199–208 (2009).
34. Castles, A., Rastle, K. & Nation, K. Ending the reading wars: Reading acquisition from novice to expert. *Int. J. Psychophysiol.* https://doi.org/10.1177/152910061877227119,5-51 (2018).
35. Zarić, J. & Nagler, T. Reading comprehension on word- and sentence-level can be predicted by orthographic knowledge for German children with poor reading proficiency. *Read. Writ.* **34**, 2031–2057 (2021).
36. Valle-Arroyo, F. Spelling errors in Spanish. *Read. Writ.* **2**, 83–98 (1990).
37. Zhang, S. *et al.* Spelling acquisition in Spanish: Using error analyses to examine individual differences in phonological and orthographic processing. *Sci. Stud. Read.* **25**, 64–83 (2021).
38. González-Garrido, A. A., Gómez-Velázquez, F. R., Zarabozo, D., Zarabozo-Hurtado, D. & Joshi, R. M. ERP effects of word exposure and orthographic knowledge on lexical decisions in Spanish. *J. Behav. Brain Sci.* **05**, 185–193 (2015).
39. Larionova, E. V. & Martynova, O. V. Frequency effects on spelling error recognition: An ERP study. *Front. Psychol.* **13**, 1977 (2022).
40. Larionova, E., Garakh, Z. & Martynova, O. Top-down modulation of brain responses in spelling error recognition. *Acta Psychol.* **235**, 103891 (2023).
41. Briesemeister, B. B. *et al.* The pseudohomophone effect: Evidence for an orthography–phonology-conflict. *Neurosci. Lett.* **455**, 124–128 (2009).
42. González-Garrido, A. A., Gómez-Velázquez, F. R. & Rodríguez-Santillán, E. Orthographic recognition in late adolescents. *Clin. EEG Neurosci.* **45**, 113–121 (2014).

43. Heldmann, M., Puppe, S., Effenberg, A. O. & Münte, T. F. Development of sensitivity to orthographic errors in children: An event-related potential study. *Neuroscience* **358**, 349–360 (2017).
44. Gómez-Velázquez, F. R., González-Garrido, A. A. & Vega-Gutiérrez, O. L. Naming abilities and orthographic recognition during childhood an event-related brain potentials study. *Int. J. Psychol. Stud.* **5**, 55 (2013).
45. Coch, D. & Benoit, C. N400 event-related potential and standardized measures of reading in late elementary school children: Correlated or independent?. *Mind Brain Educ.* **9**, 145–153 (2015).
46. Schadler, M. & Thissen, D. M. The development of automatic word recognition and reading skill. *Mem. Cogn.* **9**, 132–141 (1981).
47. Ehri, L. C. & Wilce, L. S. Development of word identification speed in skilled and less skilled beginning readers. *J. Educ. Psychol.* **75**, 3–18 (1983).
48. Guan, C. Q., Fraundorf, S. H. & Perfetti, C. A. Character and child factors contribute to character recognition development among good and poor Chinese readers from grade 1 to 6. *Ann. Dyslexia* **70**, 220–242 (2020).
49. Spironelli, C. & Angrilli, A. Developmental aspects of automatic word processing: Language lateralization of early ERP components in children, young adults and middle-aged subjects. *Biol. Psychol.* **80**, 35–45 (2009).
50. Wilson, A. C. & Bishop, D. V. M. Resounding failure to replicate links between developmental language disorder and cerebral lateralisation. *PeerJ* **2018**, e4217 (2018).
51. Abel, A. D., Schneider, J. & Maguire, M. J. N400 response indexes word learning from linguistic context in children. *Lang. Learn.* **14**, 61–71. https://doi.org/10.1080/15475441.2017.1362347 (2017).
52. Vergilova, Y., Jachmann, T. K., Mani, N. & Kray, J. Age-related differences in expectation-based novel word learning. *Psychophysiology* **00**, e14030 (2022).
53. Brem, S. *et al.* Evidence for developmental changes in the visual word processing network beyond adolescence. *Neuroimage* **29**, 822–837 (2006).
54. Bahr, R. H., Silliman, E. R., Berninger, V. W. & Dow, M. Linguistic pattern analysis of misspellings of typically developing writers in grades 1–9. *J. Speech Lang. Hear. Res.* **55**, 1587–1599 (2012).
55. Conrad, N. J. & Deacon, S. H. Print learning: A theoretical framework for the role of children's learning about the orthography in the development of reading skill. *Read. Res. Q.* **58**, 113–125 (2023).
56. Lyashevskaya, O. N. & Sharov, S. A. *The Frequency Dictionary of Modern Russian Language (Based on the Russian National Corpus)* (Azbukovnik, 2009).
57. Alexeeva, S., Slioussar, N. & Chernova, D. StimulStat: A lexical database for Russian. *Behav. Res. Methods* **50**, 2305–2315 (2018).
58. Peirce, J. *et al.* PsychoPy2: Experiments in behavior made easy. *Behav. Res. Methods* **51**, 195–203 (2019).
59. Pexman, P. M., Lupker, S. J. & Jared, D. Homophone effects in lexical decision. *J. Exp. Psychol. Learn. Mem. Cogn.* **27**, 139–156 (2001).
60. Seidenberg, M. S., Petersen, A., MacDonald, M. C. & Plaut, D. C. Pseudohomophone effects and models of word recognition. *J. Exp. Psychol. Learn. Mem. Cogn.* **22**, 48–62 (1996).
61. Ziegler, J. C., Jacobs, A. M. & Klüppel, D. Pseudohomophone effects in lexical decision: Still a challenge for current word recognition models. *J. Exp. Psychol. Hum. Percept. Perform.* **27**, 547–559 (2001).
62. Taha, H. & Khateb, A. Resolving the orthographic ambiguity during visual word recognition in Arabic: An event-related potential investigation. *Front. Hum. Neurosci.* **7**, 821 (2013).
63. Coltheart, M., Curtis, B., Atkins, P. & Haller, M. Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychol. Rev.* **100**, 589–608 (1993).
64. Grainger, J. & Ziegler, J. C. A dual-route approach to orthographic processing. *Front. Psychol.* **2**, 54 (2011).
65. Doctor, E. A. & Coltheart, M. Children's use of phonological encoding when reading for meaning. *Mem. Cognit.* **8**, 195–209 (1980).
66. Share, D. L. Phonological recoding and self-teaching: sine qua non of reading acquisition. *Cognition* **55**, 151–218 (1995).
67. Harris, L. N. & Perfetti, C. A. Individual differences in phonological feedback effects: Evidence for the orthographic recoding hypothesis of orthographic learning. *Sci. Stud. Read.* **21**, 31–45 (2017).
68. Martens, V. E. G. & de Jong, P. F. The effect of word length on lexical decision in dyslexic and normal reading children. *Brain Lang.* **98**, 140–149 (2006).
69. Zoccolotti, P. *et al.* Word length effect in early reading and in developmental dyslexia. *Brain Lang.* **93**, 369–373 (2005).
70. Schmalz, X., Marinus, E. & Castles, A. Phonological decoding or direct access? Regularity effects in lexical decisions of Grade 3 and 4 children. *Q. J. Exp. Psychol.* **66**, 338–346 (2013).
71. Mecklinger, A. & Bader, R. From fluency to recognition decisions: A broader view of familiarity-based remembering. *Neuropsychologia* **146**, 107527 (2020).
72. Rugg, M. D. & Curran, T. Event-related potentials and recognition memory. *Trends Cogn. Sci.* **11**, 251–257 (2007).
73. Costello, B., Caffarra, S., Fariña, N., Duñabeitia, J. A. & Carreiras, M. Reading without phonology: ERP evidence from skilled deaf readers of Spanish. *Sci. Rep.* **11**, 5202 (2021).
74. Paller, K. A., Voss, J. L. & Boehm, S. G. Validating neural correlates of familiarity. *Trends Cogn. Sci.* **11**, 243–250 (2007).
75. Dew, I. T. Z. & Cabeza, R. The porous boundaries between explicit and implicit memory: Behavioral and neural evidence. *Ann. N. Y. Acad. Sci.* **1224**, 174–190 (2011).
76. Voss, J. L., Lucas, H. D. & Paller, K. A. More than a feeling: Pervasive influences of memory without awareness of retrieval. *Cogn. Neurosci.* **3**, 193–207 (2012).
77. Van de Meerendonk, N., Chwilla, D. J. & Kolk, H. H. J. States of indecision in the brain: ERP reflections of syntactic agreement violations versus visual degradation. *Neuropsychologia* **51**, 1383–1396 (2013).
78. Vissers, C. T. W. M., Chwilla, D. J. & Kolk, H. H. J. Monitoring in language perception: The effect of misspellings of words in highly constrained sentences. *Brain Res.* **1106**, 150–163 (2006).
79. Mecklinger, A. Electrophysiological measures of familiarity memory. *Clin. EEG Neurosci.* **37**, 292–299 (2006).
80. Gao, C., Hermiller, M. S., Voss, J. L. & Guo, C. Basic perceptual changes that alter meaning and neural correlates of recognition memory. *Front. Hum. Neurosci.* **9**, 49 (2015).

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Author contributions

E.L., A.R. and O.M. conceived the experiment, E.L. and A.R. conducted the experiment and analyzed the results. E.L. produced the first draft of the manuscript and all authors contributed to writing and revising the paper. All authors reviewed the manuscript before submission.

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to E.L.

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