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Does learning to read affect naming skills? Insights from ERPs during letter and picture naming tasks

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ABSTRACT

Numerous studies report that poor readers display low performance in naming tasks. However, very few studies have investigated the development of naming skills along with the development of reading fluency and its variability in typically developing children. In this study, we used electro-encephalographic (EEG) recordings acquired during letter and picture naming tasks to investigate how naming skills develop and, possibly, interact with age and reading level variations. Ninety-three children aged 7–12 years named letters and pictures under an EEG recording, and their reading performance was assessed. ERP results on amplitudes show that age and reading level have similar effects on the entire letter naming time-course. By contrast, age and reading level have different effects on the picture naming time-course, with a specific effect of reading level on the N1 time-interval, associated with visuo-conceptual processing and an effect of both age and reading on later time-windows. On the microstate analysis, age remains the only predictor of the variance in global electric field at scalp for both letter and picture naming indicating that reading skill is not related to a modulation of the mental processes underlying naming.

1. Introduction

Fluent reading, described as effortless recognition of words and immediate comprehension, is important for both academic and professional achievement. Even if a great amount of time and educational resources are dedicated to teaching children to read from Grade 1, reading level varies from one child to another. In addition to dyslexic children, who experience severe and persistent difficulties in learning to read and in reaching fluent reading, poor, average, and good readers exist throughout the learning process. Previous studies investigating the predictors and precursors of reading repeatedly revealed that naming and reading are closely related (Araùjo et al., 2015; Kirby et al., 2010). On the one hand, previous behavioral research with typically developing children suggested that naming letters is a stronger predictor of concurrent and later reading skills than naming pictures (for a review, see Araùjo et al., 2015). On the other hand, research with dyslexic participants, as well as research on the development of reading networks in the brain, suggested that naming pictures is specifically related to reading (Nation et al., 2005). In this study, we aim to understand how the naming of letters and pictures interacts with both age and reading level, taking advantage of the insights revealed by event-related potentials (ERPs) recorded during naming tasks.

1.1. How naming is related to age and reading

Letter knowledge and rapid naming of letters are among the best predictors of reading efficiency. However, whereas letter knowledge seems to predict reading in early stages (Hogan et al., 2005), letter naming remains a powerful predictor throughout development (Araujo et al., 2015; Kirby et al., 2010; Wakamiya et al., 2011). Dyslexic children are slower at rapid letter naming than their age controls (Denckla and Rudel, 1976) and their reading-level controls (Araújo et al., 2011; Snyder and Downey, 1995). However, as the rapid naming task involves a large array of processing stages, from visual exploration to phonological encoding and articulation, it remains unclear which process(es) is/are responsible for slowness in letter naming. To our knowledge, there is no published study investigating discrete letter naming (i.e., items presented one after another on a computer screen) with dyslexic or typically developed children.

Reading ability also correlates with picture naming (Katz, 1986).

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Dyslexic children perform similarly to reading age controls (on average, two years younger) in picture naming tasks (Nation et al., 2001; Snowling et al., 1988; Swan and Goswami, 1997), suggesting that performance in picture naming tasks is more related to reading efficiency than to age. Following these lines, pre-school children at risk of developing dyslexia show naming weaknesses (Scarborough, 1990), as do adults with a history of reading difficulty (Dietrich and Brady, 2001). Interestingly, low performance in naming is not specific to dyslexic individuals; it was found in both poor readers (Swan and Goswami, 1997) and poor comprehenders (Nation et al., 2001). However, it should be noted that the poor readers in Swan and Goswami's (1997) study had significantly lower IQ scores than participants in both the dyslexic and control groups.

Taken together, these results suggest that the naming difficulties observed among poor readers and poor comprehenders might be a consequence of semantic weakness, whereas the naming deficit observed among dyslexic children might be a consequence of phonological weaknesses. At the behavioral level, the naming deficit seems to be fairly independent of the participants' age but related to semantic and phonologic weaknesses. The relationship between naming and reading appears to be reciprocal. On the one hand, a naming deficit can be found in at risk children before reading instruction suggesting that naming influences reading. On the other hand, improvement in reading skills often leads to improvements in naming skills, suggesting that progress in reading fluency may impact on naming performance. Indeed, longitudinal studies reported better rapid naming skills as children age and become better readers (Clayton et al., 2020; Furnes and Samuelsson, 2011; Wolf et al., 1986). To date, very few studies have investigated naming skills in typically developing children, and none have reported how naming skills develop throughout reading instruction. The present study aims at filling this gap in the literature by investigating how learning to read affects naming skills in children aged 7–12 years.

1.2. *Specific links between picture and word processing*

A large part of the visual word recognition literature conducted at the brain level has investigated the development of the visual word form area (VWFA; Cohen and Dehaene, 2004; Dehaene and Cohen, 2011; Dehaene-Lambertz et al., 2018; McClandiss et al., 2003). The results suggest that the VWFA recruits neurons that were previously dedicated to object recognition (Dehaene-Lambertz et al., 2018; McClandiss et al., 2003), and even after learning to read, the VWFA continues to be activated in various tasks requiring links between visual input and phonological retrieval (Dehaene-Lambertz et al., 2018; Vogel et al., 2012, 2014). This suggests that object and word recognition not only share common processing stages but also share a common neural basis. Thus, it appears logical that an object naming deficit may be related to poor reading skills. It has been shown that the development of sensitivity to print is not related to age, but to reading instruction, as the VWFA is not activated when illiterate adults are confronted with print (Dehaene et al., 2015). This suggests that the links between object naming and reading efficiency might develop with reading instruction, and stronger links may appear as reading efficiency develops.

According to the VWFA literature, a naming deficit is present before reading instruction and constitutes a core deficit for poor and dyslexic readers. This result aligns with studies reporting naming deficits in kindergarteners at risk for dyslexia (Scarborough, 1990), and studies reporting a naming deficit in adults with compensated reading difficulties (Dietrich and Brady, 2001; McCrory et al., 2005).

1.3. *Insights from EEG studies*

There is limited available literature on children's letter naming with electro-encephalographic (EEG) recordings, and we are not aware of previous studies that recorded ERPs during a letter naming task performed by a reading-disabled sample. Results of one previous study on typically developing participants from 7 to 10 suggest that ERPs recorded during letter naming were unaffected by reading level variations but were affected by age (Cohen et al., 2018).

Relative to letter naming, there is a larger EEG literature focusing on picture naming, although studies with children performing overt naming tasks are limited. Two studies investigated picture naming in typically developing children using ERPs (Gómez-Velásquez et al., 2013; Greenham and Stelmack, 2001), and two others focused on dyslexic children (Greenham et al., 2003; Trauzettel-Klosinski et al., 2006).

Gómez-Velásquez et al. (2013) sorted their sample of typically developing children into two groups—slow and fast namers—according to the speed at which they named pictures during a standard behavioral rapid naming task. The task performed during ERP recording was not a standard naming task; children had to decide whether or not a picture and a word (which was presented on screen after the picture) matched. The authors reported that slow namers showed larger amplitudes in both congruent and incongruent conditions compared to fast namers. However, it should be stressed that the ERP analyses were related to the processing of the word presented after the picture rather than on the processing of the picture, and the authors concluded that the slow namers' speed indicates difficulty in building adequate associations between visual and phonological representations of words. The hypothesis that slow and fast namers, or poor and good readers, have differing abilities to process pictures remains to be tested.

Greenham and Stelmack (2001) recorded ERPs during standard picture naming, word reading, and superimposed picture–word tasks performed by nine children aged 9–13 years. They reported significant differences between ERPs recorded when naming pictures or reading words, with the picture naming task eliciting larger amplitudes than the word reading task. This difference has been interpreted as the difference between words and pictures in terms of the automaticity of lexical access or effortful access to conceptual representations.

Greenham et al. (2003) and Trauzettel-Klosinski et al. (2006) investigated the effects of reading level on impaired participants' performance in a standard picture naming task. Both studies reported increased error rates and longer reaction times in dyslexic participants compared to typically developed participants. Surprisingly, no electrophysiological correlates of these differences were observed in the picture naming task. The ERP waves for words exhibited reduced N450 amplitudes in dyslexics compared to controls for reading or superimposed picture–word tasks. The authors of both studies suggested that the "visual" pathway is somehow preserved in dyslexic participants, at least in the early stages of picture processing. In addition, Greenham et al. (2003) hypothesized that electrophysiological differences between dyslexic and typically developed participants may be observed in ERP time windows beyond the 500 ms window analyzed in their study, possibly closer to articulation, and may be associated with phonological processes. This aligns with the behavioral studies summarized above suggesting that the picture naming deficit observed in individuals with dyslexia is mainly attributed to a phonological weakness (for a review, see Nation, 2005).

A study using positron emission tomography (PET) during picture naming and word reading in dyslexic adults revealed an interesting pattern: dyslexic adults showed reduced activation in the left occipitotemporal area during both picture naming and word reading tasks, even if the behavioral performance during the tasks was comparable across the dyslexic and control groups (McCrory et al., 2005). Thus, abnormal activation in this region might not be specific to orthographic decoding, but may reflect a more general impairment in the ability to integrate visual and phonological information. The fact that a significant difference in the processing of pictures and words remains in dyslexic adults suggests that this general impairment in the ability to integrate phonological and visual input is a core weakness in disabled readers.

Taken together, the results of brain imaging studies with reading-disabled participants suggest that a picture naming deficit is present in these participants, but so far, the specific underlying processes in which it appears remains unclear. Some results implicate lexico-semantic processes in the naming deficit, whereas some others implicate phonological processes.

Regarding the effect of age on the electrophysiological correlates of picture naming, a longitudinal study conducted by Ojima et al. (2011), which used the picture–word interference task, found similar ERP components in 7- and 9-year-old children and in adults, but with shifts in latencies. The authors concluded that the differences in reaction times observed between children and adults rely on acceleration of the processes underlying the task. However, different results have been reported by Laganaro et al. (2015) with an overt picture naming task in typically developing 7–8-year-olds, 10–12-year-olds, and adults. The results showed that the acceleration observed in word production from childhood to adulthood seems to rely on changes in the global topographies in the P1–N1 time-window, associated with visual and conceptual processes. Beyond the P1–N1 complex, the same sequence of global topographic patterns was found in children and adults, although older children and adults showed components earlier than younger children did. Similarly, Cohen et al. (2018) found that the P2 component appears around 320 ms for older children and around 400 ms for younger children, suggesting that lexico-semantic processing is specifically shortened with development. Taken together, the results regarding the effect of age suggest an acceleration of specific visuo-conceptual and lexical-semantic processing stages.

Cohen et al. (2018) compared the effects of age and reading level on ERPs recorded during letter and picture naming tasks. Interestingly, amplitudes in the time interval corresponding to the N1 component during picture naming were specifically linked with reading level variations, whereas age variations predicted amplitudes in a time interval corresponding to the P2 component. This pattern indicates independent effects of age and reading level during picture naming. Even though lexical processing seems to be associated with age and reading level variations, lexical concept retrieval (N1) was specifically related to reading level, whereas lexico-semantic retrieval (P2) was specifically related to age. It is important to note that Cohen et al. (2018) only reported their analysis of amplitudes, without identifying the topographies underlying these processing stages. It is therefore unclear if a difference in amplitudes during letter and picture naming is related to a difference in topography. If this was the case, it would suggest that children varying in age and/or reading level might be involved in different cognitive processes during certain time intervals.

Based on the above results, lexico-semantic and phonological processes seem to underlie the effects of both age and reading level on ERPs recorded during a picture naming task. Nevertheless, the effects of reading level on ERPs recorded during picture naming have only been investigated by comparing dyslexic and control groups. Typically developing children do not show a naming deficit, but their naming skills could evolve throughout reading acquisition, and specific processing stages may be modulated by reading fluency development. This must be addressed by future research.

1.4. *Present study*

Building on the studies presented above and the literature concerning the development of the VWFA, the present study aims to understand how naming skills develop along with reading acquisition based on ERP recordings acquired during picture and letter naming tasks performed by a large sample of typically developing children aged 7–12 years.

Based on the literature on the VWFA and on the results from behavioral and electrophysiological studies it seems that reading skills and age may be related to different processes underlying picture naming. In particular we expect the N1 component, which corresponds to visuo-conceptual processing in picture naming, to be sensitive to reading level and the P2 component, which corresponds to lexico-semantic processing, to be sensitive to age variations. By contrast, in letter naming, which is one of the best predictors of subsequent reading skills, all underlying processes (the entire time course of letter naming ERPs) should be modulated by reading level and age.

2. Method

2.1. *Participants*

Ninety-three children aged 7–12 years (mean = 9.5 years; min = 7.0; max = 12.10; 43 boys) participated in the study. Children attended grades 2–6. The data for seven children were removed from the data set due to either excessive noise in the EEG signal or extremely low scores in several tasks. The final sample comprised 86 children (mean = 9.7 years; 43 boys). The children were all native French speakers without a diagnosed reading impairment or neurological disease. The youngest children attended grade 2, meaning that they had at least one year of formal reading instruction. Seventy-seven of the children were right-handed, six were left-handed, and three were ambidextrous, as determined by the Edinburgh Handedness Scales (Oldfield, 1971). Children were recruited through announcements on the university's website. The research ethics committee at the Faculty of Psychology and Educational Sciences of the University of Geneva approved the study protocol, and written informed consent was collected from the parents of all the participating children. At the end of the experimental session, each child received a small present and a voucher.

2.2. *Tasks and material*

All the children performed one reading task involving two word lists and two discrete naming tasks while EEG/ERP recordings were taken.

2.2.1. *Reading task*

Participants overtly read two lists of 20 stimuli as quickly and accurately as possible. Two reading lists—irregular and regular words—from the Odedys battery (Odedys 2; Jacquier-Roux et al., 2005) were used. For this test, accuracy scores (the number of correct responses) and time (the total time per list) were computed. Then, a composite reading score was calculated by dividing the number of correct responses by the time taken to read the column.

2.2.2. *Naming*

Participants performed letter and picture naming tasks.

2.2.2.1. Letters. Sixteen letters were selected for the letter naming task. Letters were repeated five times, resulting in a total of 80 experimental trials. Each letter was displayed sequentially in a pseudo-random order. Letters were presented in uppercase, 48-point, black Arial font in the middle of a grey screen. Each trial began with a fixation cross presented for 500 ms in the center of the screen. The fixation cross was then replaced by a grey screen for 200 ms, followed by the letter for 800 ms. The name of the task (i.e., letter naming) was displayed in white on the grey background before the example trials began. The scores were determined as the percentage of correct responses and the reaction times (in milliseconds) from stimulus onset to vocal onset. This task was usually completed within 4 min.

2.2.2.2. Pictures. Sixteen black and white drawings and their corresponding modal names were selected from French databases (Alario and Ferrand, 1999; Bonin et al., 2003). The stimuli corresponded to 16 words with a maximum age of acquisition at 6 years and high name agreement (mean = 93.6%) to ensure that the children gave the same name for the same picture. The size of the pictures was set to 5.26 × 5.26 degrees of the visual field. For the experimental task, the 16 pictures were repeated 5 times, leading to 80 experimental trials. Each trial began with a fixation cross presented for 500 ms in the center of the screen. The fixation cross was then replaced by a grey screen for 200 ms, followed by a picture displayed in the middle of the screen for 2000 ms. As in the letter naming task, the name of the task was displayed in white on a grey background before the example trials began. Scores were determined as the percentage of correct responses and the reaction times from stimulus onset to vocal onset. This task was usually completed within 7 min.

2.3. Procedure

For the naming tasks, the children were tested individually in a dimly lit, soundproof room and seated approximately 60 cm away from a computer screen. The software E-Prime (E-Studio) was used to present the trials. An experimenter who was sitting behind the child and in visual contact with another experimenter monitoring the EEG online signal manually triggered the inter-stimulus interval. This procedure allowed for longer intervals between trials when the EEG signal became noisy due to movement or when the child commented on a trial. A similar procedure was used by Cohen et al. (2018). Participants were instructed to name the letter or picture as quickly and accurately as possible. Oral production latencies were systematically checked with a speech analysis software (Check-Vocal; Protopapas, 2007). Each task began with two practice trials. A break was offered to each participant in the middle of the experimental list.

For the picture naming task, participants were familiarized with all the pictures and their corresponding modal names before the experiment. Pictures' modal names were presented through loudspeakers. To ensure that the child paid attention to the modal name, a simple word–picture matching task was used. Each picture was paired with another image from the experimental data set, and the child had to click on the picture corresponding to the name delivered through loudspeakers. If the choice was incorrect, the name was repeated until the correct picture was selected.

The reading task was performed in paper and pencil format in a different room with one experimenter after the EEG session.

2.4. EEG acquisition and pre-analyses

EEGs were recorded continuously using the Active-Two Biosemi EEG system (Biosemi V.O.F. Amsterdam, Netherlands), with 64 channels covering the entire scalp. Signals were sampled at 512 Hz (filters: DC to 104 Hz, 3 dB/octave slope). Two external channels placed at the external corner and under the right eye recorded eye movements.

Offline, ERPs were bandpass-filtered to 0.2–30 Hz (the second order was a causal Butterworth filter with −12 dB/octave roll-off) and notch-filtered to 50 Hz and then re-referenced to the average reference. Using the software Cartool (Brunet et al., 2011), epochs of 251 time frames (491 ms) for letter naming, and 263 time frames (515 ms) for picture naming were extracted and locked to the stimuli. Only trials with correct responses and valid RTs were retained. Epochs contaminated by eye blinking, movements, or other noise were rejected and excluded from averaging after visual inspection. As a result, an average of 65 trials (range: 48–79) per participant were included in the ERP analyses for the letter naming task and an average of 62 trials (range: 45–76) per participant were included in the ERP analyses for the picture naming task. Electrodes with signal artifacts were interpolated using 3-D spline interpolation (Perrin et al., 1987), with an average of seven sites interpolated for each individual ERP for each task.

We used overt naming tasks in this study. It has been shown that artifacts generated by overt speaking occur in the 50–100 ms preceding vocal onset (Fargier et al., 2018; Ganushchak et al., 2011; Porcaro et al., 2015). In this study, the average reaction times were 891 ms for pictures and 645 ms for letters. By analyzing only the first 490 ms in letter naming and the first 515 ms in picture naming, we avoided any time interval that could be modulated by speech artifacts.

2.4.1. Analyses

Reading score and age were used as independent factors in the analyses of ERPs from naming tasks. The analyses focused on waveform amplitudes and topographic maps during periods of stable global electrophysiological signals at the scalp. Individual ERP signals were analyzed separately for each task. Analyzing amplitudes provides insights into which time window/component of the ERP signal is affected by age or reading level. If the amplitudes are low, the results of amplitude analysis are interpreted in terms of the automaticity of the processing stage corresponding to the component, and if the amplitudes are high, the results are interpreted in terms of the weakness or difficulty of computing a processing stage (Ciesielski et al., 2004). By analyzing microstates, we gained insight into the participants' global voltage distribution at scalp at each time point. Such analysis allows us to differentiate differences in amplitudes that are related to a difference or shifts in microstates from those that are purely related to amplitudes. A difference in microstates for the same component suggests that participants varying in age or reading level are not engaged in the same mental processing. Specific microstates in given time-windows can also be associated with specific brain processes (Changeux and Michel 2004; Koukkou and Lehmann, 1987). By computing the two analyses, we aimed to determine whether age and reading level similarly affect the naming time course in terms of amplitudes and of microstates.

For waveform amplitudes, parametric multiple regressions were computed at each time point (every 2 ms), and each electrode's absolute value in the naming tasks was computed with individual age and reading scores using the STEN toolbox developed by Jean-François Knebel (http://www.unil.ch/line/home/menuinst/about-the-line/software–analysis-tools.html). It should be noted that age and reading level (which have a correlation of 0.72) are independent, non-collinear predictors. The tolerance value between age and reading level is 0.48, meaning that 48% of the variance in reading level is not accounted for by age. The variance inflation factor (VIF) value is within the acceptable range (VIF = 2.08).

When correcting for multiple tests, spatial and temporal corrections are better suited for mass univariate analysis of EEG/ERP data than Bonferroni corrections (for a review, see Groppe et al., 2011). We therefore combined an alpha set to $p < .01$ with a temporal and a spatial criterion: the regression had to be significant for 10 consecutive time frames (i.e., 20 ms) and four clustered electrodes. This revealed the time points at which the participants' reading score and age predict the ERP amplitudes of letter and picture naming.

Microstates analysis was performed with the software RAGU (Koenig et al., 2011) to determine which periods of stable electrophysiological signals at the scalp are affected by age and/or reading level. This method is advantageous because the reference electrode is independent (Michel et al., 2001, 2004) and the method is insensitive to pure amplitude modulations. In addition, it accommodates the portion of data variance that is common across subjects and does not account for variance that appears to be tied to individual attributes. Microstate segmentation was performed through cross-validation, which involved computing microstate models with different numbers of microstate classes based on the average ERPs for a subset of the participants (training data). These microstate models were then tested for their predictive value (mean correlation) in relation to the average ERPs of the participants not included in the models (for a complete description of the procedure, see Koenig et al., 2014). The final microstates model with the optimal number of microstates is selected based on the best mean correlation between the two sets of data (training and test datasets) after completing 1000 randomizations of the training data.

Next, we analyzed whether age and reading level modulated the microstates recorded during letter and picture naming. We ran the analysis with the whole sample, using age and reading level as predictors of the topographic variance in a hierarchical regression model with age entered at step 1 and reading level entered at step 2 (Table 2).[1]

3. Results

3.1. Behavioral results

Overall, children were faster (t[86, 2] = 12.801; $p < .00001$) and more accurate (t[86, 2] = −3.559; $p < .0001$) in the letter naming task (mean accuracy = 97%, SD = 3.6; mean reaction time (RT) = 645 ms, SD = 121) than in the picture naming task (mean accuracy = 94%, SD = 5.7; mean RT = 891 ms, SD = 130).

Table 1 shows the correlations between age, reading score, and naming tasks. As detailed in the table, picture and letter naming measures were significantly correlated with both age and reading skills.

3.2. ERP results

Time-point-by-time-point regressions were carried out using ERP amplitudes of letter and picture naming tasks as the dependent variables and age and reading score as the predictors. Predictors were entered at the same time in a linear regression model, together with the interaction term. The results, which are presented in Fig. 1, reveal that age and reading score are associated with ERP amplitudes in both naming tasks, but in different time intervals for picture naming.

For picture naming, significant relationships between the reading scores and waveform amplitudes appeared in two specific time windows, where better readers showed larger amplitudes (see Fig. 1A). The first time window (160–295 ms) fell within the N1 time interval, and the amplitudes at the anterior and posterior sites were predicted by the reading score. In the second time window (380–410 ms), amplitudes were related to reading level at the central and frontal left electrodes. In this time window, we also found that age has an effect on amplitudes, with older children showing larger amplitudes. The interaction effect between age and reading was non-significant.

Regarding letter naming, the results of the regression analysis reveal a large significant relationship between age and reading, modulating amplitudes in several time windows and with a high number of associated electrodes (see Fig. 1B). The interaction between age and reading level was significant in two time windows associated with P1, P2. In the first time window (P1 time-interval, 140–185 ms), young poor readers were associated with smaller amplitudes, whereas young good readers were associated with larger amplitudes. In the second time window (250–370 ms and 410–450 ms, corresponding to the P2 time interval), age and reading level effects were observed for almost all electrodes, with smaller amplitudes for young poor readers and higher amplitudes for young good readers. Finally, in the final period extending until the end of the extracted signal, the amplitudes in posterior sites were predicted by age and reading level but without interaction. For this last time windows, amplitudes were smaller for better readers.

Table 1
Spearman correlation coefficients between the behavioral scores of reading and naming.

	1	2	3	4	5	6
1. Age	–					
2. Reading score	.72***	–				
3. Picture naming accuracy	.39 ***	.43 ***	–			
4. Picture naming RT	- .33 **	-.28 *	- .42 ***	–		
5. Letter naming accuracy	.24 *	.21 *	.34 **	- .28 *	–	
6. Letter naming RT	- .63 ***	-.47 ***	- .35 **	.54 ***	- .22 *	–

*p < .05; **p < .01; ***p < .001.

Table 2
Hierarchical regression results on the topographic variance for each microstate with age and reading level as predictors.

Map	Independent variable	R^2	R^2 change	β	t
Picture naming task					
Map A	1. Age	.01		−0.28	−0.51
	2. Reading level	.01	–	−10.98	−0.69
Map B	1. Age	.21		−2.26	−2.82**
	2. Reading level	.22	.01	−17.44	−0.77
Map C	1. Age	.12		−5.13	−3.14**
	2. Reading level	.12	–	37.99	0.41
Map D	1. Age	.08		7.44	3.00**
	2. Reading level	.08	–	37.55	0.37
Letter naming task					
Map E	1. Age	.02		−0.01	−0.96
	2. Reading level	.04	.02	−0.47	−1.54
Map F	1. Age	.01		−0.00	−0.49
	2. Reading level	.02	.01	−0.44	−1.04
Map G	1. Age	.08		−0.02	−2.97**
	2. Reading level	.08	–	0.17	0.54
Map H	1. Age	.02		−0.02	−2.01*
	2. Reading level	.03	.01	0.43	1.06

3.3. Topographic analysis

The topographic analysis used the eight different topographic maps extracted from the microstate segmentation and analysis (see Fig. 2) to examine the letter and picture naming time courses.

The effects of age and reading level on each of the microstates elicited along the time course of each task were analyzed with a hierarchical regression approach, with age at step 1 and reading level at step 2 (see Table 2 and Fig. 3). The analysis was also run the other way around, with reading level at step 1 and age at step 2 revealing that reading level does predict topographic variance if considered alone but does not account for topographic variance beyond the contribution of age (does not add explained variance when age is taken into account first). Overall, age predicts most of the topographic variance. Specifically, age predicts topographic variance from P1 to the end of the analyzed period in picture naming, but in time-intervals corresponding to N170 and P2 components in letter naming.

4. Discussion

In this study, we took advantage of the information from EEG/ERP recordings taken during letter and picture naming tasks to specify the processing stages linked to naming as a function of reading level and age. Our results suggest that on the one hand, the entire time-course of letter processing is modulated by age. Reading level affected amplitudes in younger children only, but not in older children. On the other hand, picture naming undergoes specific changes in two time intervals, N1 and late P2. The first interval (N1, falling around 230 ms in children) has been previously associated with visuo-conceptual processes in picture naming (Indefrey, 2011). The second time-window falls on a (late) P2 component, which has previously been associated with lexical processes. Crucially, the N1 time window in picture naming is specifically related to reading level, while the later time-window is equally related to age and reading level. In this section, we discuss the findings in relation to the issues raised at the beginning of this paper: (a) whether letter naming is similarly affected by age and reading level, and (b) whether picture naming is differentially affected by age and reading

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[1] The stepwise regression analysis was also performed in the other way around, with reading level entered at step 1 and age at step 2.

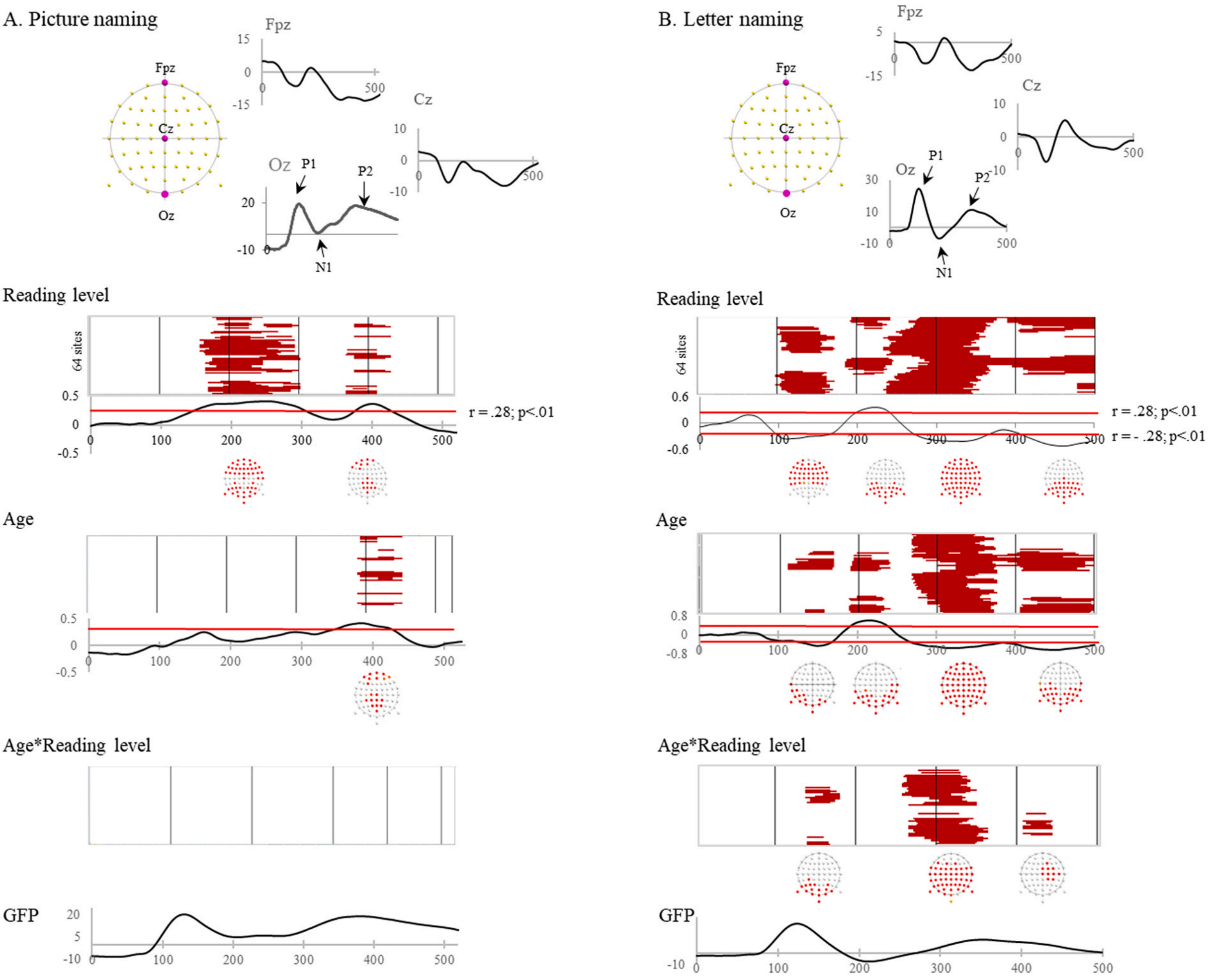

Fig. 1. Three electrodes (Fpz, Cz, and Oz) are displayed for the picture naming (panel A) and letter naming (panel B) tasks, with components of interest identified. Periods in which the amplitudes were significantly predicted by reading scores and age are highlighted in red, and the associated electrodes are displayed under each time interval. The correlation between reading score or age and amplitude is plotted on P1 for picture naming and on C4 for letter naming. A positive correlation indicates higher amplitudes for better readers. Global field power (GFP) is displayed for each task. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

level. Finally, we consider several caveats that possibly limit the conclusions that can be drawn from this work.

4.1. Letter naming

Based on previous studies, we expected the entire letter-naming time course to be affected by age and reading level, without any specific effect on particular processing stages. The amplitude analysis revealed that age and reading level had general effects on the entire time course as early as 100 ms after stimulus presentation. The interaction between age and reading level was significant for the P1 and P2 components. Specifically, young good readers showed reduced amplitudes during letter processing compared to young poor readers. This might be due to the fact that younger children show more variance in their reading performance than older children do. Indeed, younger children in the present study vary from poor to advanced readers, whereas older children are mostly advanced readers. For the N1 component, older children (or better readers) showed larger amplitudes than younger children (or poorer readers). The N1 component is usually associated with letter specification identification, indicating letter name activation (Madec et al., 2012; Rey et al., 2009). Similar results were previously reported when comparing children who could or could not read (Maurer et al., 2006). The N1 amplitude has been shown to increase in children at the beginning of learning to read and seems to decrease with reading expertise (Brem et al., 2009; Maurer et al., 2011). In the present study children were included from the very beginning of reading acquisition (i.e. end of grade 1), which could explain that the results on the entire group is similar to Maurer et al. (2006).[2]

The microstate analysis took a step further, revealing that only age predicted the topographic variance during letter naming, specifically for the N1 and P2 components. As no previous studies that recorded ERPs during letter naming performed such a topographic analysis, we had no specific hypothesis regarding the microstates elicited during the letter naming time course. We found that the N1 and P2 components appear to be associated with different microstates according to age. Overall, ERPs in older children yielded microstates with an activation of specific areas in central (for N1) and lateral (for P2) sites rather than a general activation of anterior and central or parietal sites, as observed in younger children. The results show topographic changes similar to those reported in previous studies using letters. The N1 topography of younger children in the present study is close to the early N1 topography found in first graders in previous studies (Eberhard-Moscicka et al., 2016). Similarly,

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[2] We also performed the analyses removing the youngest children of the sample (i.e. below 7; 6 years old, n = 10) we found a decrease in the N1 amplitudes as reported by previous studies comparing readers at different developmental ages.

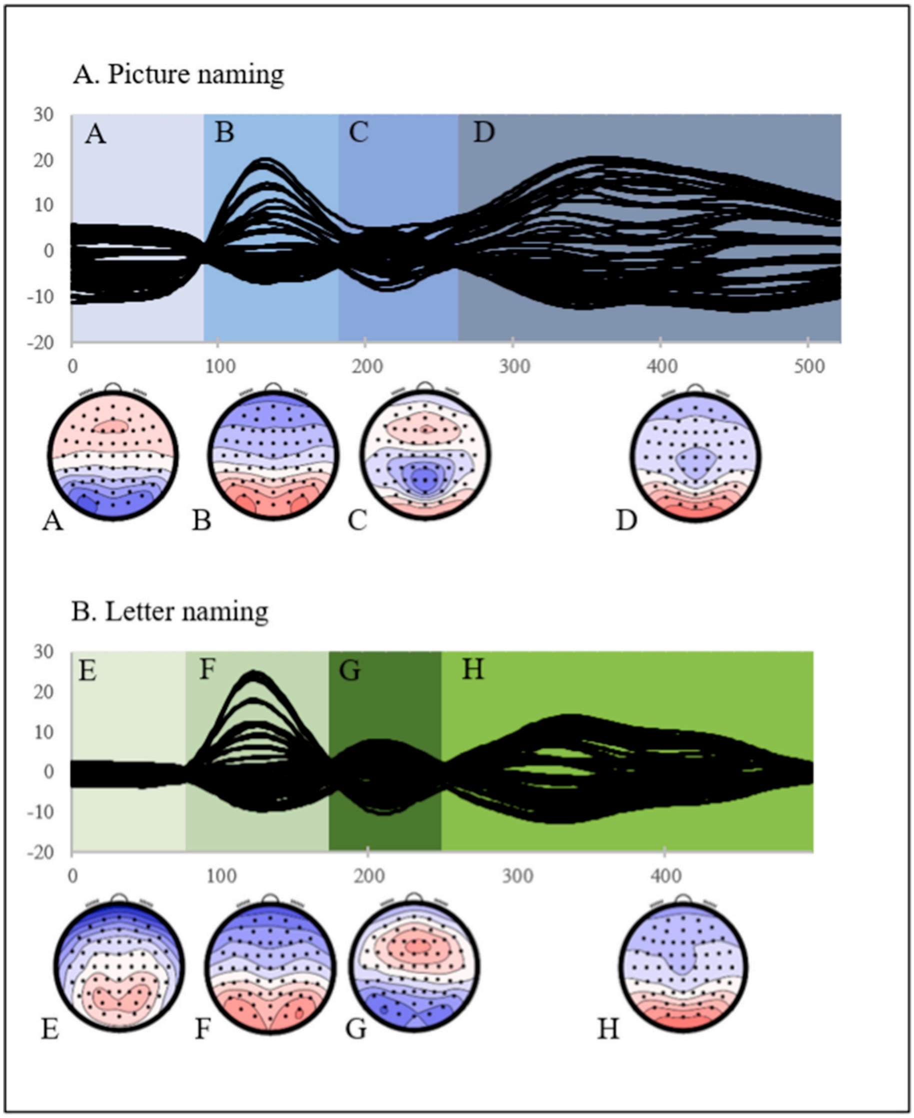

Fig. 2. Group-averaged ERPs (64 electrodes) for picture naming (panel A) from stimulus onset to 515 ms and for letter naming from stimulus onset to 490 ms. The temporal distribution of the topographic maps was revealed by the microstates analysis with 92% of total explained variance for picture naming and 97% for letter naming. Template maps for the eight stable microstates are displayed with positive values in red and negative values in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

older children in our older group present a topography similar to the one found in adults in previous studies (Eberhard-Moscicka et al., 2016). The P2 component in letter naming is usually associated with phonological code retrieval (Madec et al., 2012; Rey et al., 2009). For this component, all participants showed parietal positivity as well as frontal and central negativity. However, as children age, they show reduced activation of all sites and specific bi-hemispheric parietal activation.

Taken together, the results on letter naming indicate that age and reading level have similar effects on amplitudes but that age only predicts topographic variance. Overall, younger children with a poor reading level show greater neural recruitment during letter naming, suggesting that letter naming is less automatized and more difficult for them than for children at the same age with a better reading level (Durston and Casey, 2006). This outcome aligns with the previous behavioral literature suggesting that letter processing automaticity develops during the first years in which children learn to read (Papadopoulos et al., 2016; Savage et al., 2007; Scarborough, 1998; van den Bos et al., 2002). It should be noted that changes in EEG topographies are typically interpreted as reflecting changes in the underlying source configuration of the scalp potentials. The present results advocate for a more nuanced interpretation. Indeed, the type of analysis used in the present study does not allow to state whether the topographic change is observed because of shifts in processing stages due to differences in processing speed between younger and older children or whether it is observed because of changes in the source configuration of the scalp potentials.

4.2. *Picture processing*

Differently from letter naming, age and reading level were associated with specific time-windows in picture naming. On ERP amplitudes, the results of the present study revealed independent age and reading level effects on the picture naming time course, in line with results reported in Cohen et al. (2018). Crucially for our purpose here, reading level is specifically related to amplitude differences in the N1 time-interval, whereas both reading level and age are related to amplitudes in the late P2 time interval. This result advocates for a larger and earlier effect of reading level than age in picture naming. In picture naming, N1 is usually associated with lexical concept retrieval, and P2 with lemma selection or lexico-semantic retrieval (Aristei et al., 2011; Costa et al., 2009; Indefrey, 2011; Maess et al., 2012; Laganaro et al., 2012). Taken together, the results on ERP amplitudes suggest that age is specifically related to lexical-semantic processes and reading level is already related to picture naming during visuo-conceptual processing stages. The close ties between naming and reading were previously reported with the implication of the VWFA in both tasks (Dehaene-Lambertz et al., 2018;

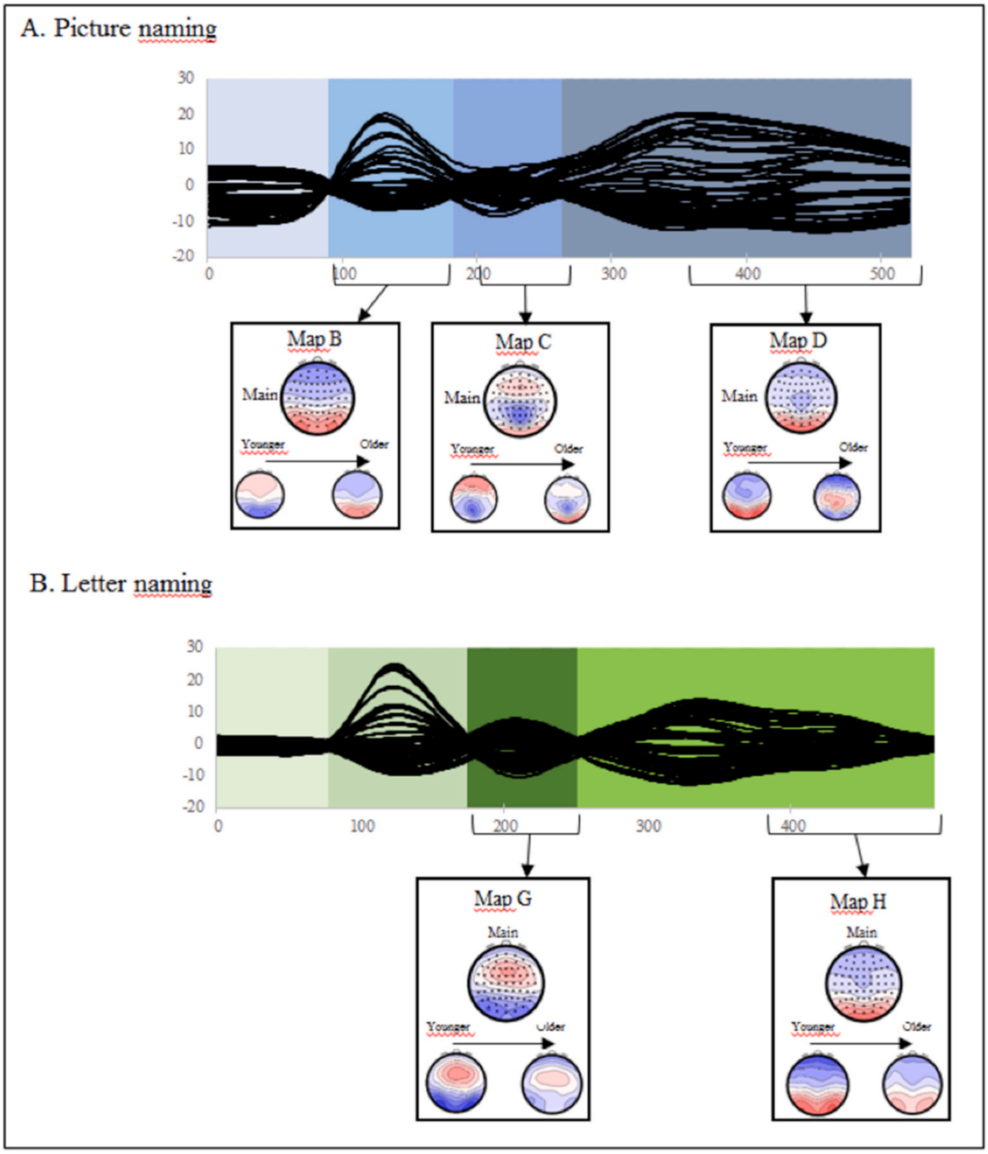

Fig. 3. Effects of age and reading level on microstates for picture and letter naming tasks from stimulus onset to 515 ms. Periods of significant modulation of microstates by age are indicated with the brackets. As shown in Table 2 reading level did not predict the topographic variance beyond age. Positive values are shown in red and negative values in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Vogel et al., 2012, 2014). Of importance, the VWFA literature stated on the independence of age and reading level, as illiterate adults do not show activation in the VWFA when confronted to print (Dehaene et al., 2015). Our results suggest that the N1 component in picture naming is specifically linking reading acquisition and naming performance, independently of age. The N1 component has previously been associated with the activation of the VWFA (Brem et al., 2006; Proverbio et al., 2006). Moreover, it has been shown that the VWFA develops by recruiting neuronal areas previously dedicated to object recognition (Dehaene-Lambertz et al., 2018; McClandiss et al., 2003). Thus, modulations of the N1 component during picture naming seem to be related to changes in the activation of the VWFA with reading acquisition.

A further step was taken with the topographic analysis. First, it revealed that only age was accounting for the topographic variance during naming for both letters and pictures. Second, it allowed a better understanding of unexpected effects on the amplitude analysis. As described above, the amplitude analysis revealed higher amplitudes for N1 and P2 among advanced readers. This pattern was unexpected as older participants usually show lower amplitudes. Lower amplitudes could be interpreted as the result of higher automaticity during a task (Durston and Casey, 2006), or as the result of anatomical changes at scalp as the skull grows. In the present study, the topographic analysis allowed a better understanding of this difference in amplitudes by revealing that older children display a different topography during the N1 and P2 components compared to younger children. We observed a complete shift from frontal activation in younger children to parietal positivity in older children in the N1 time-interval. For each of the three topographic maps younger and older children display topographies which have been reported in shifted time-windows in younger and older children (see Laganaro et al., 2015), compatible with faster processing speed in older children or with processes closer to adults in this group. We observed a similar shift in the P2 time-interval, with again different topographies for younger and older children. Interestingly, the microstate for older children at the end of P2 time-interval is similar to the microstate usually associated with pre-articulatory processes (see for instance Laganaro, 2017; Jouen, Lancheros & Laganaro, 2020). This suggests that the difference in microstates here is related to the fact that older children are faster at naming pictures than younger children are.

Younger children display the same topography during the entire P2 time-interval whereas older children display two different topographies in this time-interval. As mentioned above, change in EEG topographies is usually interpreted as reflecting changes in the underlying source configuration of the scalp potentials. However, the present results do not allow to disentangle between this standard interpretation and an interpretation taking into account the difference in processing speed among children. The topographic change observed here could reflect changes in the underlying source configuration of the scalp potentials or could reflect similar topographies but differently distributed across the time-course due to a faster processing in older children.

In summary, the results for picture naming suggest that picture processing is tied to reading efficiency in a specific time-window, namely the N1 component. The large effect of reading level on N1 indicates specific modulation of the visuo-conceptual processing stages as reading efficiency develops, independent of age. This specific reading level effect on N1 suggests that N1 might reflect the activation of the VWFA during picture naming.

4.3. Limitations

The present findings must be considered in light of certain limitations. First, our interpretation of the results is based on models of the dynamics of picture- and letter-naming processing. However, these dynamics are estimated for adults; as the children in this study have longer reaction times, the processing stages may need to be rescaled (Roelofs and Shitova, 2016). For picture naming, adults are expected to complete visual-conceptual (during the first 190 ms), lexical-semantic (from about 190 to 270 ms), lexical-phonological (from about 270 to 450 ms) and phonetic encoding (from about 450 to 600 ms; Indefrey, 2011). In our sample, the average reaction time for picture naming is 891 ms. Consequently, the dynamics of the processing of phonological code retrieval take place beyond the signal we analyzed (from about 550 to 700 ms). This long response times prevents us from discussing the "later" stages of the picture naming task. For letter naming, adults usually complete visual analysis during the first 150 ms, identify letters around 170 ms, and access phonological code around 250 ms after stimulus presentation (Madec et al., 2012; Rey et al., 2009). In our sample, the average reaction time for letter naming is 645 ms. Rescaling the dynamics of the processing would result in the N1 being delayed to around 200 ms and P2 being delayed to around 350 ms after stimulus onset. This would enable discussion of the phonological processes involved in letter naming.

Second, our data are cross-sectional. We do not know if children identified as beginning reader in our study will still show a "beginning" reader topography for N1 during a picture naming task one or two years later or if they will progressively shift toward the profile corresponding to his/her age. Future studies should follow children from grades 2–5 and record EEG data on naming and reading processes. This would be one way to understand how age-related changes at the brain level interact (or not) with changes related to reading efficiency development.

5. Conclusion

Our results suggest that the development of reading fluency has an effect on naming tasks, confirming the close ties between reading and naming, The effect of reading level can be distinguished from the effect of age, advocating for a relative independence of age and reading level. Of importance, reading level affects early components in picture naming whereas age affects time-intervals beyond the P1/N1 complex. Picture and letter naming are not similarly modulated by reading level and age. Our results suggest that picture naming continues to undergo specific changes throughout reading acquisition independently of age on visuo-conceptual and lexico-semantic processing stages. By contrast, letter naming is modulated by age on its entire time-course with a reading level effect only in the youngest participants.

Author contribution

Marjolaine Cohen: Conceptualization, Methodology, Investigation-Formal analysis, Writing, Writing – original draft. Gwendoline Mahé; : Investigation, Writing, Writing – review & editing. Pascal Zesiger: Conceptualization, Methodology, Writing, Writing – review & editing, Supervision, Project administration, Funding acquisition. Marina Laganaro: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision - Project administration, Funding acquisition

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