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Word-related N170 responses to implicit and explicit reading tasks in neoliterate adults

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Abstract

The present study addresses word recognition automaticity in Spanish-speaking adults who are neoliterate by assessing the event-related potential N170 for word stimuli. Participants engaged in two reading conditions that vary the degree of attention required for linguistic components of reading: (a) an implicit reading task, in which they detected immediate repetitions of words and symbols (one-back paradigm); (b) an explicit reading task, in which they determined if pairs of visual-auditory words matched (reading verification task). Results were compared to those of a group of people who learned to read in childhood. N170 amplitudes on left and right occipito-temporal regions were registered for each condition. A left-lateralization of N170 for word stimuli was considered as an index of word reading automaticity. No left-lateralized N170 was found for the neoliterate group in either condition. In addition, N170 amplitude for words was larger on the right than the left occipito-temporal region for the reading verification task. Participants from the comparison group showed left-lateralized N170 amplitude for words in both conditions. Findings suggest that the neoliterate group investigated here had not yet acquired automaticity of word recognition, but could be showing evidence of word familiarization.

Keywords

adult literacy, automaticity, ERP, N170

Word recognition automaticity – that is, the ability to recognize words without conscious processing or engagement – represents a major challenge for reading acquisition in adulthood (Abadzi, 1996, 2003a, 2003b, 2012). Expert readers' cognitive resources are mostly allocated to reading comprehension, rather than to subskills such as grapheme-phoneme conversion (LaBerge & Samuels, 1974; Samuels, 2004). Adults who are illiterate and undergo formal reading instruction tend to read slowly and with low accuracy, which impacts their ability to comprehend written language (Abadzi, 2003b). Such individuals are referred to as "neoliterates", that is, *new readers*.

N170 and reading automaticity

The Event-Related Potential (ERP) technique can provide insights into the rapid sub-processes involved in reading, and therefore can be used to assess the neural underpinnings of slow and halting reading reported in adults who learn to read in adulthood. One ERP component that indexes fast visual recognition is the N170, a negative voltage deflection occurring around 170 milliseconds after visual stimulus presentation (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). Two main characteristics of the N170 are its apparent capability of reflecting (a) visual expertise, because of its larger amplitude for familiar compared to unfamiliar stimuli (Gauthier, Curran, Curby, & Collins, 2003; Tanaka & Curran, 2001) and (b) automaticity of the visual recognition process, since it is elicited in response to visual stimuli even when participants are not consciously aware of seeing them (Bentin et al., 1999; Brem et al., 2005; Maurer, Brandeis, & McCandliss, 2005; Maurer, Brem, Bucher, & Brandeis, 2005; Maurer & McCandliss, 2007; Maurer et al., 2011).

N170 elicitation is possible through the presentation of various kinds of visual stimuli, especially faces (e.g., Nelson, 2001). Although object and face recognition elicit bilateral or right lateralized activation in the occipito-temporal region, the N170 activation associated with written words tends to be left-lateralized in expert readers (Bentin et al., 1999). This is evident in both transparent (Maurer, Brem, et al., 2005) and opaque (Maurer, Brandeis, et al., 2005) alphabetic scripts, as well as logographic scripts (Maurer, Zevin, & McCandliss, 2008). According to the Phonological Mapping Hypothesis (e.g., Maurer & McCandliss, 2007), left specialization for word stimuli reflects automatic connections between left hemisphere regions associated with phonological processing, and occipito-temporal regions related to visual recognition (of print, in this case). In other words, the constant pairing of print and language during literacy acquisition results in a linguistically-modulated response from visual association areas. The N170 is therefore assumed to reflect word recognition automaticity, since expert readers do not need to be consciously aware that they are reading for N170 left lateralization to occur (Maurer & McCandliss, 2007). Generators of the reading-related N170 have been localized to the left fusiform gyrus, in left occipito-temporal cortex (Cohen et al., 2000; Rossion, Joyce, Cottrell, & Tarr, 2003)—referred to as

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the Visual Word Form Area (VWFA; Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002).

Development of reading-related N170

Studies have shown that learning to read transforms visual processing, even when literacy is acquired in adulthood, as evidenced by positive correlations between reading scores and left-lateralization of N170 for word stimuli in neoliterates (Botzmann & Rüsseler, 2013; Dehaene, Cohen, Morais, & Kolinsky, 2015; Pegado et al., 2014). However, the left-lateralization of the N170 for visual words tends to be less clear in neoliterate participants compared to literate participants (Pegado et al., 2014). Also, the intensity of training received by adults in literacy classes modulates the left-lateralization of N170 (Botzman & Rüsseler, 2013), in the sense that participants that received more training show larger N170 amplitudes over the left hemisphere post training. In addition, the magnitude of training effects has a positive correlation with initial reading scores; hence, the better participants score before training, the larger the N170 amplitude seen over the left hemisphere (Botzman & Rüsseler, 2013).

The development of a left-lateralized N170 for visual words has been explored in a series of longitudinal studies involving children from pre-literacy until fifth grade. Pre-literate children carried out a one-back task requiring the detection of immediate repetitions of visual stimuli presented in blocks of words and symbols (Maurer, Brem, et al., 2015). Children were reassessed in second grade (Maurer et al., 2006), and fifth grade (Maurer et al., 2011), and their data were compared to a group of adult expert readers (Maurer, Brem, et al., 2005; Maurer et al., 2006). The course of N170 specialization for written stimuli followed an inverted U-shape: N170 amplitude differences between words and symbols were not apparent in pre-literate children; were discretely larger for words than symbols in pre-literate children who had high letter knowledge; were considerably larger for words than symbols in second-graders; and this difference was significant but reduced in fifth-graders and adults. These changes over time appear to result from widespread neural network modifications during initial word specialization. This makes differences between words and symbols more evident in early developmental stages, but due to acquired efficiency and fine-tuning, differences between stimuli become less apparent as development and specialization proceed over time.

N170 latency also shifts throughout reading acquisition. Peak latency is latest, around 210 milliseconds post-stimulus presentation, in second grade, and is reduced to 170 milliseconds by adulthood (Maurer et al., 2006). The latency shift over time reflects increasingly rapid information processing, as reading networks are progressively consolidated through developmental processes of synaptic pruning and tuning.

Topographically, N170 differentiation between words and symbols has been demonstrated in the right hemisphere for pre-literate children with high letter knowledge (Maurer, Brem, et al., 2005). The same distinction was also observed bilaterally for second-graders (Maurer et al., 2006); however, only the left hemisphere showed differential responses to words versus symbols in fifth-graders (Maurer et al., 2011) and in adults (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Maurer et al., 2008). Right-hemisphere lateralization of the N170 in pre-literate children may indicate initial specialization, but is likely related to visual familiarity effects rather than fast, automatic, linguistic processes (Maurer, Brem, et al., 2005). Bilateral activation in second-graders suggests engagement of wider circuitry including, but not limited to, language regions; such multiple activations, including bilateral occipito-temporal areas, could indicate an absence of fine-tuned recognition processes. N170 left-lateralization in fifth-graders suggests that connections between print and language have been automatized by this age, reflecting consolidation of reading networks. Taken in aggregate, these observations were interpreted by Maurer and McCandliss (2007) as support for the Phonological Mapping Hypothesis. As sensitivity to words increases in left occipito-temporal regions and decreases in right occipito-temporal regions during reading acquisition, it is assumed that fine-tuned linguistic associations in the visual areas emerge. On this view, it is the linguistic processing of visual words (specifically phonological linguistic processes) that drives left lateralization of the reading-related N170 (Maurer & McCandliss, 2007).

Adult literacy

Visual familiarity effects in early reading, like those seen in pre-literate children with high letter knowledge, have also been observed in adult participants experimentally exposed to word-like stimuli from artificial orthographies (Maurer, Blau, Yoncheva, & McCandliss, 2010). Participants showed right occipito-temporal specialization for artificial words, in contrast with meaningless symbols, on a one-back task. This suggests that short training periods might not provide enough exposure to develop fast, automatic, language-related specialization for words, but even minimal exposure to language-like symbol sets can create visual familiarity effects. Since this pattern is similar to that observed in children, it seems unlikely that the laterality shift underpinning childhood literacy acquisition is purely maturationally driven (Maurer et al., 2010).

Yoncheva, Blau, Maurer, and McCandliss (2010) also evaluated adults' N170 responses on a task involving conscious reading of a novel script (a reading verification task, requiring participants to evaluate spoken and written word pairs for match or mismatch). Participants trained using grapheme-to-phoneme conversion methods showed left occipito-temporal responses to the reading verification task, in which "words" in the novel script were associated with larger N170 amplitudes over the left hemisphere. This lateralization effect differs from the previous experiment's findings, showing that even though the short training failed to elicit a fast and automatic process in the one-back task (Maurer et al., 2010), there is evidence of emergent specialization when readers of a novel script are forced to read consciously.

If N170 left lateralization develops during reading instruction (Maurer, Brandeis, et al., 2005; Maurer, Brem, et al., 2005; Maurer et al., 2006), it is possible that progression towards left-lateralized N170 effects could be observed in people learning to read in adulthood. Given the difficulties with word recognition automaticity that behavioral studies have shown in this population, the N170 component could be used to index acquisition of reading automaticity in adult literacy training. To develop this approach, however, it is necessary to establish the extent to which adults who finish initial reading training can show evidence of reading automaticity, for example on one-back and reading verification tasks.

In this study, we evaluated N170 specialization to visual words in adults who are neoliterate compared to those who are literate. We expected to find visual specialization for words in the literate group evidenced by a left-lateralized N170 for word stimuli. This was expected since people who learn to read and write in childhood have usually had constant print exposure, reading experience, and many years of training. Conversely, we expected to find less visual specialization for words in the neoliterate group, evidenced by a lack of left-lateralization of the N170. This was expected since adult neoliterates tend to read slowly and with much effort, and since they tend to have less print exposure and reading experience than people who learned to read in childhood.

N170 specialization was assessed in this study through the presentation of two tasks that recruit different levels of linguistic processing: a task that does not necessarily involve linguistic processing, that is, one-back word matching; and a task that involves linguistic processing, that is, reading verification. The rationale for this approach comes from the findings of Yoncheva et al. (2010) who reported that participants trained on a new script showed left-lateralized N170 responses when explicitly asked to match visual words with spoken words, but not when asked to simply look at the words. We assumed our participants are learning a new script—like Yoncheva's participants—since they had not received any formal training in literacy until adulthood. We evaluated whether a left-lateralized N170 could be elicited in our participants through the use of a task that forces linguistic processing (reading verification), as opposed to a task that does not require such processing (one-back). Such findings would indicate that, although not automatic, visual specialization is taking place, but conscious attention is still required for this to be applied in linguistic processing.

Table 1. Demographic information and inclusion criteria measurements.

	Neoliterate ($n = 8$)	Literate ($n = 8$)
Handedness	8 right-handed	8 right-handed
Gender	4 males, 4 females	5 males, 3 females
Age (in years)	Mean = 39.88; *SD* = 8.6	Mean = 46.00; *SD* = 9.00
Age of literacy acquisition (in years)	After 30	Between 5 and 7
Time living in the US (in years)	Mean = 15.29; *SD* = 2.43	Mean = 12.63; *SD* = 14.48
Education	Adult literacy (first grade)	5 high school, 3 first semester of college
Language dominance (self-reported)	Spanish	Spanish
English proficiency: self-reported, scale from 0 (non-proficient) to 3 (proficient)	Mean = 0.25; *SD* = 0.46	Mean = 1.38; *SD* = 0.92
Word reading-fluent (raw 0–76)	Mean = 21.88; *SD* = 4.61	Mean = 74.75; *SD* = 1.75
Word reading-effortful (raw 0–76)	Mean = 58.38; *SD* = 10.66	Mean = 74.75; *SD* = 1.75
Phonological awareness (raw 0–30)	Mean = 15.75; *SD* = 1.75	Mean = 26.38; *SD* = 2.50
Spatial working memory (raw 0–88)	Mean = 11.88; *SD* = 2.85	Mean = 11.88; *SD* = 1.96

SD = standard deviation.

Methods

Participants

For this study, 20 right-handed adult Spanish-speaking immigrants from Latin America, living in New York City, were recruited. All completed a background questionnaire and reported no history of learning disability, language disorder, or brain damage. Four participants were excluded from the study, for reasons detailed below, leaving a sample of 16 participants. Although these 16 participants had been living in the United States for at least 13.87 years on average ($SD = 10.5$), their self-reported English knowledge was limited. All participants reported that they primarily use Spanish in their daily lives since they live in Spanish-speaking neighborhoods where they are not required to speak English; however, the urban environment in which the participants live is English-dominant.

The sample was classified into two groups according to whether they had learned to read in adulthood (8 people, comprising the neoliterate group), or childhood (8 people, comprising the literate group). All participants from the neoliterate group reported having left school in childhood for social reasons: parents' death (1); lack of schools in neighborhood (1); parents did not feel it was necessary to send children to school (3); other family reasons (3). At the time of study, participants from the neoliterate group were close to finishing a 2-year literacy-training program in Spanish (their native language) in New York City. Participants from the literate group reported completing high school, but not college. Table 1 provides a summary of demographics and inclusion criteria.

Participants were tested on word recognition, phonological awareness, and spatial working memory. We required that participants who learned to read in adulthood demonstrate their ability to read words, in order to be considered neoliterates. For this reason, they were tested on a modified version of the Woodcock-Muñoz letter and word recognition subtest (Muñoz-Sandoval, Woodcock, McGrew, & Mather, 2005). The modification consisted of obtaining two scores per participant: one score for fluent word reading (as suggested by the original test), and one score for effortful reading, in which participants were allowed to take their own time to read as many words as they could. Mean fluent word reading scores placed participants from the neoliterate group at first-grade level, while mean effortful reading scores placed them at seventh-grade level. To assess phonological awareness, all participants completed the *Prueba de la Evaluación del Conocimiento Fonológico* (Test of Phonological Awareness, Ramos Sánchez & Cuadrado Gordillo, 2006). This was used to exclude individuals at risk for reading disability, specifically those from the literate group, since there is a correlation between poor phonological awareness and dyslexia diagnosis (Lachmann, Berti, Kujala, & Schröger, 2005; Rey, De Martino, Espesser, & Habib, 2002; Spinelli et al., 2009). Working memory was assessed with the Spatial Span subtest from the Wechsler Memory Scale III (Wechsler, 1997). Spatial working memory was chosen over digit span to minimize effects of schooling or literacy on performance.

Two participants from the experimental group were excluded due to low scores on the word recognition test, indicating they were still functionally illiterate despite completing the literacy training program. One participant from the comparison group was excluded due to low phonological awareness, and another one for technical difficulties during data collection. All data reported here are from the remaining 8 participants per group (total $n = 16$).

Neurophysiological experiments

Two tasks were conducted while continuous high-density EEG data were recorded: a one-back task and a reading verification task. EEG

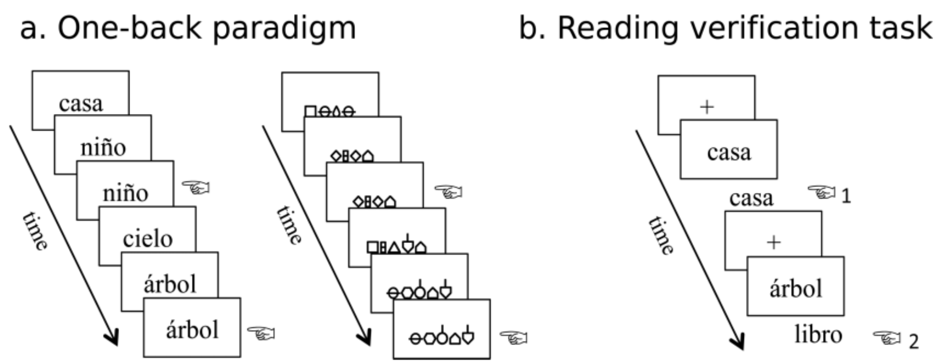

Figure 1. Neurophysiological tasks.

data were collected using a 128-channel, high density HydroCel EEG recording system (NetAmps300, Electrical Geodesics Inc., Eugene, OR). The HydroCel technology refers to the use of an electrolyte solution taken up by sponges that surround the carbon fiber silver chloride electrodes, to facilitate continuous electrical connectivity during recording. The electrodes are connected to one another with threaded elastomer that creates a geodesic arrangement, holding all electrodes in stable positions relative to one another. This system allows the rapid and accurate application of large numbers of electrodes. The electrode net is connected to a high-input impedance amplifier that accepts impedance values up to 100KΩ, but for this study individual sensors were adjusted to maintain impedances under 40kΩ (Ferree, Luu, Russell, & Tucker, 2001). The amplified analog voltages (recorded with 0.1–100 Hz bandpass) were digitized at 500 Hz, and all electrodes were referenced to the vertex during recording. Sensors were placed above and below the eyes and outer canthi to identify eye movement artifacts.

The tasks carried out during EEG data collection were as follows. For the *one-back task*, participants were asked to watch blocks of words and symbols, and to press a button with their preferred hand whenever an immediate repetition occurred (17% of the time). In total, 144 high-frequency words and 144 symbol strings were presented in 8 blocks of 36 stimuli, in the middle of a white screen, in black font at a visual angle of 1.6 to 3.6 degrees. Block presentation alternated between word blocks and symbol blocks, with the first block always being words. Stimuli were presented for 700 ms, followed by a randomly varied inter-stimulus interval (mean 500 ms, range 300–700 ms). This experiment was presented twice, for a total of 288 trials for each condition. Word stimuli were obtained from the Spanish word frequency and orthographic neighborhood database (Pérez, Alameda, & Cuetos-Vega, 2003). These were nouns that contained 4–6 letters (mean $= 4.833$; $SD = 0.69$), and were of high lexical frequency (mean $= 121$ per million instances found in text; $SD = 94.00$). Symbol stimuli were created based on the shapes developed by Maurer, Brandeis, and McCandliss (2005), and Maurer, Brem, et al. (2005). They were first designed in Adobe Photoshop image processing software and then transferred to FontCreator (High-Logic, 2006), software that converts small images into fonts. Features of symbol stimuli were matched to the characteristics of real letters in order to maintain the same print space from both stimulus types. Behavioral responses (accuracy and reaction time) to words and symbols were collected while recording continuous EEG.

For the *reading verification task*, participants were asked to determine whether or not a written and an auditory word, presented serially, matched. The visual word was first presented in the middle of the screen, and the auditory word was presented 700 ms later. Participants were instructed to press one button with their preferred hand if the words matched, and a different button if the words did not match. Again, a total of 144 written words paired with 144 auditory words were presented in 4 blocks, each consisting of 36 trials. The word stimuli had the same characteristics as the words from the one-back task. The visual stimuli were presented in the middle of a white screen, in black font at a visual angle of 1.6 to 3.6 degrees. The auditory stimuli were presented binaurally (through earphones) at 60 dB SPL, specified on the stimulus presentation software. This experiment was presented twice, for a total of 288 trials. Behavioral responses (accuracy and reaction time) to words that matched and did not match were collected while recording continuous EEG. Figure 1 depicts a graphical timeline of the neurophysiological experiments.

Experimental procedure

All informed consent and experimental procedures were carried out with approval of the College's Institutional Review Board. Participants were assessed individually. After signing the consent form, each participant was interviewed on a series of background questions, including their English language proficiency, educational experience, and general information about literacy (see Table 1 above). Each participant then carried out the assessments of word recognition, phonological awareness, and working memory. An explanation of the neurophysiological task was given, and each participant performed a practice run. The procedure for net placement was conducted (head measurement, net in electrolyte solution, positioning of net on participant's scalp, measurement of impedance). Then the experimental tasks were carried out while high density EEG was captured: first the one-back task, and then the reading verification task. The order of conditions was not counterbalanced since we wanted to capture automatic (unconscious) responses to the one-back task, and presenting the reading verification task first may have biased participants toward an overt reading response rather than implicit processing.

Data processing

Initial processing was conducted using Netstation 4.5.7 software. EEG data were band pass filtered at .3 to 30hz (Passband Gain: 99.0% (−0.1 dB); Stopband Gain: 1.0% (−40.0 dB); Rolloff: 2.00 Hz) and segmented by condition, 200 milliseconds pre-stimulus to 600 milliseconds post-stimulus. Eye blinks and vertical eye

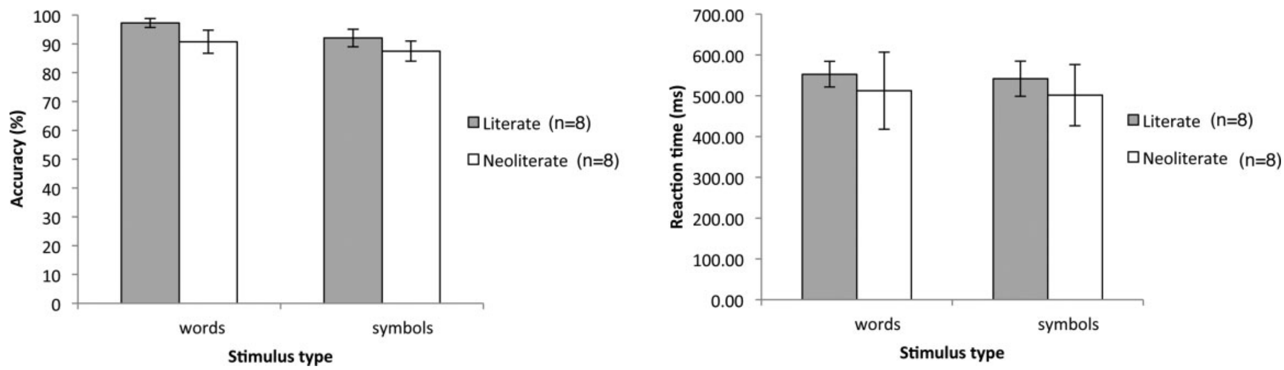

Figure 2. Behavioral results: one-back task.

movements were examined by inspecting data recorded from electrodes located below and above the eyes (channels 8, 126, 25, 127). Horizontal eye movements were measured using channels 125 and 128, located at positions to the left and right of the eyes. Artifacts were automatically detected and manually verified for exclusion from additional analysis (the criterion for identifying a bad channel was a voltage deflection >200 microvolts; identification of eyeblinks required a deflection of > 140 microvolts over relevant channels; and the criterion for identifying eye movements was a voltage deflection >55 microvolts over relevant channels). For every channel, 50% or greater bad segments was used as the criterion for marking the channel bad; for every segment, greater than 20 bad channels was used as a criterion for marking the segment bad. Channels marked bad were removed and replaced by spherical spline interpolation based on data from surrounding channels. Segments marked bad were removed from analysis.

Remaining usable trials were counted and compared between groups for each condition. After artifact rejection, the average usable trials for the one-back task for the comparison group was 171.22 for words ($SD = 75.2$), and 168.44 for symbols ($SD = 55.68$). For the experimental group, average usable trials were 168.00 for words ($SD = 19.08$), and 186.13 for symbols ($SD = 32.47$). An independent sample t test showed no statistical significant difference in the numbers of usable trials between the groups for words ($t = 0.117, p = .91$) or symbols ($t = -0.786, p = .44$). For the reading verification task, average usable trials for the comparison group was 196.22 for words that matched ($SD = 70.23$), and 206.44 for words that did not match ($SD = 65.33$). For the experimental group, average usable trials left was 225.63 for words that matched ($SD = 72.73$), and 218.00 for words that did not match ($SD = 76.03$). An independent sample t test shows no statistical significant difference in numbers of usable trials between groups for words that matched ($t = -0.847, p = .41$) and words that did not match ($t = -0.337$, $p = .74$).

Noisy channels were marked as bad and interpolated using spherical spline modeling (see Perrin, Pernier, Bertrand, & Echallier, 1989), based on recorded data from surrounding sensors. For the one-back task, bad channel replacement for the comparison group was 9.56 on average ($SD = 5.48$), and for the experimental group 13.50 ($SD = 13.28$). For the reading verification task, bad channel replacement for the comparison group was 4.89 on average ($SD = 4.73$), and for the experimental group 2.75 ($SD = 3.24$). The difference was not statistically significant between groups on an independent sample t test ($t = -0.309$, $p = .761$).

Table 2. Behavioral descriptive statistics: one-back task.

	Literate ($n = 8$)		Neoliterate ($n = 8$)	
	M	*SD*	*M*	*SD*
One-back paradigm				
Accuracy (%)				
words	97.24	1.54	90.74	4.00
symbols	92.04	3.06	87.48	3.52
Reaction time (ms)				
words	552.63	31.32	512.23	94.45
symbols	541.63	43.08	501.38	75.11

M = mean; *SD* = standard deviation.

Recorded data were re-referenced offline to the average reference to eliminate the influence of an arbitrary recording reference channel. Then, the averaged waveforms were baseline-corrected (using the 200 ms pre-stimulus period) to control for drift and to minimize the effects of background noise. Finally, two montages were applied to the data in order to examine the different responses by electrode in specific areas of the scalp. The selected montages corresponded to left and right occipito-temporal regions. RPLAB was used to generate peak and mean amplitude databases for inferential statistics, and also to generate topographical plots (Lopez-Calderon & Luck, 2014)

Data analysis

Repeated Measures Mixed Analyses of Variance (ANOVAs) were conducted to establish significance of differences between groups on each variable of interest. Partial eta squared (η_p^2) was applied as a measure of effect size, with values of 0.01–0.05 representing small effects, 0.06–0.13 representing medium effects, and ≥ 0.14 representing large effects (Cohen, 1998).

Results

Behavioral results

One-back task behavioral results. Two separate ANOVAs were conducted to evaluate participants' performance in terms of *accuracy* and *reaction time*. Accuracy was evaluated by calculating the mean percentage of correct responses to each task; for the one-back task, this means the percentage of repeated stimuli that were correctly identified via button press. Reaction time was calculated by

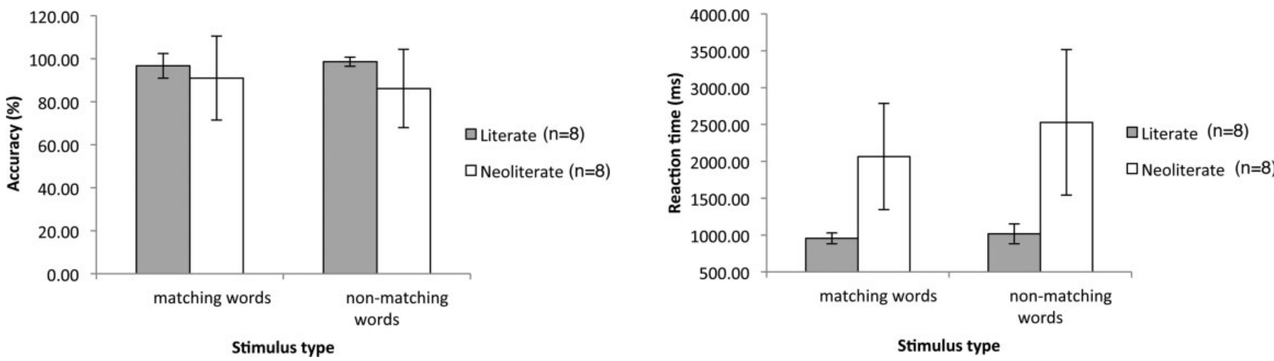

Figure 3. Behavioral results: reading verification task.

Table 3. Behavioral descriptive statistics: reading verification task.

	Literate (n = 8)		Neoliterate (n = 8)	
	M	*SD*	*M*	*SD*
Reading verification task				
Accuracy (%)				
matching words	96.69	5.71	90.98	19.50
non-matching words	98.60	2.12	86.13	18.19
Reaction time (ms)				
matching words	955.00	72.82	2064.88	719.52
non-matching words	1016.88	134.85	2528.32	987.56

M = mean; *SD* = standard deviation.

averaging the time (in milliseconds) that participants took to press the button to indicate a response (identification of a repeated stimulus) on trials where a button press was required, and only for the trials that were responded to correctly. Graphical representations of mean accuracy and reaction times are provided in Figure 2. Table 2 provides the corresponding descriptive statistics.

A two-way mixed ANOVA was used to evaluate the dependent variable *accuracy*, contrasting the between-subjects factors *groups* (literate vs. neoliterate) and *stimuli* (words vs. symbols). The results showed a significant main effect of stimuli with a large effect size, F (1, 14) = 22.258, $p < .001$, $\eta^2_p = 0.614$. Specifically, participants performed more accurately in response to word stimuli than symbol stimuli, regardless of group. In addition, there was a significant main effect of group, F (1, 14) = 18.004, p = .001, $\eta^2_p = 0.563$, indicating that regardless of stimuli, the literate group performed more accurately than the neoliterate group. There was no significant interaction between group and stimuli.

A two-way mixed ANOVA for the dependent variable *reaction time,* with between-subjects factor *groups* (literate vs. neoliterate) and within-subjects factor *stimuli* (words vs. symbols), revealed a significant stimuli × group interaction with a large effect size, F (1, 14) = 9.963, p = .007, η^2_p = .416). This reflects more rapid responses from the neoliterate group to symbols than words, while participants from the literate group responded faster to words than symbols.

Reading verification task behavioral results. Two separate mixed ANOVAs were conducted to evaluate participants' *accuracy* and *reaction time* on the reading verification task. Graphical representations of mean accuracy and reaction times are provided in Figure 3. Table 3 provides the corresponding descriptive statistics.

A two-way mixed ANOVA for the dependent variable *accuracy*, between-subjects factor *groups* (literate vs. neoliterate), and within-subjects factor *stimuli* (matching words vs. non-matching words) revealed no statistically significant main effects or interactions. However, there was a significant main effect of stimuli for a two-way mixed ANOVA evaluating the dependent variable *reaction time,* with between-subjects factor *groups* (literate vs. neoliterate) and within-subjects factor *stimuli* (matching words vs. non-matching words), F (1, 14) = 5.527, p = .034, η^2_p = 0.283. This indicates that non-matching words were harder to detect for both groups. In addition, there was a main effect for group, F (1, 14) = 20.071, p = .001, η^2_p = 0.607. This indicates that, regardless of stimuli, participants from the literate group responded faster overall to the reading verification task, compared to participants from the neoliterate group.

Neurophysiological results

One-back task. A graphic representation of the neurophysiological results for the one back task is provided in Figure 4. The figure shows that words and symbols elicited the ERP component N170 in both groups, and both regions on the one-back task (seen as a negative voltage deflection between 150 and 250 milliseconds).

A three-way mixed ANOVA was used to evaluate the dependent variable *peak amplitude*. This was calculated by obtaining the value of the minimum data point for a specific time window (140–200 ms, since N170 fell on this range on our sample), for each participant, on each stimulus type. Peak amplitude was selected as an outcome measure since the N170 peaks and latency shifts were well-defined.

The three-way ANOVA contrasted between-subjects factor *group* (literate vs. neoliterate) and within-subjects factors *region* (left occipito-temporal vs. right occipito-temporal) and *stimulus* (symbols vs. words). There was a significant group × region × stimulus interaction with a large effect size, F (1,14) = 8.350, p = .012, η^2_p = 0.374. In order to clarify this three-way interaction, separate two-way (region × stimuli) ANOVAs were conducted on each group separately. For the literate group, the two-way ANOVA revealed a significant region × stimulus interaction, F (1, 7) = 9.911, p = .016, η^2_p = 0.586, reflecting a larger negative amplitude in response to words than to symbols over the left occipito-temporal region. The opposite effect was found over the right occipito-temporal region, where responses to symbols had larger negative amplitudes than to words. By contrast, no significant region × stimulus interaction, F (1, 7) = 0.522, p = .493, main effect for region, F (1,7) = 3.821, p = .92, or main effect for stimulus, F (1, 7) = 0.173, p = .690, was found for the neoliterate group. This means

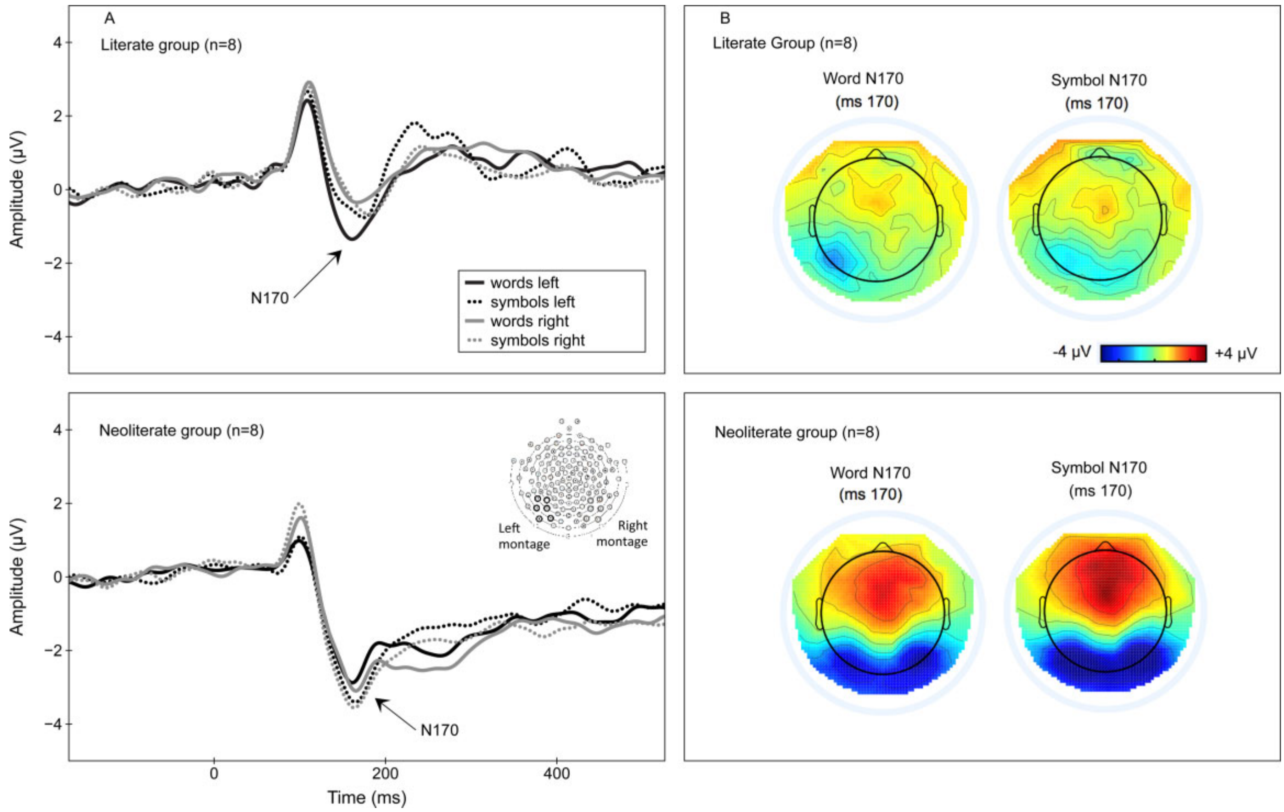

Figure 4. Neurophysiological results: one-back tasks.

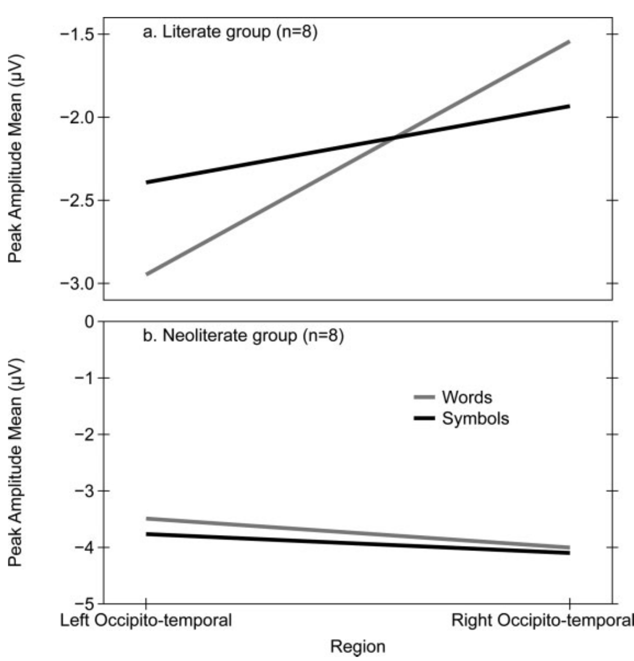

Figure 5. One-back interaction.

that both symbols and words stimuli elicited the same amplitude in both left and right occipito-temporal regions for this group. Figure 5 provides a graphical representation of the group × region × stimulus interaction, and descriptive statistics for the N170 amplitudes over the experimental montages and during the time windows of interest are provided in Table 4.

Table 4. Descriptive statistics for N170 peak amplitude on the one-back task.

	Symbols		Words	
	M (μV)	*SD*	*M* (μV)	*SD*
Literate group (n = 8)				
Left occipito-temporal	−2.393	1.610	−3.499	2.723
Right occipito-temporal	−1.933	0.889	−1.543	1.000
Neoliterate group (n = 8)				
Left occipito-temporal	−3.764	2.338	−3.490	2.723
Right occipito-temporal	−4.099	1.927	−4.003	2.146

M = mean; *SD* = standard deviation.

Reading verification task. The neurophysiological results for the reading verification task are shown in Figure 6, illustrating that the N170 ERP component was elicited in response to intentional word reading for both groups, over both left and right occipito-temporal sensors.

A mixed ANOVA was conducted to evaluate the dependent variable *peak amplitude* of the same time-window from the one-back task, since we were evaluating the same ERP component. We contrasted the between-subjects factor *group* (literate vs. neoliterate) and the within-subjects factor *region* (left occipito-temporal vs. right occipito-temporal). The analysis revealed a significant region × group interaction with a large effect size, F (1, 14) = 9.963, p = .007, η^2_p = 0.416, with the literate group showing a larger negative response to words over left hemisphere sensors,

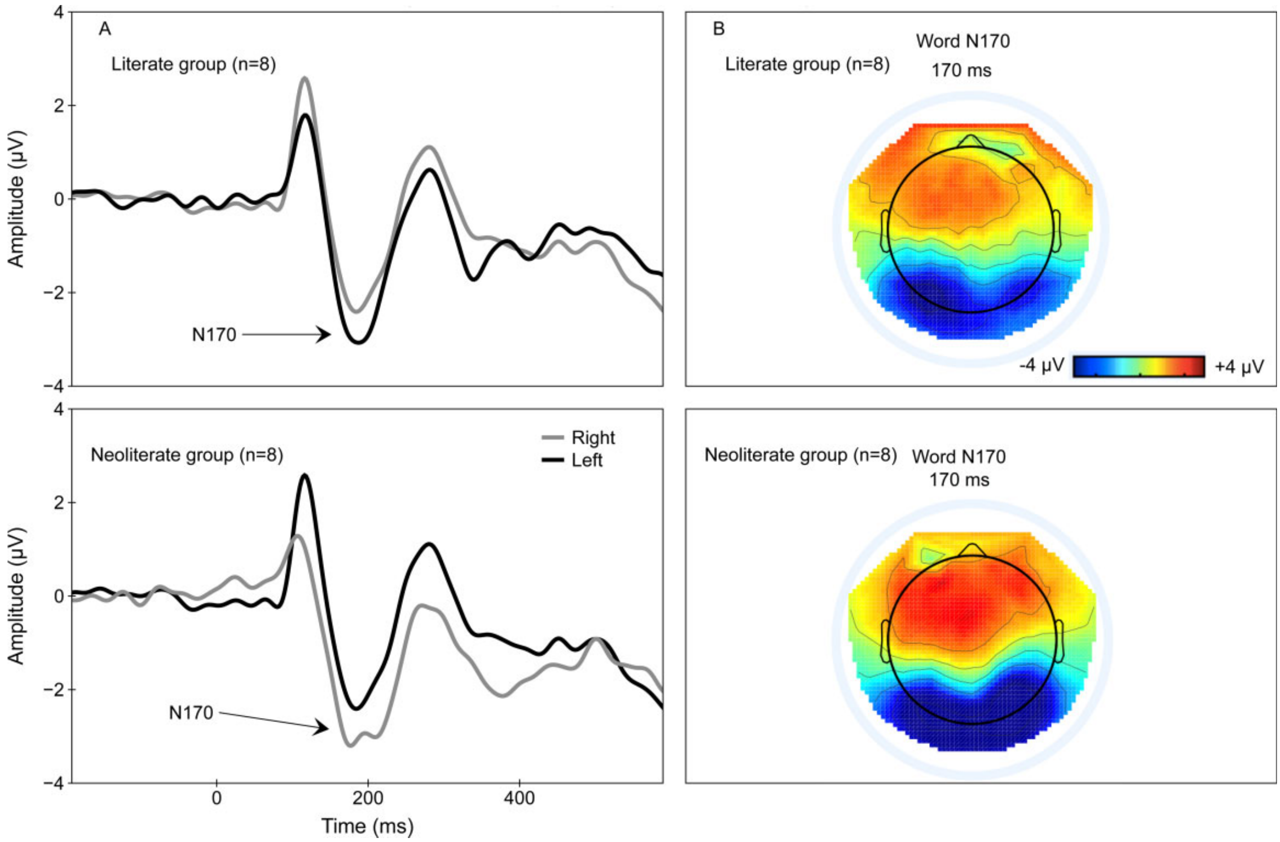

Figure 6. Neurophysiological results: reading verification task.

Table 5. Descriptive statistics for N170 peak amplitude on the Reading verification task.

	Left occipito-temporal		Right occipito-temporal	
	M (μV)	*SD*	*M* (μV)	*SD*
Literate group (n = 8)	−4.693	1.471	−3.455	1.545
Neoliterate group (n = 8)	−3.728	2.098	−4.459	2.045

M = mean; *SD* = standard deviation.

while the neoliterate group showed a larger N170 response to words over right hemisphere sensors. There were no significant main effects for region or group alone, however. Table 5 provides descriptive statistics for this analysis.

Additional neurophysiological analyses. The neurophysiological data were subjected to additional statistical comparisons to determine whether other, unpredicted, effects could be observed. No additional differences were found between groups in the one-back task, so this section focuses only on the post hoc findings associated with the reading verification task. Since this study was designed to elicit the N170 response from occipito-temporal regions, no a priori hypotheses were established with respect to brain activation in other regions. These analyses are therefore purely exploratory.

We contrasted *mean amplitude* scores elicited in response to the reading verification task over frontal and central regions in the left and right hemispheres. Mean amplitude was calculated by obtaining the mean of the data points within a specific time window, for each participant, and for each stimulus type. In order to understand the evolution of this activation over time, mean amplitude measures were collapsed over successive 200 ms windows: (a) a mid-time-window from 200 to 400 ms, and (b) a late-time window from 400 to 00 ms. Visual inspection of the waveforms from Figure 7 reveals differences between groups that may be important, and could be explored further in future studies. See Table 6 for the corresponding descriptive statistics.

A three-way mixed ANOVA was used to evaluate the dependent variable *mean amplitude* for the frontal region, contrasting between-subjects factor *group* (literate vs. neoliterate) and within-subjects factors *hemisphere* (left vs. right), and *time window* (mid vs. late). This ANOVA revealed a significant group × hemisphere × time window interaction with a large effect size, F (1, 14) = 9.898, p = .007, $\eta^2_p = 0.414$. In addition, there was a group × hemisphere interaction, F (1, 14) = 14.170, p = .002, $\eta^2_p = 0.503$, and a main effect of hemisphere, F (1, 14) = 20.341, $p < .001$, $\eta^2_p =$ 0.592. These findings reflect that both groups showed larger left hemisphere activation than right hemisphere activation in the frontal region; however, this difference was larger for the neoliterate group than the literate group.

For the purposes of investigating brain responses recorded over central electrodes, a three-way mixed ANOVA was conducted with dependent variable *mean amplitude*, between-subjects factor *group* (literate vs. neoliterate), and within-subject factors *hemisphere* (left vs. right) and *time window* (mid vs. late). This analysis revealed a significant group × time window interaction with a large effect size, F (1,14) = 13.109, p = .003, $\eta^2_p = 0.484$, indicating that,

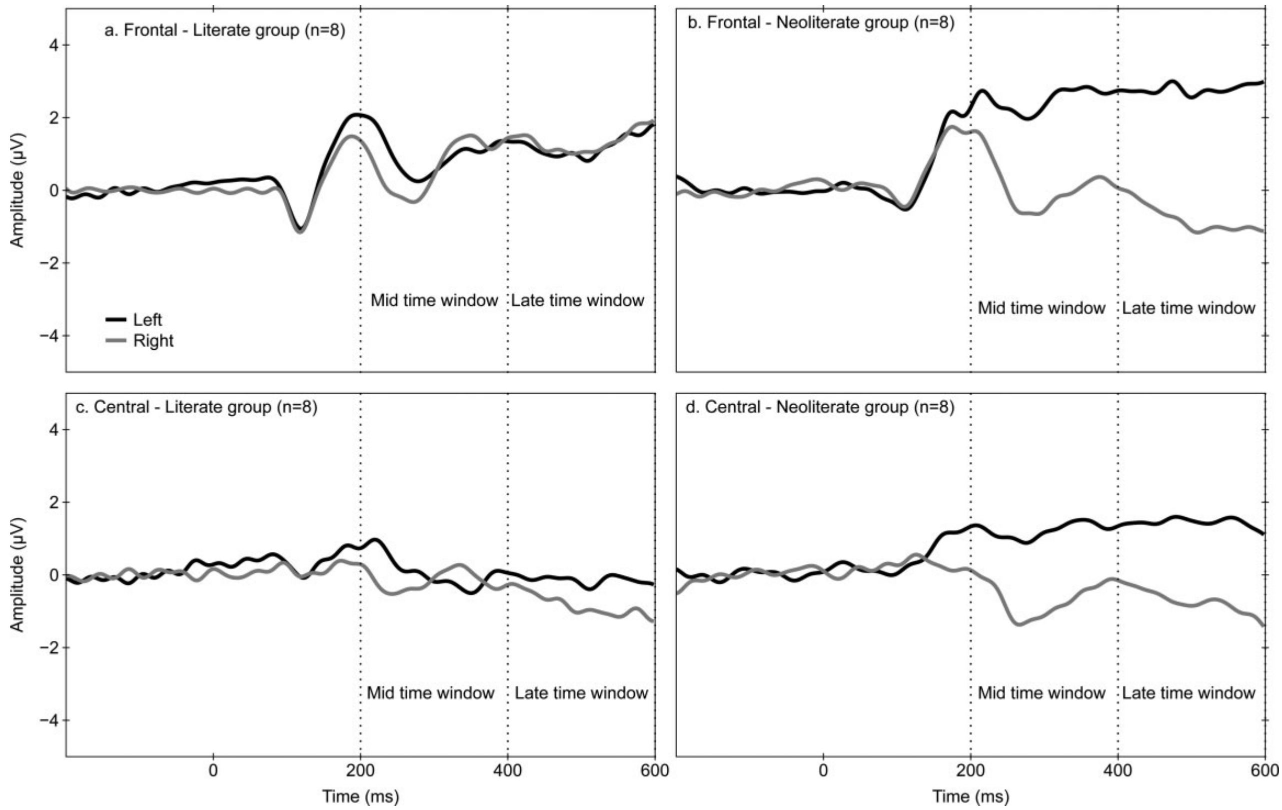

Figure 7. Additional neurophysiological analyses: reading verification task.

Table 6. Descriptive statistics for mid and late time windows mean amplitude on reading verification task.

	Left hemisphere		Right hemisphere	
	M (µV)	*SD*	*M* (µV)	*SD*
Literate group (*n* = 8)				
Frontal				
Mid time window	1.019	1.416	0.552	1.166
Late time window	1.211	1.904	1.187	1.618
Central				
Mid time window	−0.140	0.559	−0.160	0.864
Late time window	−0.444	0.607	−0.828	1.420
Neoliterate group (*n* = 8)				
Frontal				
Mid time window	2.500	1.008	0.333	1.001
Late time window	2.779	1.655	−0.511	1.751
Central				
Mid time window	1.226	0.562	−0.645	0.611
Late time window	1.446	1.110	−0.712	0.682

M = mean; *SD* = standard deviation.

regardless of hemisphere activation, larger amplitude responses were found for the neoliterate group than the literate group. In addition, there was a significant group × hemisphere interaction, $F\,(1,14) = 13.109$, $p = .003$, $\eta^2_p = 0.484$, revealing that the neoliterate group yielded larger amplitudes over the left hemisphere than the right hemisphere regardless of time window. This finding contrasted with the literate group, in which the difference between left and right activation was not apparent over central sensors.

Discussion

This study aimed to investigate visual word specialization in adults who are neoliterate, to evaluate the hypothesis that failure to achieve automaticity could be an underlying factor in reading skill attrition for adult learners. The N170 component was targeted as a likely neural correlate of reading automaticity (Maurer & McCandliss, 2007). Since the N170 can be modulated by attentional focus, we explored word recognition under conditions that varied the degree of attention required for the linguistic components of reading: (1) a one-back task in which linguistic processing is not required, with an attentional focus on visual word form rather than grapheme to phoneme conversion; and (2) a reading verification task to elicit intentional word recognition, with an attentional focus on grapheme-phoneme conversion, since visual word form information alone is insufficient to carry out this task. Outcomes from a group of neoliterate readers who had recently completed reading instruction as adults were compared to those from a group of adults who had learned to read in childhood.

One-back task

The neoliterate group did not show differences in N170 amplitude or hemispheric distribution (over temporo-occipital electrodes) in response to words or symbols on the one-back task. By contrast, the literate group showed a larger, left-lateralized N170 response to words than symbols. Visual expertise and automaticity effects are manifested by the elicitation of a larger N170 in response to common stimuli (Tanaka & Curran, 2001). Therefore, the neoliterate group did not show neurophysiological evidence for expertise in words over symbols. It appears that the extent of reading exposure available to the neoliterate participants, before and during literacy instruction, was not sufficient for neural tuning to visual expertise and automaticity of responding to linguistic stimuli. This finding differs from Botzmann and Rüsseler (2013), in which participants' responses to words and symbols were differentiated by the presence of a larger amplitude N170 to words over the left occipito-temporal cortex.

Since written words are related to language processing, in addition to being visual stimuli, it was expected that expert readers would show N170 left-lateralization. Only the group of adults who had learned to read in childhood showed this effect. This indicates that processing of written words by the neoliterate group was probably recruiting brain systems not specifically targeted by linguistic stimuli as in expert readers. The lack of expertise effects, and the lack of left-lateralization in response to written words on an implicit reading task, suggest that participants from this neoliterate group had not acquired reading automaticity from the available literacy instruction.

Reading verification task

Contrary to expectation, the neoliterate group did not show larger N170 amplitudes over left hemisphere sensors for the reading verification task, despite the presumptive engagement of grapheme-phoneme decoding for reading verification. Since the neoliterate group had studied reading for at least two years, it was predicted that their grapheme-phoneme conversion knowledge would be sufficient to elicit a left-lateralized N170 on a task requiring conscious access to the end product of the reading process. However, the neoliterate participants showed no preferential left-hemisphere response to written words during the N170 time window; rather, the data show that the right hemisphere was preferentially engaged. This finding may relate to previous observations of pre-literate children with high letter knowledge (Maurer, Brem, et al., 2005), where right hemisphere engagement was interpreted as indicating visual familiarization with written words. This effect should be explored in further studies, since it has been shown that typical adult readers trained on whole word recognition (not grapheme-phoneme conversion) in an artificial orthography showed right lateralized N170 responses in a reading verification task (Yoncheva et al., 2010). The use of orthographic strategies (whole word recognition) for reading in adults with low literacy skills has been demonstrated (Greenberg, Ehri, & Perin, 1997, 2002; Villa Carpio Fernández, Defior Citoler, & Justicia Justicia, 2002), and these effects have been attributed to deficient or slow phonological processing. Since left-lateralized N170 effects mark a specialization for words that depends on continuous grapheme to phoneme conversion during literacy training (Maurer & McCandliss, 2007), it would be informative to further explore the relationship between phonological awareness and N170 lateralization in neoliterate adults.

Training length and duration should also be considered for further investigations of word-reading automaticity. Participants in this study received classes once a week for 2 years. This is considerably less time spent on reading activities than is typical for children in elementary school. In Latin America, students spend 20–30 hours per week at school. Indeed, Boltzmann and Rüsseler (2013) reported that functionally illiterate participants who received intensive literacy training showed a left-lateralized N170 on a one-back task compared to participants who did not receive such training. Effects of intensive exposure are likely to be important in establishing automaticity of decoding for neoliterate adults. In addition, the training method for participants in the present study was not evaluated. A qualitative inspection of the teaching materials used in the program from which the neoliterate participants were recruited revealed that a combination of phonics and whole word approaches were used; however, the teaching methodology guides were not available for this investigation. Further studies should consider teaching methods in more detail, to shed light on possible causes for left vs. right lateralization of N170 effects in neoliterate adults.

Additional findings

Additional analyses, outside of the regions and time window of interest, conducted for the reading verification task revealed a significant left-lateralized response to both matched and un-matched words for the neoliterate group. This component appeared later than the expected N170 peak, over frontal and central sensors rather than occipito-temporal regions. This response could indicate the recruitment of additional cognitive resources for word recognition, a strategy that has been predicted for people who do not learn to read until adulthood (e.g., Dehaene et al., 2010). Such recruitment is associated with serial, effortful and slow reading.

The literate group showed an identifiable positive peak over anterior sensors at around 200 ms. This left anterior positivity could be interpreted as a Vertex Positive Potential (VPP). The VPP has similar characteristics to the N170 in terms of latency and amplitude sensitivity, and it has been proposed that both come from the same dipolar source (e.g., Joyce & Rossion, 2005; Rossion et al., 2003). A word recognition study by Barnea and Breznitz (1998) also reported a left anterior positivity around 200 ms over central and frontal areas of the brain. This component is thought to be associated with extraction of the orthographic and phonologic features of words in early word recognition (Barnea & Breznitz, 1998). The observed component in the current study may reflect this kind of activation in the expert reader group.

Limitations and recommendations

There are some limitations to this study. Although inclusion criteria were strict, and only social reasons for illiteracy were considered, the possibility of a confounding learning disability in the neoliterate adults cannot be definitively ruled out. The small sample size means that the groups studied are not representative of the broader population. The Hispanic adult literacy population in NYC is heterogeneous, and therefore only 8 participants per group were selected to be part of the study on the premise to keep the sample as homogeneous as possible—one putative advantage of small sample sizes, as suggested by Picton et al. (2000). The biggest problem with small sample sizes lies in the possibility of a type II error, in which we would fail to find significant differences due to a lack of power. However, this study did find significant differences, with very large effect sizes.

The present study does not shed light on the course of emergence for the N170 in neoliterate adults, and we are left with questions about the role of instructional methodologies, especially the amount of intensive instruction necessary to attain automaticity. Further studies should consider a longitudinal approach that would permit the tracking of the emergent N170 alongside observations of increasing literacy-related skills.

Additionally, participants were immigrants whose first language was not English, and there is no objective measurement to assess and control for English knowledge and exposure in this population. However, both Spanish and English languages have alphabetic scripts; and although they differ in "transparency," the low-level reading processes targeted by the present study are similar across both languages. Left-hemisphere lateralization of N170 for word recognition has been reported in the processing of transparent orthographies as well as opaque orthographies (Maurer & McCandliss, 2007). Therefore, a possible contamination from English exposure (especially exposure to English script) is unlikely to influence these results.

Conclusions

Notwithstanding these limitations, studying the neurophysiological responses of adults who recently learned to read has many implications for pedagogical approaches used to inform literacy instruction in adults. The acquisition of word recognition automaticity is crucial for acquiring literacy. Previous studies have reported successful manipulations of N170 left lateralization for word stimuli on neoliterates (Botzmann & Rüsseler, 2013; Dehaene et al., 2015; Pegado et al., 2014). It is important to investigate what the most efficient training approach would be, leading towards a left lateralization of N170. N170 lateralization did not happen with the participants studied here, who all showed bilateral activations even though they had completed literacy training. Instructional methods could be developed to support word recognition automaticity attainment, to prevent relapse back into illiteracy. Further studies could evaluate interventions targeting the N170 to determine whether or not such interventions have positive effects on reading automaticity acquisition. This information could be used to evaluate effectiveness and impact of different instructional programs, different amounts of practice, and different pedagogical techniques, and to answer questions about optimal parameters for effective literacy instruction.

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