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BASIC RESEARCH PROGRAM

WORKING PAPERS

SERIES: PSYCHOLOGY

WP BRP 115/PSY/2020

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BRAIN DYNAMICS REFLECTS PHONOLOGICAL AND SEMANTIC TOP-DOWN INFLUENCES DURING ORTHOGRAPHIC PROCESSING OF NOVEL WORD FORMS[6]

The acquisition of new vocabulary is usually mediated by previous experience with language. In visual domain, orthographically unfamiliar word-forms may already have corresponding phonological or even conceptual representations in linguistic system, which facilitates orthographic learning. The neural correlates of this advantage were investigated by recording EEG during reading novel and familiar words across three different experiments (n=22 each), manipulating the availability of previous knowledge for the novel written words. In Experiment 1, participants received no previous training before reading these stimuli; Experiments 2 and 3, however, provided a previous training (six exposures) in the phonology of novel words (auditory exposure) and in both phonology and meaning (auditory exposure + picture), respectively. During reading, a different pattern of ERP responses was found for the novel written words depending on their previous training, resembling cross-level top-down interactive effects during the process of vocabulary acquisition. Thus, whereas phonological experience produced a different modulation at early lexical (~180 ms) and post lexical (~520 ms) stages of visual recognition of novel written words, additional semantic training influenced their lexical processing at a later stage (~320 ms). Importantly, a clear lexicality effect was found at the early peak in experiment 1 (no previous training); however, neural responses for trained and familiar words were found indistinguishable at this latency regardless of the phonological or semantic nature of training, reflecting similar orthographic processing and word-form access. These results suggest the key role of phonology in orthographically transparent reading systems, in which bidirectional decoding mechanisms contribute to the rapid formation of novel word-form representations even in the absence of visual exposure.

JEL Classification: Z.

Keywords: ERPs, P200, N400, LPC, reading, top-down processing

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[6] The study was funded by a grant from the Russian Science Foundation (project No. 19-78-00140).

Introduction

An unresolved issue as to the acquisition of new vocabulary concerns the interplay between different levels of linguistic processing —i.e. phonological, orthographic, semantic, syntactic— across spoken and visual language domains. According to previous statements (Leach & Samuel, 2007; Perfetti & Hart, 2002), the more the levels at which a novel word gains activation, the more interactive its processing will be, contributing to its faster lexicalization. The lexicalization process of novel word-forms refers to the development of fully-fledged representations involving activation across different levels of analysis and which, crucially, show dynamic interaction with other word representations. This process is particularly important for the efficient use of new vocabulary (Share, 1995, 2008). Indeed, such cross-level network representation likely assist the reading process contributing to the parallel activation of word units, and hence to its whole-form recognition (McKay et al., 2008; Perfetti & Hart, 2002; Suárez-Coalla & Cuetos, 2017). In contrast, word processing is likely more serial and effortful when activation and mapping across different levels of representation is reduced or not possible due to the lack of experience at one or more levels. Therefore, previous experience with words at various levels of processing likely leads to a more interactive processing for these stimuli, which in turn improves its lexicalization and hence its efficient use. The present study is aimed to investigate the neural dynamics of such cross-level interactivity during the acquisition of new vocabulary.

Several cognitive models of word recognition consider the interaction across multiple levels of analysis, in both visual (Grainger & Holcomb, 2009; Harm & Seidenberg, 2004; Plaut et al., 1996) and spoken domains (McClelland & Elman, 1986; Tyler et al., 2000). Moreover, such approaches include continuous bi-directional (bottom-up, top-down) flow of information, in which sensory input and prior knowledge interact for the completion of the most efficient word processing (McClelland et al., 2014; McClelland & Rumelhart, 1981; McClelland & Elman, 1986). Accordingly, a higher facilitation would be expected during the visual processing of novel written word-forms whether representations at other levels —i.e. phonological and semantic— can be also activated during its orthographic analysis. This is indeed a very common situation when facing novel vocabulary in childhood and also during foreign linguistic immersion in adulthood. Very often, the orthographic form of a novel word is not accessible as it has never been experienced visually, but its pronunciation or even its corresponding meaning can be accessed, as it has already been experienced at phonological or semantic level. Given the dynamic nature of visual word recognition, the activation of phonological and semantic information driven by top-down mechanisms likely facilitates the grapheme-to-phoneme decoding involved during orthographic processing of the novel written word-forms; this would in turn contribute to a faster transition from serial letter-by-letter processing to a whole-word reading strategy, which is known to occur over the course of the orthographic learning (Kwok et al., 2017; Kwok & Ellis, 2015; Maloney et al., 2009).

This question has been empirically addressed by prior behavioral research, showing facilitatory top-down processes from both phonological and semantic levels during orthographic processing of novel word-forms (Álvarez-Cañizo et al., 2019; Bakker et al., 2014; Duff & Hulme, 2012; McKague et al., 2001; McKay et al., 2008; Nation & Cocksey, 2009; Suárez-Coalla & Cuetos, 2017; Wang et al., 2013; Wegener et al., 2018; Zhou et al., 2015). In general, findings reported in these studies point out that phonological knowledge generally improves the orthographic processing of novel words. However, the evidence for a semantic benefit is more blurred and inconsistent; whereas recent studies inform of better reading performance after training word pronunciation in combination with meaning (Álvarez-Cañizo et al., 2019; Suárez-Coalla et al., 2016), other studies report no additional benefit from semantics (Duff & Hulme, 2012; McKague et al., 2001; Wang et al., 2013) or claim that semantic facilitation depends on the depth of the orthographic system (McKay et al., 2008) or the specific script (Zhou et al., 2015).

Although the above-mentioned studies have shed light into this question, other measures than behavioral are required to better determine the specific stages of visual word recognition ─and, importantly, the underlying processes─ influenced depending on previous training. Only methods with high temporal resolution, however, are able to provide such level of fine-grain information regarding ongoing modulations during the course of word processing. Indeed, several studies using EEG/MEG methodology have isolated specific processes during early and late stages of visual word recognition, with particular ERP components reflecting such mental operations. Thus, brain responses elicited within first 200 ms of word processing have been related to orthographic analysis (Assadollahi & Pulvermüller, 2001, 2003; Bentin et al., 1999; Dehaene, 1999; Hauk et al., 2009; Kutas, Van Petten & Kluender, 2006). In particular, the amplitude of the P200 component reflects differences in the extraction of visual features during visual word recognition (namely, grapheme-to-phoneme decoding). This is a fronto-central distributed component which usually shows larger responses for high than for low frequency words and pseudowords; is thus sensible to physical characteristics of the stimuli and to lexical frequency and it is considered to index holistic recognition of word-forms (Barnea & Breznitz, 1998; Carreiras et al., 2005; Liu et al., 2003; Proverbio et al., 2004; Wu et al., 2012). Later on, from ~250-500 ms, higher-level analysis of the word are carried out, relative to lexico-semantic access and contextual integration processes, as reflected in the amplitude of the N400 component; in particular, larger responses of this parietally-distributed negativity are considered to reflect the difficulty to anticipate, process and integrate the word into the ongoing semantic context (Bentin et al., 1985; Kutas & Hillyard, 1980; see Kutas & Federmeier, 2011 for a review).

Therefore, these ERP components index processes carried out at different stages of visual word processing and indeed reflect changes in the visual recognition of words as a consequence of increased reading experience. Thus, several studies have reported facilitation in the processing of novel written words as a consequence of repeated visual exposure, thus showing top-down facilitation processes within the orthographic level of representation. The majority of these studies have reported reductions in the amplitude of the N400 component elicited by novel written word-forms (Angwin et al., 2014; Batterink & Neville, 2011; Bermúdez-Margaretto et al., 2018, 2019; Borovsky et al., 2010; Liu et al., 2003). This reduction is considered to reflect facilitated lexico-semantic access for novel written words due to repeated visual exposure under meaningful training contexts (i.e. in association with pictures or definitions or embedding them under semantically constrained sentences). Moreover, the N400 reduction is often followed by the enhancement of a late positive component (LPC) associated with post-lexical processes. Specifically, such modulation is considered to reflect the formation and enhancement of episodic memory traces for novel written words across their repeated exposures, contributing to their further recognition (Bakker et al., 2015; Batterink & Neville, 2011; Bermúdez-Margaretto et al., 2015, 2018; Liu et al., 2003). Much less frequent in these studies, however, is the modulation of earlier ERPs, reflecting a facilitation in processes purely related to the orthographic analysis of the novel written words. This could be due to the paradigms used in these studies, in which the task (i.e. semantic categorization, lexical decision) leads to a deeper processing of the novel written words likely masking the modulation of earlier brain responses. In support of this argument, a recent study has reported the enhancement of early neuromagnetic responses (~100 post-onset) using a passive paradigm in which novel written words were repeated outside the participant´s focus of attention (Partanen et al., 2018). This early modulation was considered as an index for the fast and automatic formation of surface-form representations for novel written words.

However, prior ERP research has not addressed the putative cross-level top-down facilitation during the orthographic processing of novel written words. Some studies have reported cross-level top-down facilitation during visual word recognition (Balass et al., 2010); however, such facilitation has been only tested on familiar words and thus do not inform about the neurophysiological mechanisms underlying cross-modal, top-down facilitation for visual recognition of novel words. On the other hand, many other EEG/MEG studies have tested the effect of training new phonological word-forms, either with or without semantic information (François et al., 2017; Gagnepain et al., 2012; Hawkins et al., 2014; Kimppa et al., 2015, 2016; Nora et al., 2015).

However, in these studies, the effects of such phonological or phonological/semantic exposure with novel words were explored only within the spoken domain, showing for instance facilitation in the acquisition of novel spoken words when these stimuli resemble the native phonotactic structure (and thus driven by the access to previous phonological representations) or lexical competition effects in the spoken recognition of familiar words (driven by activation of the newly-acquired ones). However, the intermodal effect that the phonological/semantic training could have on the orthographic processing of these stimuli has been not explored so far using EEG/MEG methodology. Therefore, the neural mechanisms underpinning a putative facilitation in the visual recognition of word-forms driven by access to cross-modal levels of representation still remain poorly understood.

The current study

The present ERP study is aimed to evaluate the time course and functional role of cross-level top-down facilitation processes during the visual recognition of novel written word-forms. For this purpose, we carried out three different experiments in which we manipulated the training of novel words in their phonology and/or meaning. The impact of this training in the visual recognition of novel written word-forms was evaluated using a silent reading task, in which the brain dynamics underlying the orthographic processing of the previously trained stimuli were measured and compared to that exhibited by familiar, already lexicalized words. The election of this task was motivated by the shallowness of the processing involved, likely more appropriate for the study of visual word recognition processes than other paradigms involving categorization or lexical decision of the stimuli, as already reported in previous studies (Bermúdez-Margaretto et al., 2019; Partanen et al., 2018). Thus, in the first experiment, the novel written words were presented in a silent reading task but, crucially, no previous training was provided for these stimuli; therefore, this experiment served as a baseline. In the second experiment, however, the novel written words were trained in their phonology before their visual presentation at the silent reading task and in the third one, these stimuli were previously trained both in their phonology and meaning. As note, each training was conducted in a separate experiment and group of participants in order to detect the effects of each particular training and avoid any influence or cross-over effects between one training and another. Importantly, the same materials and procedure were carried out across the three experiments, as well as the same sequence of preprocessing steps and analysis of the EEG signal; thus, the control between-experiments enables to extract conclusions directly derived the training manipulation.

Regarding to our hypotheses, we expected that the cross-modal top-down access to semantic and/or phonological codes during the reading of novel written words would cause a different facilitation in their visual processing, leading to a different pattern of brain activation depending on the previous training. Thus, in the experiment 1, we expected to find differences in the orthographic and lexico-semantic processing of familiar and unknown (non-trained) novel words; such differences at early and late stages of their visual recognition will be likely reflected in a lexicality effect in P200 and N400 components. Nonetheless, taking into account the shallow processing involved during the silent reading task, in which no particular response is asked from participants, such modulation might be reduced in the case of the late component. In the experiment 2, the access to phonological codes previously trained was expected to cause a facilitation in the analysis of visual features and their phonological decoding during reading of novel written words, likely resulting in the reduction of the P200 lexicality effect; furthermore, the repeated exposure to novel words during the training might also cause an LPC modulation, as this late component has been found sensible to stimuli repetition. Finally, the additional meaningful training carried out in the experiment 3 was expected to enable the recollection of a semantic reference during the reading of novel written words, thus affecting the amplitude of the N400 component.

Experiment 1: no previous training

Method

Participants

Twenty-two participants took part in the experiment for course credits (six males; mean of age=21.2, SD=2.43). All of them were native Spanish speakers, right-handed (mean score of 77.90 in Edinburgh Handiness Inventory, Oldfield, 1971) and had normal audition and normal or corrected-to-normal vision. None of them reported history of cognitive, neurological or psychiatric disorders.

Tab. 1. Main psycholinguistic properties of the stimuli used in the three experiments of the study. These were maximally matched between the experimental conditions. Standard deviation is shown in brackets. Independent-samples t tests confirmed no differences between novel and known words across the variables.

	Novel Words	Known Words	*t* (46) value	*p* value
Lexical Frequency	0	57.78 (103.99)	–	–
Number of syllables	2 (0)	2 (0)	0	1
Number of letters	5.50 (0.51)	5.50 (0.51)	0	1
Number of Orthographic Neighbors	1.42 (1.31)	1.46 (1.21)	-0.11	0.91
Bigram Frequency (token type)	518.92 (285.91)	601.7 (350.51)	-0.89	0.37
Mean (1st and 2nd) Syllable Frequency	2046.83 (3150.97)	2108.54 (2997.74)	-0.07	0.94

Note: Novel words used in the study: cofín, dorna, fudre, bruño, gelfe, nabla, notro, pajel, paila, sisón, cuatí, facón, dolmán, puntel, reitre, roblón, runcho, seisén, holmio, trujal, jínjol, pambil, timple, carmes; Known words: color, toldo, valle, traje, golfo, bicho, litro, papel, nieve, mujer, baile, gafas, balcón, doctor, huella, millón, rastro, violín, garfio, crimen, cactus, césped, templo, pintor.

Procedure

The experiment consisted of a single phase (testing) during which participants conducted a silent reading task. In this task, the novel and known words were presented to participants during the recording of their EEG activity (see Figure 1B). Therefore, no previous training was carried out in this experiment. The aim was to stablish a baseline for the lexicality effect, thus a comparison between the brain signals elicited during the reading of well-known and novel stimuli.

In more detail, the silent reading task consisted of two blocks of stimuli presented in consecutive pseudo-randomized order. First, a set of known, familiar words was presented to participants to be read; this block was followed by the presentation of the novel word-forms. Both sets of stimuli were presented only once during this reading task, with one trial per each of the stimuli. The sequence of stimuli presentation was randomized within each block. EEG signals were recorded by 64 Ag/Cl active electrodes (actiCap, Brain Products GmbH, Gilching, Germany) and amplified and digitized by an ActiChAmp amplifier (Brain Products GmbH, Gilching, Germany) at 1000 Hz sampling rate. Ocular activity was recorded by two electrodes, placed at the horizontal and vertical canthus of the left eye. A vertex reference (Cz channel) was used during on-line recordings, while the activity obtained from two electrodes placed in the left and the right mastoid bones was used for off-line referencing. High and low pass filters at 0.1 and 100 Hz were applied during the recordings.

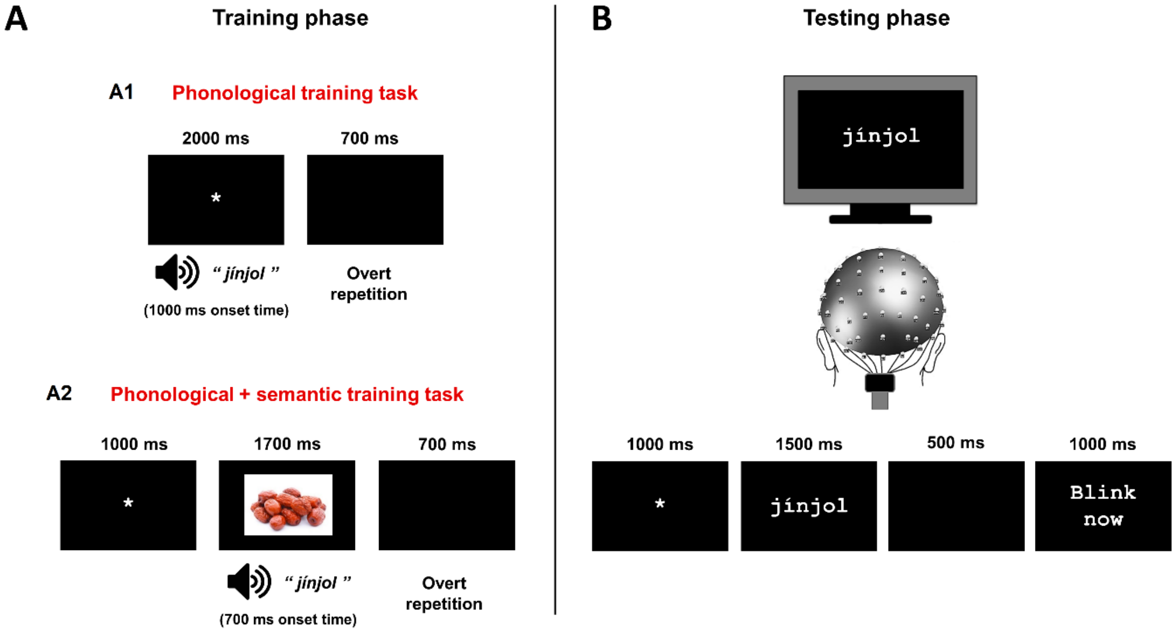


Fig. 1. Left panel A. Sequence of presentation during the training phase. For the Phonological training task (A1), a fixation cross was presented in the center of the screen for 2000 ms; novel words were auditory presented 1000 ms after the presentation of the fixation cross. A blank screen was presented for 700 ms, during which participants pronounced the word presented immediately before. For the Phonological and Semantic Training Task (A2), the sequence of presentation was similar except that a photograph was displayed in the screen. In particular, a fixation cross was presented at the center of the screen for 1000 ms, followed by the presentation of a photograph, displayed by 1700 ms. An audio with the novel word was played 700 ms after the presentation of the photograph. Finally, a blank screen was displayed during 700 ms for the aloud pronunciation of the word. Right panel B. Sequence of presentation at the testing phase, during which participants silently read the stimuli presented in the screen while their EEG signals were recorded. The sequence started with a fixation cross at the middle of the screen presented for 1000 ms and followed by the target word, displayed for 1500 ms; a blank screen was then presented for 500 ms, and finally the message ''blink now'' appeared during 1000 ms. Note that, for the experiment 1, participant underwent this phase directly with no previous training, whereas in experiments 2 and 3, participants underwent the corresponding training phase (phonological or phonological and semantic, respectively) before complete the testing phase.

During the task, participants were instructed to pay attention and to read the stimuli presented in the screen using sub-vocalic, covert articulation. The task started with six filler trials for demonstration. The stimuli were presented at the center of the screen, in white, 18-point bold Courier New font over a black background by mean of E-Prime 2.0 software (Psychology Software Tools Inc., Pittsburgh, USA, Schneider et al., 2002). Figure 1B shows the specific sequence of presentation at the reading task.

Analysis

EEG signals obtained at the reading task were preprocessed using Brainstorm software (Tadel et al., 2011), which is documented and freely available for download online under the GNU general public license (http://neuroimage.usc.edu/brainstorm). First, a low pass filter was applied at 30 Hz. Data was downsampled to 250 Hz and epoched between -200 to 1000 ms post stimulus onset. The baseline was corrected using the 200 ms interval preceding the stimulus onset. Independent component analysis (ICA) was used to remove ocular artifacts and a triangular interpolation of bad channels was applied. Additional artifact rejection (using exclusion criteria at ± 100 μV) was applied to remove any remaining contaminated epochs. Data was re-referenced offline to average mastoid reference. Finally, for each dataset separately, EEG epochs were averaged per subject and per condition (namely for known and for novel words) and ERPs were computed (with a mean of 20 epochs included per condition).

Statistical analyses of ERPs were also carried out using Brainstorm. First, a permutation t-test was conducted across the whole ERP segment (time and space), in order to explore significant differences between known and novel words. A total of 1,000 permutations were carried out for each sample point (300 time points by 60 channels=18,000 sample points), in which conditions (known and novel words) were contrasted by means of paired t-test; only those differences maintained for a minimum of 5 consecutive time points (20 ms) in at least 3 adjacent channels were considered significant (alpha level of 0.025). Based on the pattern of results found in this initial permutation test, specific time windows were selected in which the activity was averaged for further analysis. In these time windows, parametric paired t-tests (alpha level=0.05) were carried out across the whole set of scalp positions, aimed to determine the exact scalp topography for the differences between known and novel words.

Furthermore, a source estimation analysis was carried out, in order to determine the exact neural generators for the brain activity differences obtained at surface level. In particular, a current density map was obtained for each subject and condition (trained and novel words) at the particular averaged time window in which differences were obtained at surface level, by mean of the Minimum Norm Imaging method (Hämäläinen & Ilmoniemi, 1994), implemented in Brainstorm software. These maps, representing current density magnitudes (ampere per square millimeter), were calculated on a realistic head model (BEM) including 4,025 nodes, defined in regular distances within the gray matter of a standard MRI (Montreal Neurological Institute's average brain). Finally, the difference in the current density map obtained for novel and known words was explored; the mean value of current density was extracted for each condition in those regions showing maximal differences (mean differences of 10 as minimum size threshold), and contrasted by means of parametric paired t-test (alpha level 0.05). The choice for the Minimum Norm Imaging method was based on its higher sensitivity for superficial sources instead for deep, intracranial generators, and its localization power in conditions of minimal a-priori assumptions about the nature of the source, particularly in comparison to dipole methods (Komssi et al., 2004).

Results

Permutation t-test conducted for the comparison between known and novel, completely unknown words (namely, not trained before the reading task), showed significant differences ($p<0.025$) in a period ranging from 184 to 214 ms. No other difference was found at other time period across the analyzed ERP segment (t-values across the whole ERP segment of analysis are displayed in Supplementary Figure 1A). Such differences revealed more positive activity for known than for novel words, distributed across frontal and central scalp sites (see Supplementary Figure 1A). Further parametric t-test computed for the averaged activity at 180 – 210 ms time window confirmed significant differences between both conditions at fronto-central scalp sites ($t=2.67$, $p=0.015$). Both the morphology of the ERP waveforms and the topography of the obtained difference suggested that this effect was probably reflecting the modulation of the P200 component. See Figure 2A.

Brain source estimation carried out at the 180 – 210 ms averaged time window revealed frontal and temporal areas of the left hemisphere, particularly at its anterior pole, as the most likely brain generators for the differences between known and unknown words found at surface level. In particular, differences between both conditions were found maximal at the left middle temporal gyrus ($t=2.25$, $p=0.034$), with known words showing higher activation than unknown words. A similar pattern of activation was also found at the left superior ($t=2.19$, $p=0.039$) and inferior ($t=-2.23$, $p=0.036$) temporal gyri, as well as at the left inferior frontal gyrus both at pars orbitalis and triangularis ($t=2.73$, $p=0.012$). Although unknown words exhibited higher activation than known words at the right middle temporal gyrus, this contrast did not reach significance ($p>0.05$). Thus, the higher P200 amplitudes observed for known words in comparison to unknown word-forms were probably generated by a language-related perisylvian brain network, strongly activated at the left hemisphere. See Figure 2B.

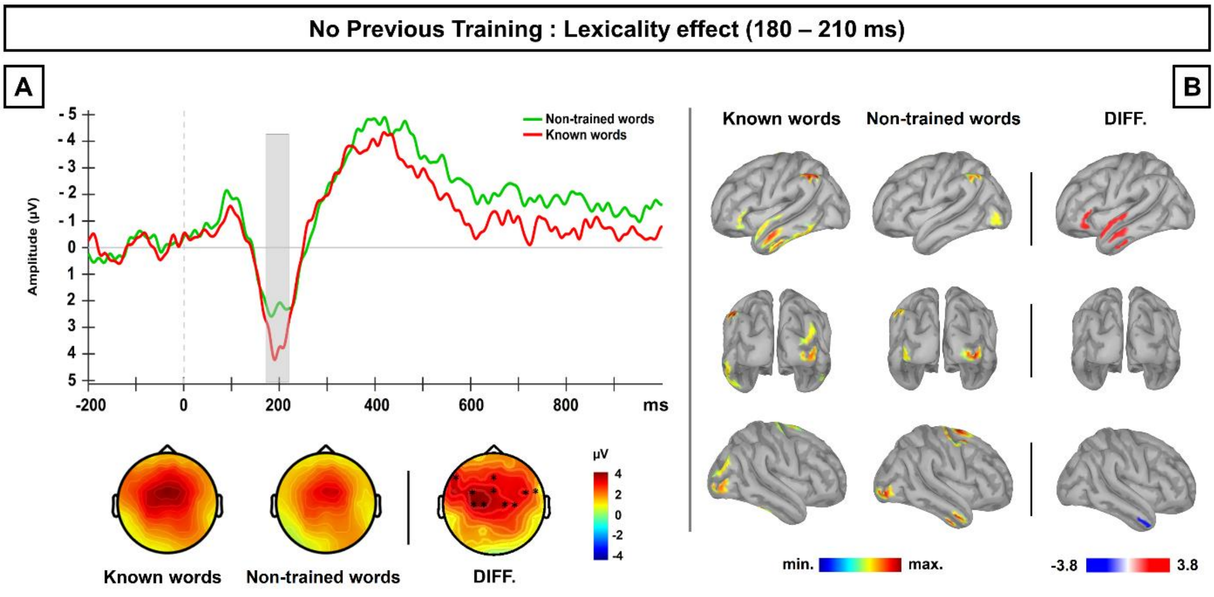


Fig. 2. Left panel A. Grand-average ERP waveforms at frontocentral scalp sites for known and novel written word-forms obtained in Experiment 1 (no previous training). ERP activity is averaged over electrodes reaching significant differences between conditions (depicted in the map above the label DIFF). Grey shaded area highlights the time window (180 – 210 ms) at which known words showed larger neural responses than novel words, an effect compatible with the modulation of the P200 component. Topographic maps displayed below represent the ERP activity for each condition as well the scalp distribution of the difference between them. Right panel B. Current density maps obtained for each condition as well as for the difference between both of them at the averaged time window showing differences at scalp level. Contrasts between conditions revealed the left inferior frontal gyrus and left temporal gyrus as the most likely neural sources for the larger P200 responses elicited by familiar, known words at surface level.

Discussion

In this experiment, brain activity differences between known and novel word forms were observed in the amplitude of the P200 component, with larger responses for familiar than for novel stimuli. This P200 lexicality effect is similar to that found in previous studies (Barnea & Breznitz, 1998; Carreiras et al., 2005; Liu et al., 2003; Proverbio et al., 2004; Wu et al., 2012) and reflects the differences between known, frequent words and completely unknown words at early stages of their lexical processing, related to the extraction of visual features during decoding processes. Therefore, this effect shows the advantage exhibited by familiar words in their orthographic processing and in their whole-form access, as compared to unknown words. This advantage is also reflected in the pattern of results obtained at source level, in which known words showed higher activation than unknown words at left frontotemporal brain areas, typically related with language processing.

Experiment 2: phonological training

This experiment was aimed to determine whether a training with novel words at spoken domain would cause a facilitation in the visual recognition of these stimuli and, particularly, in the phonological decoding processes carried out at earlier stages of reading. Taking into account lexical differences observed in P200 component in experiment 1, it was expected that such putative facilitation would affect the amplitude of this ERP, producing short P200 differences between known and previously trained words. Moreover, a modulation of the LPC component was also expected due to repeated exposure to novel word-forms. That pattern of results would provide neurophysiological evidence for the first time about cross-modal top-down facilitation processes during the visual recognition of novel written word-forms.

Method

Participants

A different group of twenty-two participants (three males; mean of age=22.40, SD=2.32) took part in this experiment for course credit. Criteria for the selection of these participants was the same as in the previous experiment.

Materials

Materials used were the same as in Experiment 1. In order to carry out a phonological training for the novel words, the utterances for each of the 24 unknown words were produced by a female, Spanish native speaker and recorded for its presentation to participants during the training phase of the experiment. Utterances were uploaded in Praat software (Boersma, 2011) for accuracy check and necessary latency adjustment. The duration of recordings was approximately the same for all words (mean= 724 ms; SD= 81.94).

Procedure

The experiment consisted of two different phases, training phase and testing phase (see Figure 1). During the training phase, participants were repeatedly presented with the spoken form of the novel words through headphones, across 6 different training blocks (namely, each novel word was presented six times). The training task was introduced to participants as a training to learn novel words; they were required to listen as much attentively as possible to the words presented and to repeat aloud each word after its auditory presentation. The purpose of repetition was to increase the phonological knowledge about the trained words by mean of overt pronunciation. Therefore, these utterances were not recorded for any further purpose. The novel spoken word-forms were presented in randomized order within each block of repetition, by means of E-prime 2.0 software (Psychology Software Tools Inc., Pittsburgh, USA). See Figure 1A for the sequence of presentation used during the phonological training.

Immediately after the training phase, an EEG cap with 64 Ag/Cl active electrodes (actiCap, Brain Products GmbH, Gilching, Germany) was mounted in the head of participants and the next testing phase started (see Figure 1B). Thus, the lapse between the end of the training and the beginning of the test phase was approximately 45 minutes. During this testing phase, participants carried out the same silent reading task as used in Experiment 1, in which the orthographic form of the previously trained stimuli was presented together with control known words (see Figure 1B). The instructions, sequence of presentation and EEG recordings were carried out in the same manner as described in Experiment 1.

Analysis

The sequence of preprocessing steps and analyses carried out for the silent reading task were the same as described in Experiment 1.

Results

Results from the permutation t-test showed significant differences ($p<0.025$) between known words and those word-forms previously trained in phonology at a late time window, ranging from 440 to 800 ms, broadly distributed at central and posterior scalp regions and maximal at central sites (see Supplementary Figure 1B). In particular, this result showed that trained words exhibited more positive amplitudes than known words at this temporal range. The parametric t-test carried out in a more constrained, averaged time window from 520 – 780 ms confirmed this result (t=-3.188, p=0.009), with highly significant differences between both conditions at central and posterior scalp sites (see Figure 3A). Both the inspection of the ERP waveforms and the topographic distribution of this effect likely suggest the modulation of the LPC component, whose amplitude was found more enhanced for the newly-trained words at spoken domain than for already known words.

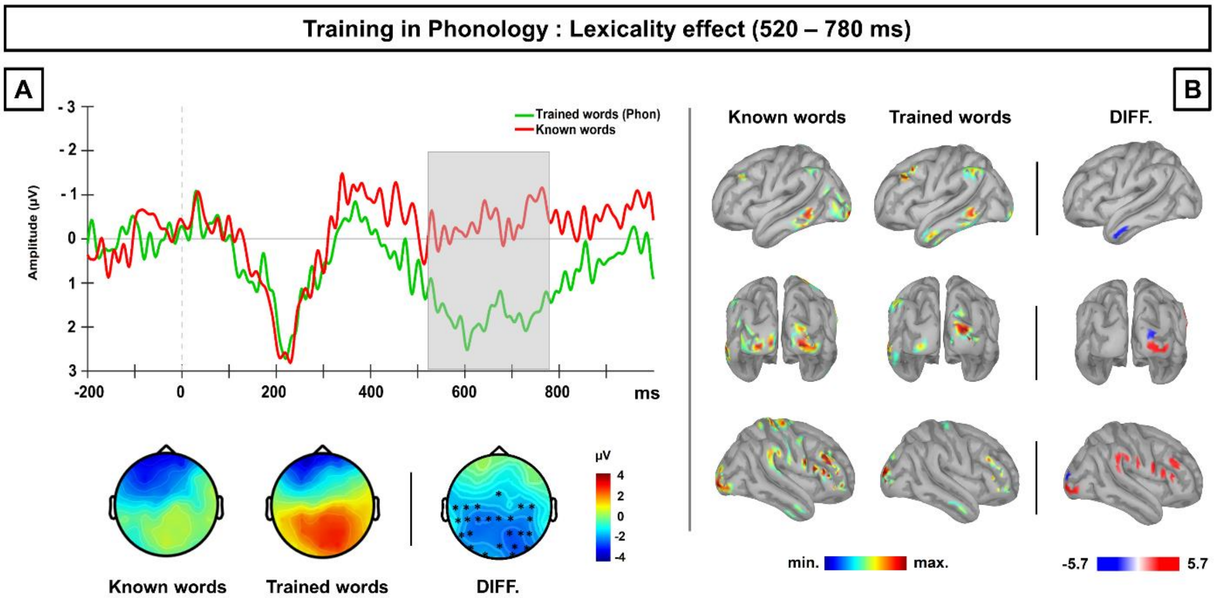


Fig. 3. Left panel A. Grand-average ERP waveforms at central and posterior scalp sites for known and novel written word-forms after previous phonological training. ERP activity is averaged over electrodes reaching significant differences between conditions (depicted in the map above the label DIFF). Grey shaded area highlights the time window (520 – 780 ms) at which differences between conditions were found significant, with a like-LPC enhancement for previously trained novel written word-forms. Topographic maps displayed below represent the ERP activity for each condition as well the scalp distribution of the difference between them. Right panel B. Current density maps obtained for each condition as well as for the difference between both of them at the averaged time window showing differences at scalp level. Contrasts between conditions revealed the middle part of the left temporal pole as the most probably neural generator for the LPC enhancement found at surface for trained

At source level, the parametric t-test carried out for the comparison between brain sources obtained at the averaged 520 – 780 ms time window revealed differences between known and newly-trained words at right frontotemporal areas, maximal at the pars triangularis of the inferior frontal gyrus (t=2.07, p=0.05), where known words exhibited higher activation than the novel words previously trained in phonology (see Figure 3B). Similar pattern of activation was also found at the right precentral (t=2.25, p=0.035) and postcentral gyri (t=-2.52, p=0.019), supramarginal gyrus (t=-2.90, p=0.048), as well as at bilateral occipital regions (right inferior occipital pole, t=-2.53, p=0.019; left occipital pole, t=2.07, p=0.05 and left middle occipital gyrus, t=-2.12, p=0.045). Trained words showed higher activation than known words at the right superior occipital pole and the left middle anterior pole. Although these contrasts did not reach significance (p>0.05), the higher LPC enhancement obtained at surface level for trained words was likely generated at the right superior occipital pole and the left middle temporal pole.

Discussion

An LPC lexicality effect was found in experiment 2, reflecting post-lexical differences between the processing of known and newly trained word forms. The larger LPC responses exhibited by novel written words in comparison to non-trained familiar words are likely consequence of their repeated exposure during the training phase, in similar way as found in previous studies carrying out repetition of novel word forms (Bakker et al., 2015; Batterink & Neville, 2011; Bermúdez-Margaretto et al., 2015, 2018). Therefore, such LPC lexicality effect, together with the higher activation of the left temporal pole exhibited by trained words likely reflect the access to episodic memory traces for these stimuli, built-up across their phonological repetition.

Moreover, no P200 lexicality effect was found in this task, reflecting similar orthographic processing between known words and those novel written words previously trained at spoken domain. Therefore, the pattern of results obtained in P200 and LPC components suggest the cross-level top-down facilitation at both lexical and post-lexical stages during the processing of novel written words, as a consequence of their previous phonological training.

Experiment 3: phonological and semantic training

In this experiment, the facilitation in the visual recognition of novel written word-forms lead by top-down access to semantic information was studied by training these stimuli both in their phonological form and meaning. Such additional training was expected to promote the recollection of semantic cues during the visual presentation of novel written word forms at the reading task and thus facilitate their lexico-semantic processing, likely reflected in the modulation of the semantically-related N400 component.

Method

Participants

Another group of twenty-two undergraduate students took part in the experiment for course credits (two males; mean of age=20.63, SD=2.51). These participants were different from those in previous experiments. Their selection criteria were the same as followed in experiments 1 and 2.

Materials

The stimuli were the same as used in previous experiments 1 and 2 (thus, utterances recorded for each unknown word as well as the orthographic form for each set of unknown and known words). In order to carry out the additional semantic training for the novel words, a set of 24 photographs was selected, each of them presented in association to each particular spoken word-form during the training phase (i.e. a photograph of a little red fruit, presented in association to the novel word *jínjol*, see Figure 1A). All of them were color photographs with similar size and appearance (520 x 360 cm on average).

Procedure

As described in Experiment 2, this experiment consisted of two phases, training and testing. During the training phase, utterances for novel words were repeatedly exposure to participants through headphones, in the same way described in experiment 2. However, in this case, the phonological form of the unknown words was presented together with a photograph aimed to reflect the word´s meaning, displayed in the middle of the screen over a black background (see Figure 1A). The same associations between phonological word forms and photographs were carried out across the experiment, with the presentation of each associated phonological form – photograph randomized within each block of exposure. Participants were required to listen as much attentively as possible to the words presented, paying attention to the photograph displayed in the screen, and to repeat aloud each word after its auditory presentation.

After preparing participants for EEG recordings they underwent the testing phase, in which they carried out a silent reading task, with the presentation of the orthographic form of previously trained novel words together with control known words (see Figure 1B). Instructions for this task, sequence of presentation and EEG recordings were carried out in the same manner was for experiments 1 and 2.

Analysis

The sequence of preprocessing steps and analysis carried out for the silent reading task were the same as implemented in experiments 1 and 2.

Results

Permutation t-test revealed reliable differences ($p<0.025$) between brain activations exhibited by known words and novel written words previously trained in phonology and meaning at a period ranging from 314 to 624 ms post-stimulus onset (see Supplementary Figure 1C). These differences were broadly distributed across fronto-central and posterior regions, maximal at posterior scalp sites and revealed that newly-trained words elicited less negative amplitudes than known words. Further parametric t-test carried out on an averaged time window from 300 to 500 ms confirmed this effect ($t=-2.71$, $p=0.020$), with both conditions showing differences at posterior electrodes (see Figure 4A). Thus, combined training at both phonological and semantic levels produced a reduced activation for newly-trained words in comparison to well-known but non-trained words in a time window coinciding with the N400 component.

The estimation of neural sources for both conditions at the 300 – 500 ms averaged time window revealed maximal differences between both conditions at the left occipital pole, where known words exhibited higher activation than trained words ($t=-2.34$, $p=0.028$). Similar differences were obtained at the right occipital pole, although significance was marginal ($p=0.06$). Therefore, the higher negativity exhibited by known words at surface level was likely generated at left occipital gyrus. On the other hand, novel written words previously trained on phonology and meaning showed significantly higher activation than known words at the left angular gyrus during their first visual encounter at the reading task ($t=-2.19$, $p=0.039$). See Figure 4B.

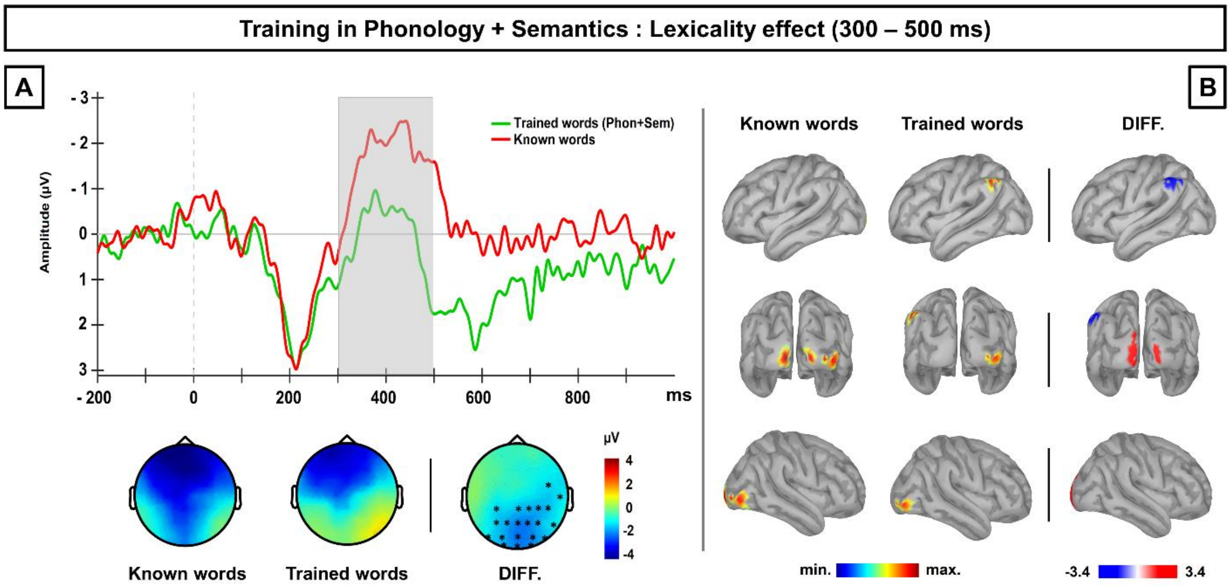


Fig. 4. Left panel A. Grand-average ERP waveforms at posterior scalp sites for known words and novel written word-forms previously trained at phonology and meaning. ERP activity is averaged over electrodes reaching significant differences between conditions (depicted in the map above the label DIFF). The grey shaded area shows the time window at which differences between conditions were found significant, corresponding with an N400 latency. Topographic maps displayed below represent the ERP activity for each condition as well the scalp distribution of the difference between them. Right panel B. Current density maps obtained for each condition as well as for the difference between both of them at the averaged time window at which differences were found at scalp level (300 – 500 ms). Contrasts between conditions revealed the left angular gyrus as the most probably neural generator for the N400-like reduction found for trained word forms at the scalp surface.

Discussion

Experiment 3 revealed that novel written words previously trained in both their phonology and their meaning exhibited more reduced negative responses than known words at a time window coinciding with the modulation of the N400 component. Such N400-like reduction would reflect a lexico-semantic facilitation, in particular the ability of participants to recover information related to a semantic referent for the novel words, trained immediately before the testing phase; in agreement with this idea, the reading of these stimuli recruited the left angular gyrus at this particular time window. These findings contrast with results found for known words, which, importantly were not repeatedly associated to any semantic reference in the context of the experiment. Therefore, this pattern of results suggests the interplay of cross-level top-down facilitation during the visual recognition of novel written words, particularly at a late, lexico-semantic stage.

As already found in experiment 2, no differences were detected between novel and known words at an earlier stage of their processing, related to orthographic analysis. Indeed, the modulation of P200 is similar in both conditions of stimuli, again suggesting the critical role of training novel words at spoken for their effective visual word recognition.

General discussion

The present study aimed to investigate the neural dynamics underpinning the putative cross-level top-down facilitation during the processing of novel written word-forms, as a result of previous experience at different levels of representation. To address this question, EEG was recorded during the first visual encounter with novel written word-forms, which were previously trained in their phonological form or either in their phonological form and associated meaning. Familiar words were also presented at this reading task serving as comparison stimuli. Importantly, both types of stimuli were meticulously controlled, ensuring that lexical differences between trained and known words obtained across the experiments could only being explained by the effect of the different trainings applied. Our findings reflect a dissociated pattern of neural responses depending on previous exposure, with phonological experience causing a modulation at early lexical (~180 ms) and post lexical (~520 ms) stages of visual word recognition, and additional semantic training affecting lexical processing at a late stage (~300 ms). Therefore, these results resemble cross-level top-down interactive effects during the acquisition process of novel vocabulary. In what follows, the effects found at both early and late stages of visual processing of novel word-forms depending on specific training conditions, as well as its underlying neural sources, are discussed in detail.

The short experience with the phonological form of novel words influenced an early stage during their visual processing, as shown by the differential early modulation (~180 ms) found across experiments. In particular, the lack of previous experience with novel written words (experiment 1) was reflected in the reduced positivity exhibited by these stimuli at this early time window in comparison to familiar words, likely resembling a P200 lexicality effect. However, when novel written words received previous phonological training, either with or without semantic information (experiments 2 and 3), these stimuli matched that early brain responses exhibited by familiar words. Consistently with previous findings, the P200 lexicality effect found in experiment 1 likely reflects differences between familiar and unknown stimuli during the extraction of visual features at early stages of visual word recognition (namely, grapheme-to-phoneme decoding), with larger amplitudes resembling holistic recognition of the word-form for familiar words (Barnea & Breznitz, 1998;

Carreiras et al., 2005; Liu et al., 2003; Proverbio et al., 2004; Wu et al., 2012). Moreover, our data from source estimation is also compatible with these results, with two language-related areas within left perisylvian cortex (left inferior frontal gyrus and left temporal gyrus) as the most likely neural sources for the P200 responses elicited by familiar, known words at surface level. In this line, early activations of the left inferior frontal gyrus, higher for known words than for letter strings, have been related to grapheme-phoneme decoding processing and the assembly of phonological codes in reading (Cornelissen et al., 2009; Pammer et al., 2004; Wheat et al., 2010). Besides this, the higher activation found at the left middle and superior temporal lobe for familiar words in comparison to novel written word-forms likely reflects early activation of semantic representations for known stimuli, in agreement with in previous ERP data using source estimation (i.e. Hauk et al., 2009). Therefore, the differential P200 lexicality effect found across experiments points to a change at an early stage during the visual processing of novel written word-forms when trained in phonology, with previously trained words resembling the whole-form recognition carried out in familiar, already lexicalized words. Importantly, such change can only be explained by top-down activation of phonological codes represented for these stimuli as a consequence of previous experience, which in turn contribute to the parallel activation of grapheme-to-phoneme decoding processes during visual word recognition.

The fact that those novel words previously experienced at phonological level show matched orthographic processing with already lexicalized words likely points to two different facilitation processes driven by bimodal grapheme-to-phoneme (and thus phoneme-to-grapheme) decoding processes. On one hand, phonological codes for novel words, activated and stored during the previous training, are likely re-activated during the grapheme-to-phoneme decoding carried out during their reading. Such activation of phonological information leads to a top-down facilitation in the processing of trained words, which might enable its parallel grapheme-to-phoneme decoding in a similar fashion as for familiar words. In contrast, when phonological features have not been previously experienced, the orthographic processing of novel words is significantly different than the exhibited by familiar words, as reflected in P200 amplitude, likely resembling the sublexical processing carried out for these stimuli.

On the other hand, the repeated exposure with novel words at spoken domain likely contributes to the formation of new orthographic traces, even in the absence of visual experience. The fact that orthographic codes are activated during spoken language has been demonstrated in different studies both at behavioral (Chéreau et al., 2007; Ziegler et al., 2003) and, importantly, neurophysiological level (Gow Jr et al., 2008; Gow Jr & Olson, 2015; Pattamadilok et al., 2009; Perre & Ziegler, 2008). For instance, using an auditory lexical decision task, Perre & Ziegler (2008) found differences in the recognition of spoken words with different orthographic consistency (namely, with consistent or inconsistent mapping of phonemes onto graphemes) at both early and late ERP components, and thus informing about on-line activation of orthography during spoken word recognition. Although the present study did not track the neural activation during the training at spoken domain, the differential orthographic processing showed by novel words depending on the previous training clearly reflects an orthographic facilitation occurred at the training phase. The reason for such activation of orthographic patterns during the processing of spoken language has been claimed to be a product of literacy exposure. Thus, during the process of literacy acquisition, there is a continuous association between orthographic and phonological features of words, with the activation of corresponding brain areas at fusiform and frontal gyrus (Dehaene, 1999; McCandliss et al., 2003); later on, when the reader has become competent, the presentation of phonological word-forms propagates the activation across the entire neural network built through reading experience, and thus causing the processing of orthographic aspects of such phonological word-form even in the absence of visual input. Such activation of orthographic features of novel words during their phonological training likely cause its representation at orthographic lexicon, and thus contributing to the parallel, whole-word orthographic processing of these stimuli during their first visual encounter.

Therefore, our results reflect that in a consistent and completely transparent orthographic system such as Spanish, vocabulary exposure at spoken domain seems to be highly beneficial for the orthographic processing of novel words when encountered during reading. Importantly, this effect could be also generalized to many other languages characterized by a shallow orthographic system, such as Finish, Italian or Greek. However, a different pattern of results should be expected under inconsistent orthographies (i.e. English), in which the lower reliability of phonology would lead to a slower representation of orthographic features through such bimodal decoding processing. Although behavioral studies have reported results consistent with this idea (i.e. McKay et al., 2008) more cross-linguistic ERP research is needed to further clarify whether inconsistent orthographies are less benefited by lower phonological top-down processes.

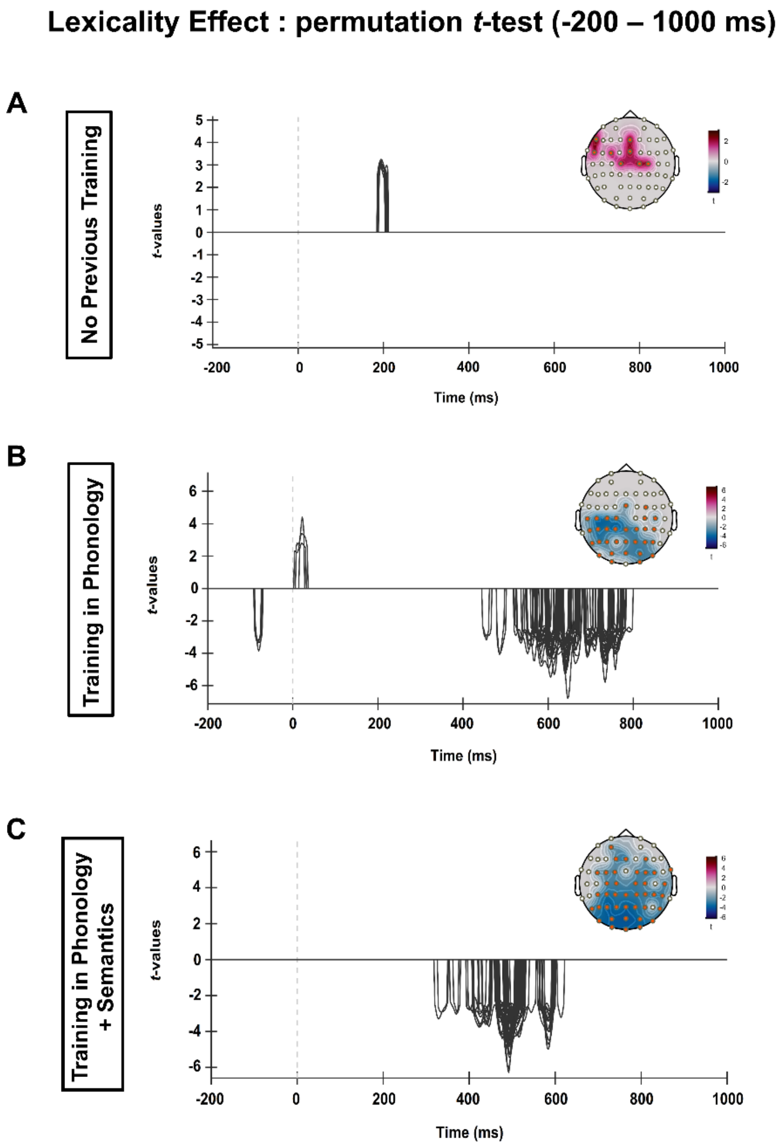
Furthermore, the exposure with the phonological form of novel words also caused a later, post-lexical effect during their visual processing (~520-780 ms). Thus, those novel written word-forms previously experienced at spoken domain showed an enhancement of a late positivity during their first visual encounter, compatible with the modulation of the LPC, and thus causing a lexicality effect. LPC enhancements, resulting from repeated exposure to novel stimuli, have been considered as an index for the formation and strengthening of episodic memory traces for newly-trained stimuli, which likely facilitate its recognition and performance along the task through memory recollection (Bakker et al., 2015; Batterink & Neville, 2011; Bermúdez-Margaretto et al., 2015, 2018). Therefore, the LPC lexicality effect found in the present study under phonological training (experiment 2) likely reflects the access to episodic memory traces for phonological forms built-up during the training phase, which does not occur in the absence of previous training. Moreover, the finding of the left middle temporal pole as one of most likely neural generators for the LPC effect showed by novel words is compatible with the recollection of phonological word-forms carried out during the reading of these stimuli. Indeed, this is a region mainly involved in memory retrieval processes (Damasio et al., 1996, 2004; Tranel, 2009) and it has been also obtained as neural generator for LPC effects in previous ERP studies (Bermúdez-Margaretto et al., 2015; Mazerolle et al., 2007). Importantly, such LPC modulation was much weaker under the combined training (experiment 3), when semantic information was delivered together with phonological cues. Indeed, the late activity elicited by novel words previously trained at both phonology and semantic is likely resembling an after effect driven by the N400-like modulation, rather than a LPC modulation itself. A possible explanation for this differential pattern found in experiment 3 is that the access to semantic information during the combined training likely promotes stronger and interactive memory traces for these stimuli; this information, interconnected across both levels of representation, must be easily accessed during visual word recognition at reading, and hence leading to a less recruitment of episodic memory processes to assist recognition. This pattern of results is compatible with those found in behavioral studies, in which the more associated information provided during training (phonological and semantic rather than only phonological), the better outcomes during visual word recognition (i.e. (Suárez-Coalla et al., 2016).

Finally, results from experiment 3 indicate that access to semantic features during previous experience with novel words at spoken domain influences the visual recognition of these stimuli at late lexical stage (starting around 320 ms), and thus resembling semantic top-down facilitation mechanisms. Thus, a different pattern of results was found at this time window across experiments, with novel written words previously trained at both phonological and semantic level showing a reduced N400-like component in comparison to familiar words; however, such lexicality effect was not found neither after phonological exposure nor in the absence of previous training. Thus, the N400-like lexicality effect is likely reflecting a facilitation in the lexico-semantic processing of novel written words, lead by the access to their semantic referent, represented by the photograph previously associated with their spoken form. Consistently with this idea, the left angular gyrus was found as the most likely neural generator for this N400-like reduction showed for newly trained words; this is an area typically related to multimodal concept representation and retrieval of semantic memories (Binder et al., 2009; Bonner et al., 2013; Bonnici et al., 2016; Davey et al., 2015) and particularly, pointed as a neural correlate of lexical access during visual word recognition

(Binder et al., 2003). Thus, this finding is supporting the statement that previous meaningful training with novel spoken word forms leads to the access to recently-acquired semantic memory traces for these stimuli during their reading (most likely, to visual information extracted from photographs), facilitating their lexico-semantic processing. Importantly, this pattern of results must be understood as lead by a local repetition effect within this particular study, rather than reflecting general differences in the semantic processing of novel and known words. In this sense, although known words were familiar and meaningful, these stimuli were not repeatedly associated to their semantic referents in a previous phase, and hence no semantically-related modulation was observed.

To sum up, the differential pattern of results obtained across the three experiments carried out in this study inform that previous experience of novel written word-forms at spoken domain causes a substantial facilitation during the visual processing of these stimuli, particularly at early orthographic stages. Although access to semantic cues seems to not contribute to such early stages during visual recognition of novel written-words, it promotes a facilitation during their lexico-semantic processing. Overall, the present study provides new evidence about cross-level top-down influences during the visual processing of novel word-forms derived from the access to previously acquired information at other levels of representation. Importantly, tools of extremely precise resolution such as EEG are revealed as excellent methods to determine the temporal locus of such cross-modal top-down facilitatory processes in comparison to behavioral measures, and should be considered as primary methods in future studies within this this strand of research.

Supplementary material



Supp. Fig. 1. Results from permutation t test analyses carried out between known and trained words after each training carried out across Experiments 1, 2 and 3, respectively. Known and trained words were contrasted by means of paired t tests, including a total of 1,000 permutations computed for each sample point across the whole ERP segment, ranging from -200 to 1000 ms. For each comparison at each sample point, t-values reaching statistical significance are displayed (below 0.025 alpha level and maintained for a minimum of 15 ms), together with the topographical map showing the scalp distribution and electrodes in which comparisons reached significance. Based on these results, specific time windows were selected in each experiment, in which the activity for known and novel words was averaged for further analysis.

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