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A robust index of lexical representation in the left occipito-temporal cortex as evidenced by EEG responses to fast periodic visual stimulation

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A B S T R A C T

Despite decades of research on reading, including the relatively recent contributions of neuroimaging and electrophysiology, identifying selective representations of whole visual words (in contrast to pseudowords) in the human brain remains challenging, in particular without an explicit linguistic task. Here we measured discrimination responses to written words by means of electroencephalography (EEG) during fast periodic visual stimulation. Sequences of pseudofonts, nonwords, or pseudowords were presented through sinusoidal contrast modulation at a periodic 10 Hz frequency rate (F), in which words were interspersed at regular intervals of every fifth item (i.e., $F/5$, 2 Hz). Participants monitored a central cross color change and had no linguistic task to perform. Within only 3 min of stimulation, a robust discrimination response for words at 2 Hz (and its harmonics, i.e., 4 and 6 Hz) was observed in all conditions, located predominantly over the left occipito-temporal cortex. The magnitude of the response was largest for words embedded in pseudofonts, and larger in nonwords than in pseudowords, showing that list context effects classically reported in behavioral lexical decision tasks are due to visual discrimination rather than decisional processes. Remarkably, the oddball response was significant even for the critical words/pseudowords discrimination condition in every individual participant. A second experiment replicated this words/pseudowords discrimination, and showed that this effect is not accounted for by a higher bigram frequency of words than pseudowords. Without any explicit task, our results highlight the potential of an EEG fast periodic visual stimulation approach for understanding the representation of written language. Its development in the scientific community might be valuable to rapidly and objectively measure sensitivity to word processing in different human populations, including neuropsychological patients with dyslexia and other reading difficulties.

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1. Introduction

In alphabetic script, words are constituted of letters combined with specific orthographic and phonological rules and conveying a meaning. Though complex, reading proceeds rapidly and effortlessly in literate adults (85–90% of adults across the world). A skilled reader reads about five words per second in a text, so that word identification takes only about 200 ms (Rayner, 1998; Rayner et al., 2012). However, despite decades of research on this uniquely human ability, whether there are brain processes dedicated to automatic (i.e. without any explicit judgment task) discrimination of a valid visual word from a meaningless orthographically legal string of letters (i.e., a pseudoword) remains an outstanding issue.

To address this issue, the present study introduces an original paradigm of EEG recording during fast periodic stimulation of visual words.

Behaviorally, a widely used task for assessing word recognition is the lexical decision task (LDT, Rubenstein et al., 1970), in which participants decide as rapidly as possible if a visually presented letter string is a word as opposed to a nonword (i.e., orthographically illegal) or a pseudoword (i.e., orthographically legal). This task has allowed to identify many variables that affect lexical decision performance, whether intrinsic to stimuli (e.g., frequency, length, orthographic regularity, semantic concreteness, number of semantic attributes, etc.), or extrinsic to stimuli (e.g., effects of the surrounding list as word-likeness at phonological or orthographic levels), constraining functional models of reading to account for these influences along the visual word recognition processes (see Balota et al. (2006) for a review; Grainger, 2008). The LDT has also helped distinguishing between subtypes of surface dyslexia since it provides access to the functional locus of a patient's deficit

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without requiring a phonological output (Friedmann and Lukov, 2008). However, since the LDT requires explicit attention to, and decision about, strings of letters, it measures the outcome of several perceptual, cognitive and decisional processes. Consequently, behavioral studies using LDTs have been unable to determine whether selective representations of visual words can be activated without explicit judgments of the words, an outstanding issue in the reading literature (Shtyrov et al., 2013).

At first glance, since electro- or magneto-encephalography (EEG, MEG) can reveal differential brain responses without requiring explicit processing of the stimuli, this technique seems particularly well suited to address this issue. A visual word presented centrally triggers a negative event-related potential (ERP) peaking over left occipito-temporal sites around 170 milliseconds (ms), the word-related N170 (e.g., Bentin et al., 1999; Rossion et al., 2003; Maurer et al., 2005; Yoncheva et al., 2010) or the M170 in MEG (e.g. Tarkiainen et al., 1999). This component is larger in response to alphabetic items than to nonalphabetic strings such as pseudofonts, symbols and shapes (Bentin et al., 1999; Tarkiainen et al., 2002; Brem et al., 2009) and has been associated with a source in the left ventral occipito-temporal region (Maurer et al., 2005; Cohen et al., 2000). However, most studies report no N170 difference between words and pseudowords, or relatively late differential responses (after 200 ms) over more anterior regions (Bentin et al., 1999; Cohen et al., 2002; Wydell et al., 2003; Pammer et al., 2004; Tarkiainen et al., 1999; see also Nobre et al. (1994) for a lack of words/nonwords difference on N200 visual potentials recorded on the ventral occipito-temporal cortical surface) and a few studies have reported inconsistent effects, i.e. a small increase (Hauk and Pulvermüller, 2004; Maurer et al., 2005) or a decrease (McCandliss et al., 1997) of the N170 to words relative to pseudowords.

The lack of consistent (i.e., reliable) indexes of selective visual word representation in ERP studies is in line with the lack of systematic discriminative response in the left ventral occipito-temporal cortex in neuroimaging (Price, 2012; Seghier et al., 2012), suggesting that selective visual representation of words (i.e. different from pseudowords) do not exist. For instance, in the interactive account framework (Price and Devlin, 2011), responses to visual words merely arise as an interaction between bottom-up visual input and higher level phonological/semantic processing, and not from any selective tuning to orthographic representations. It may also be that selective responses to words are heavily task-dependent (Bentin et al., 1999; Ziegler and Goswami, 2005; Ziegler et al., 1997), so that lexicality-related N170 modulations (e.g., Hauk et al., 2012) require explicit processing of the visual stimuli. Yet, at this stage, one cannot exclude that the lack of consistent indexes of automatic selective visual word representation arises due to the difficulty of isolating selective differences between visual stimuli with a poor signal-to-noise ratio (SNR) approach such as ERPs, or an approach that accumulates neural activity over seconds such as fMRI.

Here we introduce a fast periodic visual stimulation paradigm in EEG for visual word stimulation, to potentially provide a reliable index of visual word vs. pseudoword discrimination without an explicit word-related task. Such an index would not only support the proposal of automatic activation of whole word representations (Glezer et al., 2009; Shtyrov et al., 2013), but would be valuable in assessing potential defective processes of reading in patient populations (e.g., dyslexia) and during both typical and abnormal development. Our approach is based on scalp EEG recordings during periodic visual stimulation, which results in periodic responses defined as "steady-state visual evoked potentials" (SSVEPs, Regan, 1966, 1989). Although this approach has long been confined to the study of low-level visual processes and attention, it has recently been used to measure visual discrimination

responses of complex visual stimuli such as faces (Rossion and Boremanse, 2011). Most recently, Liu-Shuang et al. (2014) measured the discrimination of individual faces by presenting a sequence of identical face stimuli at a fast periodic rate (base frequency=F, 6 Hz) interspersed with different identity face stimuli ("oddball") at a slower periodic rate (i.e., 1 novel face every 5 identical faces). In this study, a robust individual face discrimination response was recorded over the right occipito-temporal cortex, specifically at the oddball frequency rate ($F/5 = 1.2$ Hz) and its harmonics ($2F = 2.4$ Hz, etc.). This approach, with two embedded periodic frequency rates and an analysis of the responses of interest in the frequency-domain (Braddick et al., 1986; Heinrich et al., 2009; Liu-Shuang et al., 2014), has several important advantages for the present question of interest (for review see Rossion, 2014). That is, within a few minutes of stimulation, it provides (1) high SNR visual discrimination responses that are (2) selective to the contrast between the frequent and rare stimuli, (3) objectively identifiable (i.e., at an experimentally-defined frequency rate) and directly quantifiable in the EEG spectrum and (4) obtained without any behavioral task requiring the processing of the parameter of interest, i.e. implicitly.

Considering that these advantages may prove crucial for identifying an automatic representation of visual word form, we applied this approach to the discrimination of written words from control stimuli. Specifically, human observers were presented with visual stimuli at a fast rate of 10 Hz (stimulus onset asynchrony of 100 ms), in sequences structured as follows: xxxx**W**xxxx**W**xxxx**W**…, where "W" refers to words, and "x", depending on the experimental condition, to one of the following stimulus types: pseudofonts (PF), nonwords (NW, sequences of orthographically illegal letter strings), or pseudowords (PW, sequences of orthographically legal letter strings). We hypothesized that if words are discriminated from pseudofonts, nonwords, or even pseudowords, their periodic occurrence should lead to a periodic EEG response at the oddball frequency, i.e., at 2 Hz and its harmonics. Further, we hypothesized that if behavioral list context effects as reported in the literature (e.g., the more or less word-like sequence; Lupker and Pexman, 2010; Stone and Van Orden, 1993; Pugh et al., 1994) are due to visual discrimination processes rather than decisional levels, then the sequence type should determine the strength of the discrimination response. More precisely, the oddball response to words should be larger in nonword sequences (which are less word-like) than in pseudoword sequences (which are more word-like).

2. Experiment 1

2.1. Material and methods

2.1.1. Participants

Ten right-handed healthy participants (2 males, mean age=25.3; range 20–42), all native French speakers, with normal/corrected-to-normal vision, were tested after giving written informed consent for a study that was approved by the Biomedical Ethical Committee of the University of Louvain. They received financial compensation for their participation. They were unaware of the goals of the experiment and that a change of stimulus type occurred at a periodic rate.

2.1.2. Stimuli

Words, pseudowords, nonwords, and pseudofonts (30 of each type) all constituted of 5 elements (letters or pseudoletters) (Fig. 1). French words were selected from the *Lexique 3.55* database (New et al., 2001) with the following criteria: They were frequent common nouns (84.99 per million) in singular form, with limited orthographic neighbors (average 1.9, range from 0 to 4), no foreign
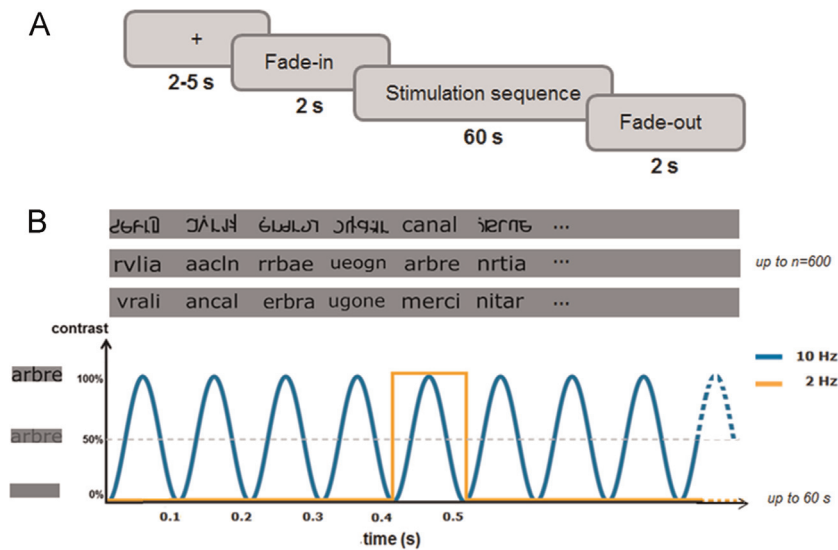
Fig. 1. Experimental paradigm. (A) Timeline of a trial. (B) Stimuli were presented by sinusoidal contrast modulation at 10 Hz during 60 s, each stimulus reaching full contrast after 50 ms before fading down in 50 ms (duration of one cycle was 100 ms). Given that such stimuli are visible even at very low contrast, the presentation duration ranges from 80 ms to 100 ms. Examples are given for the three types of sequences: base stimuli were either pseudofonts (top row), nonwords (middle row), or pseudowords (bottom row), and the oddball stimuli were words that appeared every fifth item (10/5=2 Hz). Stimuli were randomly selected, with no immediate repetition, and appeared continuously on the screen until 60 s were elapsed (thus, there were 600 stimuli per trial).

language origin (e.g., hotdog, Frisbee, etc.), and no accents. Pseudowords and nonwords were built on an item-by-item basis by rearranging the letters of the words (e.g., *avril* (W, English translation: April), *vrali* (PW), *rvlia (NW)*). Pseudowords were pronounceable and respected the phonological rules in French. Nonwords were unpronounceable. Pseudofont items were also built on an item-by-item basis: letters from words were vertically flipped and segmented. These segments were then rearranged into pseudo-letters, respecting the number of elements (5) and the overall size (width × height) of the original word. Pseudo-letters contained junctions, ascending/descending features, and close-up shapes (see Fig. 1 for examples of stimuli, and supplementary material for a full list of stimuli). Each word thus had a corresponding PW, NW, and PF containing the exact same amount of black-on-white contrast, so that all conditions were similar in terms of lower-level visual properties, especially spatial frequency. Bigram frequencies were calculated with Wordgen (Duyck et al., 2004) and are reported as summated type bigram frequencies (from the French CELEX database), which differed between words (mean ± SE: 12,038 ± 678) and nonwords (4650 ± 512; $t(29)=$ 10.665, $p < 0.0001$) as well as between words and pseudowords (9059 ± 784; $t(29)=4.485$, $p < 0.0001$). Stimuli were presented in Verdana font, as images with a height between 40 and 70 pixels and a width between 140 and 225 pixels, depending on the shape of individual letters. At a distance of 1 m with a screen resolution of 800 × 600 pixels, they ranged from 3.7 to 6.7 (width) and 1.0 to 1.8 (height) degrees of visual angle.

2.1.3. Procedure

Each trial started with a fixation cross displayed for 2–5 s (duration randomly jittered between trials), after which the stimulation gradually faded-in by progressively increasing modulation depth from 0% maximum contrast level to 100% in 2 s. The sequence of stimulation was presented for 60 s, after which the stimulation faded out in 2 s (Fig. 1A). The stimulation fade in and fade out were used to avoid abrupt eye-movements or blinks at the beginning or near the end of a trial. Stimuli were presented by means of sinusoidal contrast modulation at a base frequency rate of 10 Hz[1] (i.e., one item every 100 ms, from a grey background to

full contrast and back in 100 ms, hence reaching full contrast at 50 ms) (Fig. 1B). Given that the stimulus can be recognized at very low contrast (20%) the actual duration of stimulus visibility is close to 100 ms. Every fifth item of the sequence was a word (oddball frequency of 2 Hz, thus every 500 ms). MATLAB 7.8 (The Mathworks) with PsychToolbox (Brainard, 1997, see http://psychtoolbox.org/) was used for stimulus display. A sinusoidal contrast-modulation function was used, as in several SSVEP studies with low-level visual stimuli (Victor and Conte, 2000; Di Russo and Spinelli, 2002; Sutoyo and Srinivasan, 2009; Zemon and Ratliff, 1984; see also Giani et al. (2012), for a sinusoidal modulation of luminance and size) and our previous studies with face stimuli (e.g., Rossion and Boremanse, 2011; Liu-Shuang et al., 2014). A practical advantage of this mode of stimulation is that it is a smoother stimulation mode than a squarewave stimulation, a parameter that makes the experiment more comfortable for the participant. This factor is especially important given the long stimulation duration used here.

The base rate of 10 Hz was selected based on two criteria. First, this frequency gives the largest SSVEP to luminance changes (Regan, 1966, 1989). Second, a 10 Hz rate corresponds to a stimulus onset asynchrony (SOA) of only 100 ms, minimizing the contribution of high-level visual areas to the base rate response obtained (Prieto et al., 2013). Based on previous studies, the response at 10 Hz should be localized over medial occipital sites (Prieto et al., 2013) making it easier to disentangle this response from a potential discrimination response at a slower oddball rate (i.e., 2 Hz) that we expect to observe over high level visual areas (i.e. lateral occipital cortex, or occipito-temporal cortex, Prieto et al., 2013; Liu-Shuang et al., 2014). Note that at a base rate of 10 Hz, the oddball frequency, corresponding to the presentation of a word, was 2 Hz, or a SOA of 500 ms between two words in a sequence.

We used only a small number of trials by condition (3) because the approach has a very high SNR and one of the objectives of the

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[1] Due to the refresh rate of the computer screen, the precise stimulation occured at 9.9946 Hz for the base rate, hence at 1.9989 Hz for the oddball rate. For clarity of reading, we use the rounded format of 10 Hz and 2 Hz throughout the paper.

study was to demonstrate that we could obtain selective responses to visual words in a short amount of time. However, the trials were of a relatively long duration (60 s). With a long stimulation window, one can apply the Fourier transform to a long recording window, so that the frequency resolution of the spectrum is very high (1/duration (s); Regan, 1989). It means that all of the response of interest, and thus all the potential difference between conditions, can be concentrated in a discrete frequency band around the stimulation frequency. This frequency band occupies a very small fraction of the total EEG bandwidth. In contrast, biological noise is distributed throughout the EEG spectrum, resulting in a SNR in the bandwidth of interest that can be very high (Regan, 1989; Rossion, 2014). Note that such long duration windows have been used in a number of previous studies (e.g., Chen et al., 2003; Di Russo and Spinelli, 2002; Giani et al., 2012; Srinivasan et al., 1999; Sutoyo and Srinivasan, 2009; Zemon and Ratliff, 1984) and the combination of few trials with a long duration has been used in all our previous studies with face stimuli (for review see Rossion (2014)).

Three conditions were compared. Oddball stimuli always consisted of randomly selected words (W), inserted in three different sequences of base stimuli (PF, NW, or PW). Each condition was repeated 3 times, resulting in a total of 60 s × 3 (repetitions) × 3 (conditions), and thus 9 min of experimentation in total. There was a break of about 1 min between stimulation sequences, which were initiated manually to ensure low-artifact EEG signals.

During the stimulation, participants continuously fixated a central cross, and were instructed to press the space bar upon detection of each brief (200 ms) fixation cross color change (blue to red; 6 changes randomly timed per sequence). Color changes occurred independent of word-type manipulation and were included to maintain a constant level of attention throughout the entire experiment. There were neither significant differences between condition with respect to correct response time [$F(2,8) < 1$], nor accuracy [$F(2,8) < 1$], for this orthogonal task.

2.1.4. EEG acquisition

During EEG recording, participants were seated comfortably at a distance of 1 m from the computer screen in a dimly-lit and sound-attenuated room. EEG was acquired at 512 Hz using a 128-channel Biosemi Active II system (Biosemi, Amsterdam, Netherlands), with electrodes including standard 10–20 system locations as well as additional intermediate positions (http://www.biosemi.com). Two additional electrodes (Common 252 Mode Sense [CMS] active electrode and Driven Right Leg [DRL] passive electrode) were used as reference and ground electrodes, respectively. Eye movements were monitored using four electrodes placed at the outer canthi of the eyes and above and below the right eye.

2.1.5. EEG analysis

2.1.5.1. Preprocessing. All EEG analyses were carried out using Letswave 5 (http://nocions.webnode.com/letswave), and Matlab 2012 (The Mathworks). After band-pass filtering between 0.1 and 100 Hz, EEG data were segmented to include 2 s before and after each sequence, resulting in 64-s segments (-2–62 s). Data files were then downsampled to 250 Hz to reduce file size and data processing time. Artifact-ridden or noisy channels were replaced using linear interpolation (only one electrode in one participant). Note that the approach is highly resistant to artifacts, and the data was virtually identical without interpolation (Fig. S1 in Supplementary material). All channels were re-referenced to the common average. EEG recordings were then segmented again from stimulation onset until 59.5 s, corresponding exactly to 119 complete 2 Hz cycles within stimulation. This is the largest amount of complete cycles of 500 ms at the oddball frequency (2 Hz) within the 60 s of stimulation period.

2.1.5.2. Frequency domain analysis. The three trial repetitions of each condition were averaged in the time domain, for each condition (PF, NW, PW) within each individual participant separately in order to reduce EEG activity that is not phase-locked to the stimulus. A Fast Fourier Transform (FFT) was then applied to these averaged segments, and amplitude spectra were extracted for all channels (square root of the sum of squares of the real and imaginary parts divided by the number of data points). Thanks to the long time-window (59.5 s), the frequency analysis yielded spectra with a high frequency resolution (1/59.5 s=0.0166 Hz) and allowed the unambiguously identification of the response at the exact frequencies of interest (i.e., 10 Hz for the base stimulation rate and 2 Hz and its harmonics for the oddball-word stimulation).

Z-scores were calculated (difference between amplitude at the frequency of interest and mean amplitude of 20 surrounding bins divided by the standard deviation of the 20 surrounding bins) to identify the presence of statistically significant responses at the oddball frequency and harmonics. Z-scores larger than 1.96 ($p < 0.05$, two-tailed) were considered significant.

Finally, SNR spectra were computed for the whole frequency spectrum as the ratio of the amplitude at each frequency to the average of the 20 surrounding bins (10 on each side, excluding the immediately adjacent bins) (e.g., Rossion et al., 2012; Liu-Shuang et al., 2014; see also Meigen and Bach (1999) for the value of noise estimates from neighboring spectral lines). For the group analysis, SNR spectra of individual participants were averaged within each condition.

2.2. Results

2.2.1. Base stimulation frequency

In all conditions, the response at the base stimulation rate (10 Hz) peaked on medial occipital sites, around electrode Oz, as expected (Fig. 2A). EEG amplitude and SNR values at the base stimulation rate (10 Hz) are provided in Table 1 for each condition. SNR spectra between 8 and 12 Hz, with topographical maps of the 10 Hz response, are shown in Fig. 2A.

According to our previous studies with such an oddball paradigm (e.g., Liu-Shuang et al., 2014), we hypothesized to find a peak at 10 Hz, which reflects the synchronization of the visual system to the periodic stimulation, and serves to ensure that participants attended the stimuli. A one-way ANOVA on the SNR response in Oz yielded no significant difference between conditions at the base stimulation rate ($F(2,8) < 1$; $p=0.4$, Fig. 2B). Since the response to frequency-tagged stimuli is substantially increased by selective attention (e.g., Morgan et al., 1996; Walter et al., 2012), the lack of difference between conditions suggests that the level of attention was comparable in all conditions, in particular when pseudowords were presented as compared to nonwords or pseudofonts.

2.2.2. Oddball frequency (nF/5): discriminative response to words

In sequences where words were inserted in pseudofonts, significant responses were found at 2 Hz (see Table 1), with a peak on left occipito-temporo-parietal sites (around electrode PO7) and a lower response on the homologous right hemisphere channel (electrode PO8) (Fig. 3A). First, we ranked all 128 electrodes according to the SNR values, from the highest to the lowest. This ranking confirmed that PO7 was among the first 3 electrodes with the highest SNR in each condition and at each harmonic of the response. Then, Z-scores were computed for each condition at 2 Hz and its harmonics (4 Hz, 6 Hz, 8 Hz) on PO7. They are reported in Table 1, with their significance level. As in previous fast periodic oddball studies (Heinrich et al., 2009; Liu-Shuang et al., 2014), there were also significant responses at the harmonics of 2 Hz ($2F/5=4$ Hz, $3F/5=6$ Hz, see Table 1), indicating that the shape of the responses to individual stimuli is such that the chain of
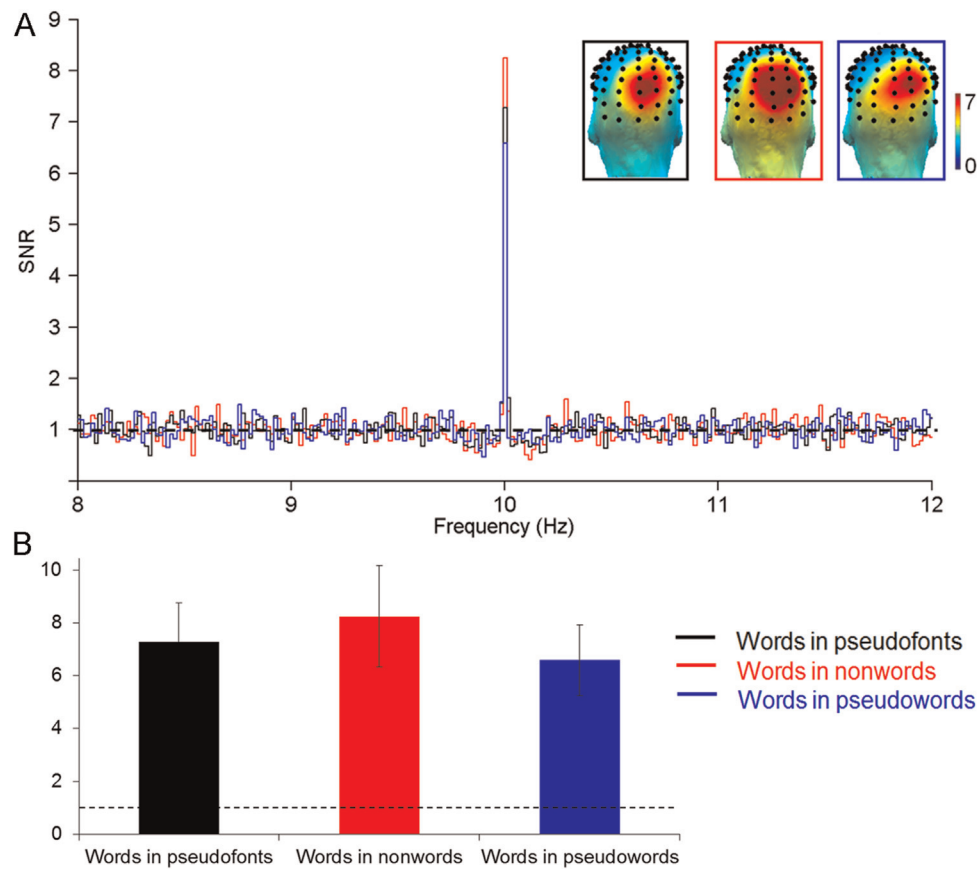
Fig. 2. (A) EEG spectra (SNR) and scalp topographies of the three conditions on electrode Oz (central- occipital) from 8 to 12 Hz, showing a peak at the base stimulation frequency (10 Hz). (B) The same data (SNR at electrode Oz) is represented as a bar graph, with standard errors of the mean. The response at the base frequency did not differ statistically across the three conditions at medial occipital sites (i.e. ANOVA with conditions (3) x electrodes (O1, Oz, O2); no main effect of condition $F(2,9)=1.620$; $p=0.2$; electrode $F(2,9)=1.002$; $p=0.4$; and no interaction $F(4,7)<1$; $p=0.7$). The dotted line indicates a SNR of 1 (i.e., no signal). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

overlapping single-stimulus responses differs from a sine wave with a frequency equal to the oddball stimulation frequency (for discussion see Heinrich (2010)). This $n2$ Hz response reflect the discrimination of words from pseudofont stimuli, and its scalp topography contrast with the response observed at the 10 Hz base rate, which peaks at medial occipital sites (Oz, Fig. 2A). Critically, distinct oddball responses to words at 2, 4 and 6 Hz were also found in the other two types of sequences containing letters (NW and PW) (Fig. 4A). These visual discrimination responses were smaller than in pseudofont sequences, and were mainly left-lateralized over the occipito-temporo-parietal region.

To compare the conditions, the data were averaged across the first three oddball harmonics for each condition and participant separately (Liu-Shuang et al., 2014). The fourth harmonic (8 Hz) was excluded from further analyses since it was weaker than all other harmonics and did not reach significance in all of the conditions (see Table 1). Based on the scalp topographies (Fig. 5B) and the importance of the left and right occipito-temporal areas (LOT and ROT) for letter and word recognition (see Carreiras et al., 2014) for a recent review), the left occipito-temporo-parietal region (5 electrodes including and around electrode PO7) was defined as the primary region of interest. This region included the two electrodes

Table 1
Grand averaged data for all conditions displayed in columns. At the base stimulation frequency (10 Hz), data are reported for electrode Oz (medial occipital), where the 10 Hz response was the largest in all conditions. For the oddball stimulation frequency (2 Hz), and its harmonics (4, 6, 8 Hz), the values are reported for electrode PO7 (left occipito-temporal), the electrode giving rise to the largest response on average. Significant responses are found for all conditions, except for the fourth harmonic of the oddball response. p-Values were calculated on the basis of Z-scores and are reported as follows: [ns]: p-value > 0.05, * $Z > 1.64$, p-value < 0.05; ** $Z > 2.03$, $p < 0.01$. SNR is calculated by computing the ratio between the amplitude at the frequency bin of interest and the 10 surrounding frequency bins on each side (i.e., a SNR of 2 corresponds to a 100% increase of signal).

| Grand averaged values	Frequency of interest (Hz)	Words in pseudofont			Words in nonwords			Words in pseudowords		
		SNR	μV	Z-score	SNR	μV	Z-score	SNR	μV	Z-score
Base frequency response, electrode Oz	10	7.27	1.028	35.20**	8.24	1.056	34.94**	6.58	0.912	32.89**
Oddball frequency responses, electrode PO7	2	3.791	0.458	14.67**	2.012	0.594	3.54**	1.763	1.036	3.15**
	4	6.734	0.300	40.92**	1.996	0.394	8.67**	1.779	1.275	4.82**
	6	4.125	0.278	22.10**	2.096	0.316	8.95**	1.957	0.644	5.04**
	8	1.569	0.148	2.43*	1.530	0.194	2.47*	ns	0.227	0.55[ns]
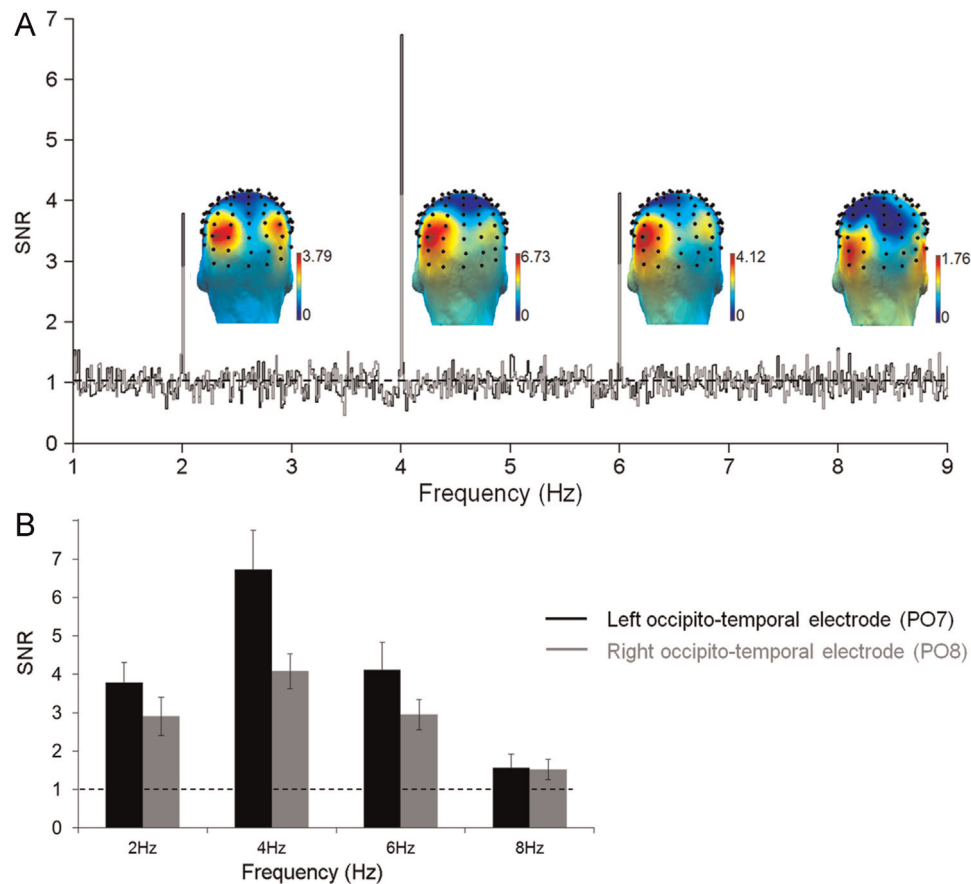
Fig. 3. (A) Grand averaged EEG spectrum (signal-to-noise ratio, SNR) displayed from 1 Hz to 9 Hz for the discrimination response to words (at 2 Hz and harmonics) in the pseudofont condition on a left (PO7) and right (PO8) occipito-temporal electrode. (B) The same data is represented as a bar graph, with standard errors of the mean. The dotted line indicates a SNR of 1 (i.e., no signal). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

showing the largest response for all three conditions. The right homologous region was also considered.

2.2.3. ROI analysis

Fig. 5A depicts the mean SNR at the average of the oddball frequency and its second and third harmonic (i.e., 2, 4, and 6 Hz), for each condition in the LOT and ROT. In the LOT, all conditions had an SNR significantly higher than 1 (1=noise level): words in pseudofont sequences ($t(9)=5.784$; $p < 0.0001$); in nonword sequences ($t(9)=3.515$; $p=0.007$); in pseudowords sequences ($t(9)=2.820$; $p=0.02$). In the right ROI, only words embedded in pseudofont and nonword sequences resulted in an SNR higher than 1 ($t(9)=6.954$; $p < 0.0001$ and $t(9)=3.323$; $p=0.009$, respectively), while it was not significant for words in pseudowords ($t(9)=0.4951$; $p=0.6$).

We calculated a 2×3 ANOVA on SNR with factors *Hemisphere* (left, right) and *Condition* (PF, NW, PW) as within-subjects factors. Two main effects were significant: *Hemisphere* [left > right; $F(1,9)=8.397$; $p < 0.01$] and *Condition* [$F(2, 8)=34.509$; $p < 0.0001$] but the interaction between these terms was not significant [$F(2, 8) < 1$]: the discrimination response to words was larger in the left than in the right hemisphere in all conditions.

Nevertheless, as the left hemisphere is known to play a capital role in reading (Bentin et al., 1999; Price, 2012) and that it is unclear from the literature if the left occipito-temporal region codes only for letters, for orthographic structures, or even for whole-words (Price and Devlin, 2003; Cohen et al., 2002; Glezer et al., 2009), we contrasted specifically the conditions in the left ROI. Paired *t*-tests revealed that the oddball response in the LOT to words embedded in pseudofonts was larger than that to words in

nonwords ($t(9)=-6.956$; $p < 0.0001$) and pseudowords ($t(9)=-6.937$; $p < 0.0001$), and the response was larger for words in nonwords than in pseudowords ($t(9)=2.730$; $p=0.023$).

Overall, these results show a significant response in the LOT to words embedded in all three stimulus types, and in the ROT for words embedded in pseudofonts and nonwords. However, this response increases with the high-level contrast between the oddball and the type of base stimuli in the sequence.

2.2.4. Individual discrimination responses

We also assessed the sensitivity of our approach by evaluating (1) whether each individual participant showed a discrimination response to words and (2) the congruency of the scalp topography among participants, that is, to check whether individual responses would all fall within the ROI that we had defined at the group level. To do so, the responses at the three first harmonics (2, 4, and 6 Hz) were averaged separately for each participant; for visualization, each harmonic response in the EEG spectra was displayed centered on the frequency bin of interest, with 10 neighboring bins on each side (Fig. 6). In the absence of signal at the central bin of interest, the value at this bin has 1 chance out of 21 (i.e., $p < 0.05$) to be the highest in the spectrum. Strikingly, and considering only an electrode falling in the ROI defined on grand-averaged data (i.e., LOT), the bin of interest showed the highest SNR for all of the 10 participants when words were inserted in pseudofonts, and in 8 out of 10 participants for words in nonwords and pseudowords (Fig. 6). In one of the participant (P#8) who did not show this effect for words *vs.* pseudowords, the SNR was also relatively weak even in the words *vs.* pseudofonts sequences. Moreover, in every participant, the response is left-lateralized and
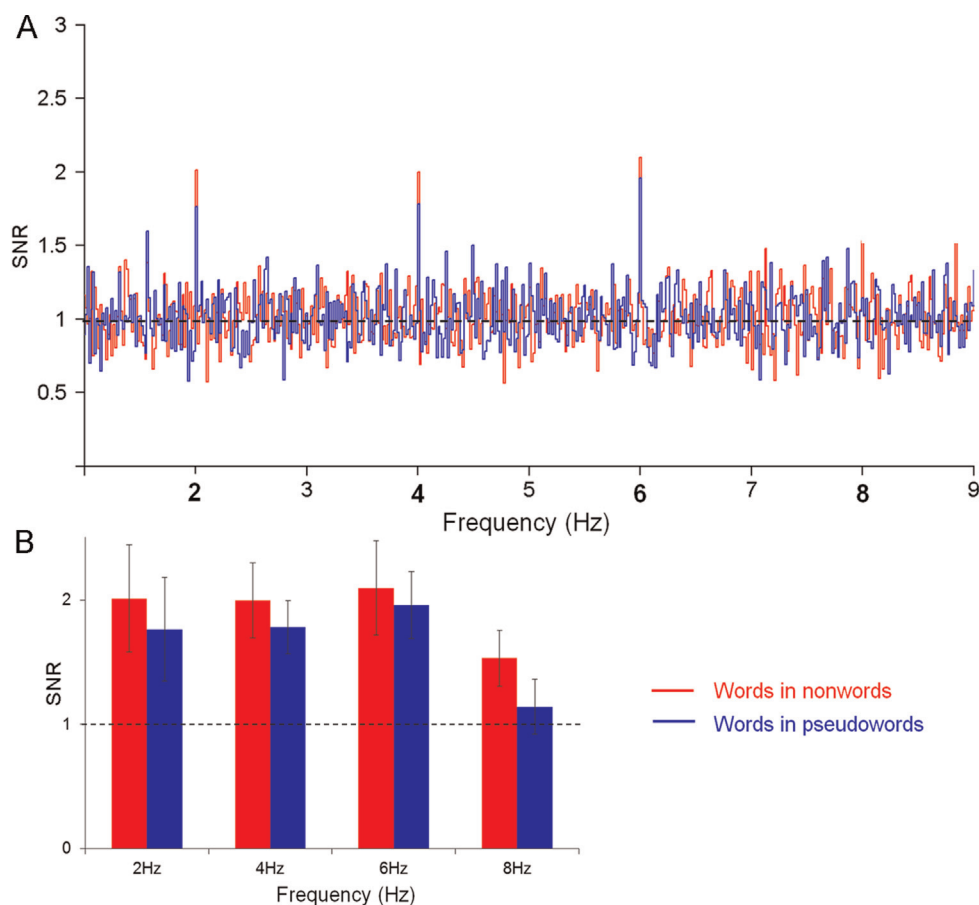
Fig. 4. (A) Grand averaged EEG Spectrum (SNR) on a left occipito-temporal electrode (PO7) at the oddball frequency (2 Hz) and its harmonics for the words in nonwords or pseudowords sequences, showing the larger discrimination response for words in nonwords, at all harmonics. (B) The same data is represented as a bar graph, with standard errors of the mean. The dotted line indicates a SNR of 1 (i.e., no signal). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
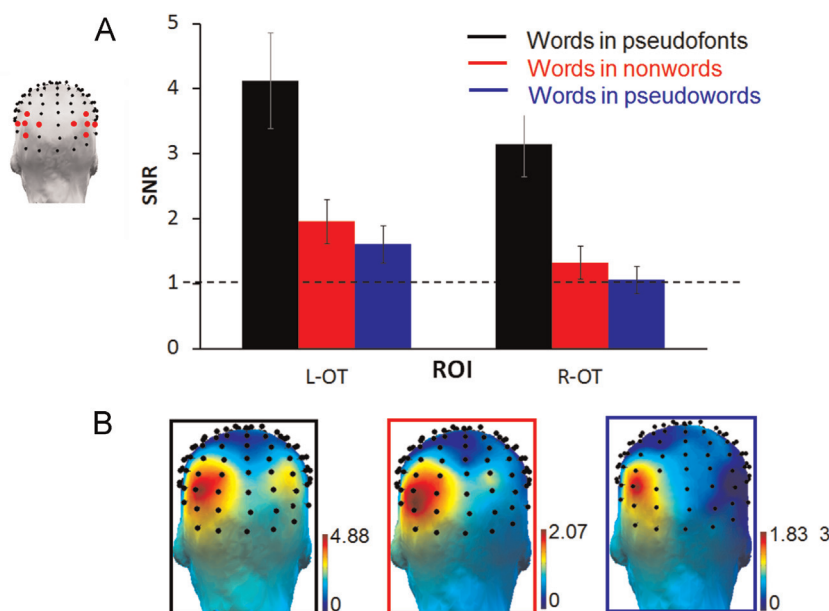

Fig. 5. (A) In the upper-left panel, electrodes selected for each ROI are represented by red dots. The histogram depicts the mean SNR values and standard deviation for each condition in left occipito-temporal and right occipito-temporal ROIs, with a dotted line at noise level. In the L-OT, the signal of all three conditions differs significantly from noise, and all conditions significantly differ from each other. In the R-OT, responses to oddball words significantly differ from noise in pseudofont and nonword conditions but not in the pseudoword condition. (B) Topographical maps of the grand averaged data of the oddball response to words for the average of the three first harmonics (2, 4, 6 Hz) for each condition (black frame: pseudofonts, red frame: nonwords, blue frame: pseudowords). ROI=region of interest; L-OT=left occipito-temporal; R-OT=right occipito-temporal. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

concentrated on the ROI defined at the group-level (on five different electrodes), except for two participants (P#1 and P#5) whose responses are more bilateral and/or right-lateralized (Fig. 6).

2.3. Summary and discussion

Our results show that words embedded periodically in sequences of pseudofonts or alphabetic strings generate a discrimination response at 2 Hz and harmonics. This response is strongest in the left occipito-temporal region, and is largest for words embedded in pseudofonts, then in nonwords and finally in pseudowords, thus varying with the nature of the contrast. Considering the very short duration of experimental testing (three minutes for each condition) the observation of a discrimination response for words among alphabetic sequences (non-words and/or pseudowords) is particularly remarkable.

At a neural level, the recorded oddball response presumably stems from population of neurons coding for properties that differentiate the stimuli. Classically, access to lexical levels of representation is assessed by comparing effects obtained on words

to effects on pseudowords, whether behaviorally (see Balota et al., 2006) or with EEG (Hauk et al., 2006a,b). Therefore, a first interpretation of our findings in this experiment is that the discrimination response to words stems from an automatic lexical access to whole-word forms.

However, recent research and models of word recognition argue that the statistical regularities in the combination of letters that co-occur in visual words builds an orthographic code based on frequently occurring letter combination and their relative order (e.g., open-bigrams proposal, Grainger and Van Heuven, 2003; Mariol et al., 2008), therefore emphasizing the importance of bigram frequency during orthographic processing. Here our pseudowords and nonwords were anagrams of words, since they contained the same letters rearranged in a different order, and thus our results suggest that the discrimination stems from levels at which the content of what is coded is more than just location-specific letter detectors (Dehaene et al., 2005). However, since bigram frequency affect brain responses around 100 ms, in a close succession of, or even overlapping, orthographic and lexical processes (Hauk et al., 2006b; see also Vinckier et al. (2007) for a posterior-to-anterior increasing gradient of selectivity to word-like
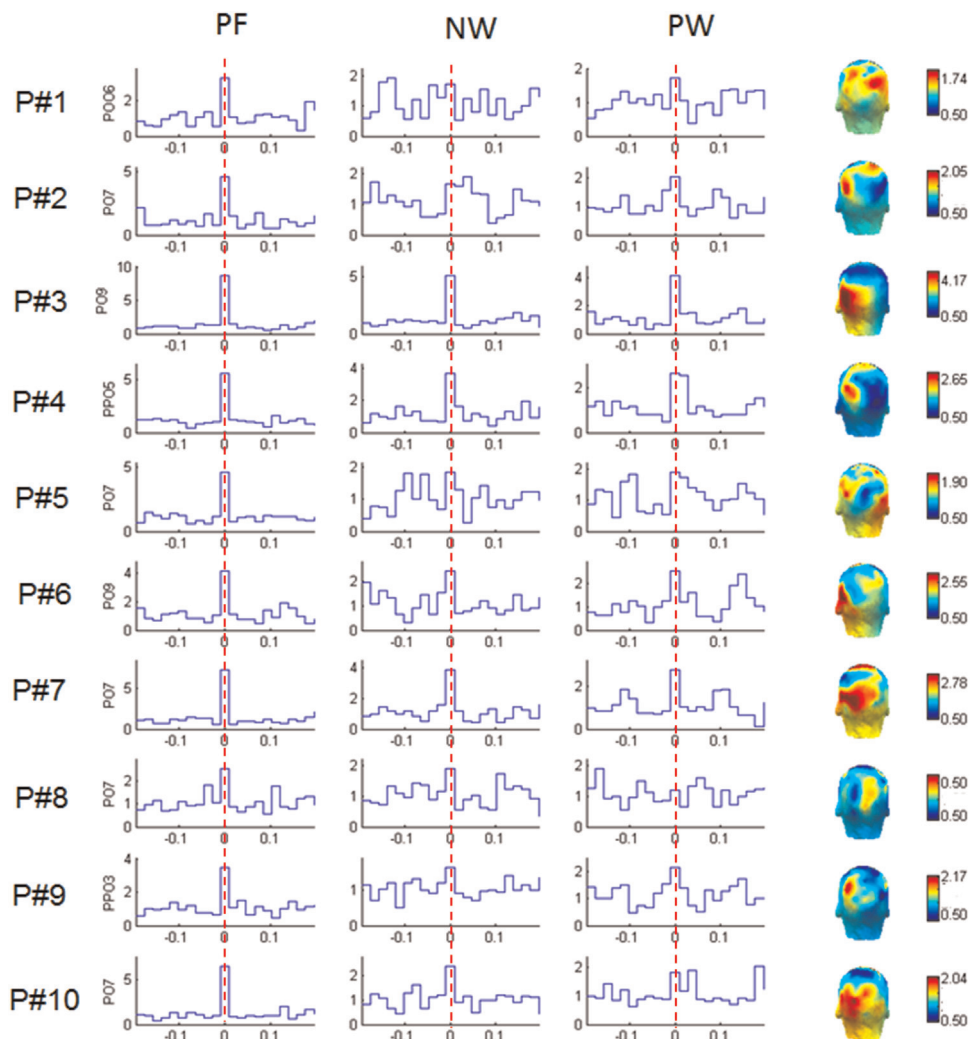

Fig. 6. Mean SNR of the electrode giving the largest mean oddball response at the first three oddball harmonics (2, 4, and 6 Hz) and the 10 surrounding frequency bins on either side, plotted with the averaged oddball harmonic response centered on zero (red dotted line). The three conditions are shown in columns, and individual participant data is plotted in the rows. The data displayed for each condition was recorded in 3 min. First column: words in pseudofonts, (2) in nonwords, and (3) in pseudowords. Scalp topographies are shown for the discrimination of words among pseudowords (i.e., the most fine-grained contrast to reveal lexicality effects). Note that the electrode showing the largest mean oddball response in the left hemisphere is localized in the occipito-temporal ROI in 9/10 participants, and that this electrode is exactly PO7 in 5 out of 10 participants. Three of these participants show scalp topographies that are nevertheless bilateral or right-lateralized, but one participant (P#1) shows the largest response in the right hemisphere. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

stimuli in the left ventral occipital cortex) our results could reflect both lexicality and sensitivity to bigram frequency (Woollams et al., 2011). Indeed, in our study, bigram frequency differed between conditions (see Methods).

Thus, two factors can account for the discrimination responses for words embedded in pseudowords sequences in this experiment: lexical access or higher bigram frequency, or a combination of both. In order to clarify this issue, we ran a second EEG experiment, manipulating these two factors separately. In a first condition, words were embedded in pseudowords as in Experiment 1, but this time we controlled for bigram frequency: words and pseudowords were equated on this factor, by increasing the bigram frequencies of pseudowords (hbf PW, high bigram frequency pseudowords). Therefore, if a discrimination response is found for words, it cannot be accounted for by this pre-lexical factor. In a second condition, we varied the bigram frequencies in two sets of pseudowords, thus canceling the lexical access factor. The base stimuli were pseudowords with high bigram frequency (hbfPW), and the oddball stimuli were also pseudowords, but with significantly lower bigram frequency values (lbfPW, low bigram frequency pseudowords). If oddball EEG responses are observed in the first condition (hbfPW-W) but not in the second condition (hbfPW-lbfPW), then the oddball discrimination responses can be attributed to word-specific processes, such as lexical access. If oddball responses are not observed in the first condition but only in the second condition contrasting only bigram frequency values (hbfPW-lbfPW), then they can be attributed solely to this pre-lexical factor. Finally, another possibility is that both conditions give rise to oddball discrimination responses, leading to the conclusion that both factors are automatically detected and play a role in the discrimination response that we observed for words in pseudowords sequences in Experiment 1

3. Experiment 2

3.1. Materials and methods

3.1.1. Participants

Ten right-handed healthy participants (2 males, mean age=22.7; range 20−24), all native French speakers, with normal/corrected-to-normal vision, were tested after giving written informed consent for a study that was approved by the Biomedical Ethical Committee of the University of Louvain. They received financial compensation for their participation. They were not informed about the goal of the experiment and that a change of stimulus type occurred at a periodic rate.

3.1.2. Stimuli

Words (W), pseudowords with high bigram frequency (hbfPW), and pseudowords with low bigram frequency (lbfPW) (30 of each type) were all constituted of 5 letters. Words were the same as in Experiment 1. For the first condition contrasting words and pseudowords, a new set of pseudowords was built by rearranging letters of the words (high bigram frequency pseudowords, hbfPW), so that summated type bigram frequency (calculated in Wordgen, Duyck et al., 2004) was not significantly different than for words (hbfPW mean value: 11521 ± 751; $t(29)=0.458$, $p=0.65$). For the second condition contrasting two types of pseudowords varying in bigram frequency, a new set of pseudowords (low bigram frequency pseudowords, lbfPW) was built so that the summated type bigram frequency was significantly lower (6153 ± 437; $t(29)=15.46$, $p < 0.0001$) than in the base hbfPW. Both sets of pseudowords were pronounceable. Stimuli were presented in Verdana font, as images with a height between 40 and 70 pixels and a width between 140 and 225 pixels, depending on the shape
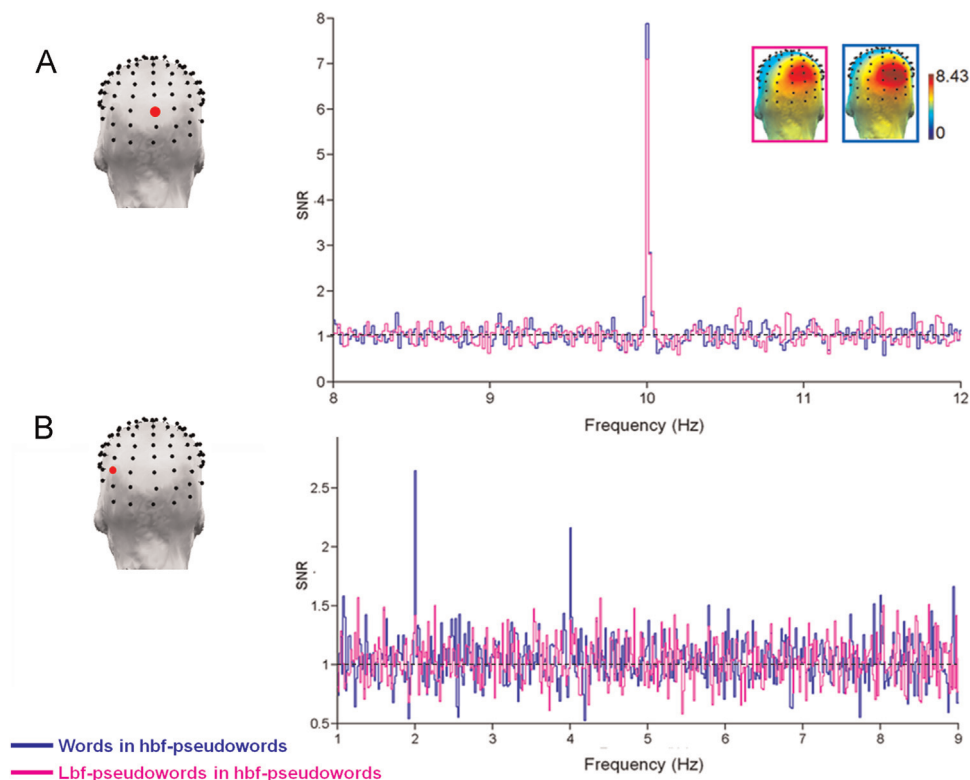

Fig. 7. Experiment 2. (A) EEG spectra (SNR) and scalp topographies of the two conditions on electrode Oz (central- occipital) from 8 to 12 Hz, showing a peak at the base stimulation frequency (10 Hz). The response at the base frequency did not differ statistically across the three conditions at medial occipital sites (i.e. around electrode Oz). (B) Grand averaged EEG Spectrum (SNR) on a left occipito-temporal electrode (PO7) at the oddball frequency (2 Hz) and its harmonics for the words in pseudowords sequences, showing the greater discrimination response in the former, at all harmonics. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of individual letters. At a distance of 1 m with a screen resolution of 800 × 600 pixels, they ranged from 3.7 to 6.7 (width) and 1.0 to 1.8 (height) degrees of visual angle.

3.1.3. Procedure

Two conditions were compared. In both cases, the base stimuli consisted of the high bigram frequency pseudowords (hbfPW) matched to words. In the first condition, the oddball stimuli consisted of matched words (W) in sequences of the type: hbfPW hbfPW hbfPW hbfPW **W** hbfPW hbfPW hbfPW … In the second condition the oddball stimuli consisted of randomly selected pseudowords with low bigram frequency (lbfPW) in sequences of the type: hbfPW hbfPW hbfPW hbfPW **lbfPW** hbfPW hbfPW hbfPW …. Each condition was repeated 5 times, resulting in a total of 60 s × 5 (repetitions) × 2 (conditions), and thus 10 min of experimentation in total.

The rest of the procedure was the same as in Experiment 1.

3.1.4. EEG acquisition and analysis

EEG acquisition and analysis were the same as in Experiment 1.

3.2. Results

3.2.1. Base stimulation frequency

In both conditions, the response at the base stimulation rate (10 Hz) peaked on medial occipital sites, around electrode Oz, as expected (Fig. 7). SNR spectra between 8 and 12 Hz, with topographical maps of the 10 Hz response, are shown in Fig. 7A. There was no significant difference in SNR between conditions at the base stimulation rate (Oz, $t(9)=0.148$; $p=0.88$)

3.2.2. Oddball frequency (nF/5): discriminative response to words

In the first condition, where oddball words were inserted in sequences of hbf-pseudowords, significant discrimination responses were found at 2 Hz (Z-score=3.53) and its second harmonic (Z-score=2.29), with a peak on left occipito-temporo-parietal sites (around electrode PO7). These responses reflect the discrimination of words from hbf-pseudowords stimuli, even when they do not differ in terms of bigram frequency, unlike Experiment 1. In the second condition, where lbf-PW were inserted periodically in hbf-PW, there was no significant discrimination response at 2 Hz and its harmonics, on any electrode of the whole scalp (all Z-scores < 1.65). This indicates that a bigram frequency difference between the pseudowords stimuli presented at the base rate and the pseudowords oddball stimuli is not sufficient to trigger a discrimination response. As in Experiment 1, and in order to compare the conditions, the data were averaged across the significant oddball harmonics for each condition and participant separately (Liu-Shuang et al., 2014). Based on the scalp topographies (Fig. 8), the same two occipito-temporal ROIs as in experiment 1 were defined for statistical analysis.

3.2.3. ROI analysis

Fig. 8 depicts the mean SNR at the average of the oddball frequency and its second harmonic (i.e., 2 Hz, and 4 Hz), for each condition in the LOT and ROT. In both regions, we compared the response obtained to noise level (SNR=1). Only the response to words in hbfPW had an SNR significantly higher than 1 both in the left ($t(9)=2.913$; $p=0.017$) and in the right ($t(9)=3.183$; $p=0.011$) hemispheres. In contrast, SNR did not differ from 1 for lbfPW inserted in hbfPW, both in the left ($t(9)=1.550$; $p=0.156$) and in the right ($t(9)=1.379$; $p=0.201$) hemispheres.

Then, we calculated a 2 × 2 repeated-measures ANOVA on SNR with within-subjects factors *Hemisphere* (left, right) and *Condition* (hbfPW-W, hbfPW-lbfPW). Significant main effect of *Hemisphere* [left > right; $F(1,9)=5.568$; $p < 0.041$], and *Condition* [W > HBF-PW;
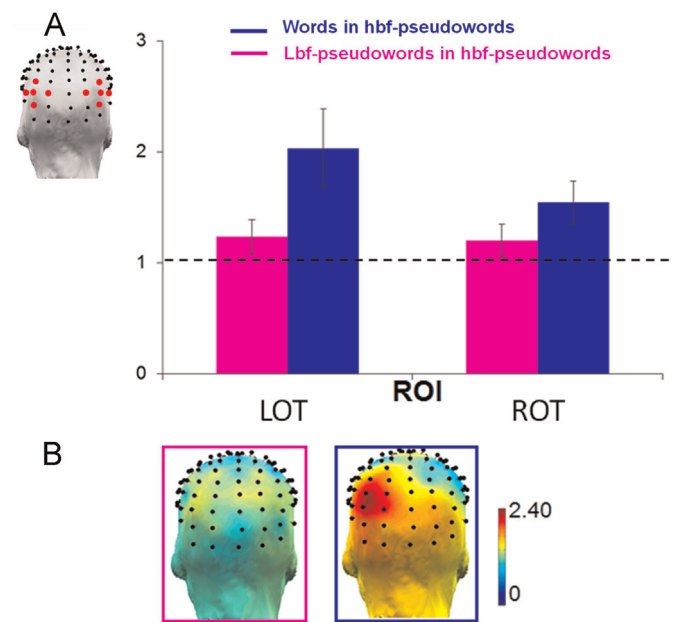

Fig. 8. Experiment 2. (A) In the upper-left panel, electrodes selected for each ROI are represented by red dots. The histogram depicts the mean SNR values and standard deviation for each condition in left occipito-temporal and right occipito-temporal ROIs, with a dotted line at noise level. In both regions, only the response to words in pseudowords (blue) differs significantly from noise. (B) Topographical maps of the grand averaged data of the oddball response to words for the average of the two first harmonics (2 and 4 Hz) for each condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$F(1,9)=5.828$; $p < 0.039$] were found, but no interaction between these factors [$F(1,9) < 1$].

4. General discussion

4.1. An index of automatic lexical access

The present study innovated in the domain of visual word recognition by introducing a fast periodic stimulation EEG approach that is rarely used in cognitive electrophysiology (Luck, 2014). This approach revealed automaticity and specificity of word discrimination: visual words elicited clear differential responses from letter-like control stimuli (experiment 1) and from alphabetic control stimuli (experiments 1 and 2), within a few minutes of stimulation. Remarkably, this response was recorded without any explicit task driving attention to the linguistic aspects of the stimuli.

These data can be interpreted as revealing automaticity of lexical access, in agreement with the findings of a recent mismatch-negativity (MMN) study showing detection of rare (oddball) visual words into long sequences of standard stimuli that were not attended in any linguistic task (Shtyrov et al., 2013). In this study, the authors found a MMN response to a specific word or pseudoword oddball stimulus in sequences of standard words or pseudowords, respectively. Lexicality effects were also found as a higher posterior negativity for words than pseudowords in early time windows. However, contrary to the present results, there was no specific response for deviant words embedded in a standard sequence of pseudowords. Several differences between the two studies might explain this divergence of results. First, we presented the stimulus centrally while it was parafoveal in Shtyrov et al. (2013), which is less optimal especially in reading. Second, we used a fast rate of stimulation with a periodic oddball, while

the MMN paradigm used a slow rate and a nonperiodic oddball stimuli. Also, the oddball stimuli in a classical MMN paradigm, as in Shtyrov et al. (2013)' study, are less frequent (several seconds between two rare stimuli) than our oddball stimuli (500 ms between two oddball stimuli). All these factors, as well as the high sensitivity of the fast periodic visual stimulation approach used here, may have contributed to the significant discrimination response between words and pseudowords, which were obtained here in only a few minutes. Indeed, a high sensitivity approach is better positioned to reveal a small contrast between two categories of stimuli, like words and pseudowords.

Automaticity of lexical access has also been studied in masked priming studies (e.g., Dehaene et al., 2001). In these studies, the prime is presented so briefly (e.g. 20–30 ms) that the participants cannot report seeing it. Nevertheless, the prime influences processing of the probe. Hence, this type of study does not isolate processing of the prime in itself, but rather its influences on (and thus, interactions with) the probe. Participants are usually also asked to perform a linguistic task on the probe, which is not the case with our approach. Here, words were presented every 500 ms, which is largely enough for lexical access (Kutas and Federmeier, 2000), and at sufficient contrast to be visible for about 100 ms (see methods). Even if individual contrast thresholds might vary, and rhythmic temporal presentation rates have been shown to improve contrast sensitivity (Cravo et al., 2013), this factor affects all conditions in the same manner and therefore cannot account for our word discrimination findings.

4.2. The nature of the EEG word discrimination response

Even though our measure is implicit and there was no linguistic task demand, words can be occasionally read even at this fast presentation rate. Furthermore, the fact that words have a meaning and are presented in streams of meaningless stimuli might make them particularly salient. This saliency could lead to expectations from participants, and for this reason words could have been processed differently than the other stimuli. Moreover, reading is mandatory, or at least very difficult to refrain from (e.g., the Stroop task; Glaser and Glaser, 1989), and there is wide evidence that presentation of words activates semantic and phonological representations even at very short presentation times (e.g., priming studies). Even if subjects are not explicitly instructed to access words, their presentation activates a whole network of language-related areas (Van Orden et al., 1988; Price et al., 1996; Price, 2012). For these reasons, the oddball discrimination EEG response recorded here could reflect purely orthographic processes, but also semantic processes, or a mixture/ interaction of both. Indeed, written words possess a set of properties beyond being strings of letters in a certain order. In the present case, words and pseudowords differ on a series of factors that usually co-vary with lexicality: orthographic (bigram frequency, syllabic structure, etc.), phonologic (even though pseudowords are pronounceable, their phonotactic properties differ from words), and semantic (only words bear a meaning).

The first experiment showed that words are clearly discriminated from alphabetic stimuli sharing the same letters (nonwords and pseudowords). Experiment 2 replicated this finding and went one step further by showing that such discrimination occurs even if bigram frequency is controlled, ruling out an account based on this sole orthographic factor. Also, experiment 2 revealed that a difference in bigram frequency in itself does not generate an oddball response. Within a classical cognitive model like DRC (Coltheart et al., 2001), words frequently used in language, like the words of our experiment, activate a lexical route in the sense that they address whole-word form representations. Pseudowords and nonwords cannot be processed lexically, and

they therefore activate a graphemic conversion route. To further understand whether whole-word form representations are indeed activated and at which level of the cognitive architecture (orthographic lexicon or further levels), future studies using this approach could manipulate word frequency, regularity, orthographic neighborhood, number of semantic associates, etc.

4.3. Words selective responses over the left occipito-temporal cortex

As in our previous studies using a fast oddball periodic visual stimulation paradigm (Liu-Shuang et al., 2014; Dzhelyova and Rossion, 2014), there was a clear spatial dissociation between the response at the base rate – typically larger at medial occipital sites – and at the oddball rate, which is the largest over the lateral occipital, or occipito-temporal sites. However, in contrast to these previous studies that used faces and reported a clear dominance of the right hemisphere, here the oddball response was dominant over the left occipito-temporal region, electrode PO7 in particular. This observation is consistent with the contrasted hemispheric lateralization for faces and words as evidenced in neuropsychology (Farah, 1991), divided visual field studies (Hellige et al., 2010), ERPs (Rossion et al., 2003; Maurer et al., 2008; Mercure et al., 2011; Dundas et al., 2012) and neuroimaging (e.g., Puce et al., 1996; Dehaene et al., 2010).

Given that there is an inherent uncertainty regarding the localization of the generators of electrophysiological responses recorded on the scalp ("the inverse problem", Luck, 2014; Nunez and Srinivasan, 2006), one should be cautious when discussing potential neural sources. Nevertheless, our data showing a left occipito-temporal scalp topography suggest two plausible sources of the response: the left ventral occipito-temporal cortex (orthographic/word form processing), or the posterior part of the left superior temporal gyrus (semantic processing). The left ventral occipito-temporal cortex is a brain region that has been proposed to be specialized for word form processing (the visual word forma area, "VWFA", Dehaene et al., 2005; Dehaene and Cohen, 2011; however, see Price and Devlin, 2003; Vogel et al., 2014). This region is usually equally activated by real words and readable pseudowords but less by nonwords (consonant strings for instance) and shows, as we found here, a gradually increasing response to alphabetic stimuli with increasing letter probability, thus with higher word-likeness (Binder et al., 2006). VWFA is often suggested as one of the potential sources of the N170, which, in this perspective, reflects access to orthographic representations (McCandliss et al., 2003; Maurer et al., 2005; Brem et al., 2009). However, despite hundreds of studies focusing on this region over the last 15 years, its precise function is not clear yet: it has been associated with lexical processing (Bruno et al., 2008; Glezer et al., 2009; Kronbichler et al., 2007), prelexical processing (Cohen et al., 2002; McCandliss et al., 2003), and also with strict visual form processing (Price and Devlin, 2003).

On the other hand, rather than originating from the VWFA, it might well be that the source of the word discrimination response stems from either the posterior section of the middle superior temporal gyrus (Wernicke area) or more anterior parts of the temporal cortex, or both, reflecting semantic processing. As previously stated, visual words automatically engage processing of their meanings, and most current theories of visual word recognition propose that semantic information can mediate early word recognition processes (Coltheart et al., 2001; Plaut et al., 1996) by providing feedback to the processing of visual attributes (Hauk et al., 2006a; Price and Devlin, 2011; Twomey et al., 2011; see Carreiras et al., 2014 for a review). In this view, our data are compatible both with the idea that there are lexical representations in the occipito-temporal cortex, or that orthographic processing in the occipito-temporal cortex is modulated by a top-

down input in an interactive model of orthographic processing (Price and Devlin, 2011). Let us note however, that if the discrimination response to words reflected *only* semantic processing or feedbacks from high-level processes, then this response would not gradually increase when words are inserted in pseudowords, nonwords, or pseudofont, as the semantic processing itself would be the same, irrespective of the condition.

4.4. An effect of list context without behavioral decisions

Importantly, we found that the lexical discrimination response depends on the nature of the contrast. Indeed, the amplitude of the oddball response was larger when words were embedded in pseudofont than alphabetic stimuli (experiment 1). Moreover, among alphabetic stimuli, the response was stronger when words were discriminated from less word-like (nonwords) than more word-like (pseudoword) stimuli. This observation is in agreement with behavioral list context effects in lexical decision tasks, showing better performance (faster responses) to words when the surrounding list is less word-like (e.g., like our nonwords), rather than more word-like (e.g., our pseudowords) (Stone and Van Orden, 1993; Lupker and Pexman, 2010). However, while such behavioral effects of the surrounding list type could be accounted for by cognitive/decisional factors (Grainger and Jacobs, 1996; Ratcliff et al., 2004; Norris, 2006; Usher and McClelland, 2001), our paradigm did not require any decision, or any explicit processing of the stimuli. Hence, our observations indicate that list context effects can stem from perceptual rather than from decisional levels.

4.5. Perspectives: a powerful approach to index visual word processing

Even though the fast periodic visual stimulation approach used here to study word recognition does not provide unambiguous timing information (i.e., when does the word processing happen), the point that we made above illustrates how it allows the disentanglement of stimulus-related and response-related processes that are usually conflated with each other in behavioral measures. Moreover, this approach has many additional strengths, being objective, in the sense that if there is discrimination the oddball response occurs exactly at the a priori determined frequency of interest (in our case, $F/5$) and its harmonics, and having a high signal-to-noise ratio, so that it can provide clear results at the individual level in a few minutes only. Also, the discrimination index lies in the response itself, so that there is no need to subtract responses to a set of trials from the response to another set of trials to isolate the response of interest (Heinrich et al., 2009; Liu-Shuang et al., 2014). Given these strengths, this approach should open an avenue of future research in word processing. Oddball paradigms in general allow testing the sensitivity of the system to parameters that are manipulated between the base (standard) stimuli and the oddball (deviant) one. Contrary to the MMN approach, requiring hundreds of trials that are very demanding for the attentional system, in our stimulation paradigm, a few minutes of testing are sufficient to reveal a discrimination response. Therefore, fast periodic visual stimulation in EEG seems particularly well-suited to investigate issues related to word frequency, orthographic regularity, syntactic categories, and so on. The approach may also be very well suited for patient studies, since it does not require explicit stimulus processing, and may therefore reduce the patients' feeling of failure or task difficulty. Importantly, as it does not require explicit responses, the approach allows for testing patients that are unable to produce verbal output, and yet investigate cortical sensitivity to phonological *vs.* orthographic properties of words.

Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at. http://dx.doi:10.1016/j.neuropsychologia.2014.11.007

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