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# THE TIME-COURSE OF VISUAL INFLUENCES IN LETTER RECOGNITION

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Running Head: VISUAL INFLUENCES IN LETTER RECOGNITION

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# VISUAL INFLUENCES IN LETTER RECOGNITION

## Abstract

This study builds on a specific characteristic of letters of the Roman alphabet, namely that each letter name is associated with two visual formats corresponding to their uppercase and lowercase versions. Participants had to read aloud the name of single letters, and event-related potentials (ERPs) for six pairs of visually dissimilar uppercase and lowercase letters were recorded. Assuming that the end product of processing is the same for uppercase and lowercase letters sharing the same vocal response, ERPs were compared backward, starting from the onset of articulatory responses, and the first significant divergence was observed 120 ms before response onset. Given that naming responses were produced around 414 ms on average, these results suggest that letter processing is influenced by visual information until 294 ms after stimulus onset. This therefore provides new empirical evidence about the time-course and interactive nature of visual letter perception processes.

## Keywords

Letter processing; Visual perception; Event-related potentials

# VISUAL INFLUENCES IN LETTER RECOGNITION

## Introduction

Letters are the building blocks of alphabetic writing systems. They consist of two-dimensional visual patterns associated with a single name, and in most alphabetic writing systems each letter can be represented by uppercase and lowercase forms (i.e., “A” and “a” are both associated to the letter name /a/). Due to their visual simplicity on one side and their variability on various dimensions (e.g., size, shape, case) on the other side, letters gather several interesting properties for the experimental study of reading processes and visual perception (Grainger, Rey, & Dufau, 2008). With this kind of simple and easy-to-control experimental material, several recent studies have shed new light on the functional organization of letter perception and on its temporal dynamics.

Concerning the functional organization of letter perception, neuropsychological dissociations and classical electrophysiological studies suggest that letter perception can be decomposed in four levels of processing: a visual feature level (coding for elementary visual properties or visual features; e.g., Hubel & Wiesel, 1959), a perceptual level (coding for template representations of letters; e.g. Perri, Bartolomean & Silveri, 1996), an abstract or shape-invariant level (i.e., a level that is independent of specific visual properties associated with different case and different fonts; e.g., Miozzo & Caramazza, 1998), and a phonological level (coding for the letter’s name; e.g., Mycroft, Hanley & Kay, 2002; Rey & Schiller, 2006). This neuropsychological evidence is generally consistent with the idea of a hierarchical architecture of the ventral visual cortex, in which visual representations become gradually invariant from their retinal image representation (DiCarlo & Cox, 2007; Grainger et al., 2008; Grill-Spector & Malach, 2004). Moreover, fMRI studies reveal that computations corresponding to these different stages of processing are distributed among differential brain areas. Visual, abstract and phonological processing would then be spatially embedded in a network corresponding to a specific set of cerebral areas (Rothlein & Rapp, 2013).

## VISUAL INFLUENCES IN LETTER RECOGNITION

Concerning the temporal dynamics of letter perception, magneto-encephalographic (MEG) studies have revealed an occipital activation at 100 msec after stimulus onset that was not sensitive to the specific content of the stimulus, and that has been interpreted as reflecting low-level visual feature processing (Tarkiainen, Cornelissen, & Salmelin, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Subsequent inferior occipito-temporal activation was found after 150 msec poststimulus onset and was interpreted as reflecting the earliest stage of stimulus-specific processing. Similarly, several events-related potential (ERP) studies have reported results consistent with those obtained in MEG, with ERP differences reflecting low-level visual processing appearing around 100 ms after stimulus onset (e.g., Petit, Midgley, Holcomb, & Grainger, 2006; Carreiras, Perea, Gil-López, Mallouh, & Salillas, 2013), followed by stimulus-specific processing around 150-170 ms (Wong, Gauthier, Woroch, DeBuse, & Curran, 2005). It has been proposed that visual templates would be processed around 150-170 ms (Rey, Dufau, Massol, & Grainger, 2009), followed by abstract and phonological processing around 220 ms (Petit et al., 2006). Recent evidence suggests that phonological processes (i.e., access to the letter's name) may start earlier, i.e., between 150 and 190 ms, and that letter identification processes would be supported by recurrent interactions between visual and phonological codes until response selection (Madec, Rey, Dufau, Klein, & Grainger, 2012).

These results are consistent with a model of letter identification in which visual information (i.e., visual features and letter templates) are processed and contribute to letter identification in a time-window roughly starting at 100 ms after stimulus onset and with strong implications of visual codes between 150 and 190 ms. Abstract and phonological letter representations would then be progressively activated through feedforward and feedback loops (Carreiras et al., 2014). However recent empirical evidence suggest that visual

## VISUAL INFLUENCES IN LETTER RECOGNITION

information would still actively influence letter identification after 220 ms (Mitra & Coch, 2009; Carreiras et al., 2013; Keage, Coussens, Kohnler, Thiessen & Churches, 2014).

In a masked priming study, Mitra and Coch (2009) compared ERPs for letters and false fonts and found no differences in priming between these conditions on the P150 but also on the P260, suggesting that letter processing would still be influenced by visual information in this later time-window. Similarly, Carreiras et al. (2013) compared the magnitude of the priming effect for visually similar and dissimilar letters on the P3 component and found a modulation of the relatedness effect as a function of similarity on this component, suggesting again that, even at this relatively late stage of processing, letter identification would still be modulated by visual similarity. Finally, Keage et al. (2014) compared ERPs for fluent and disfluent typefaces (i.e., typefaces occurring rarely in our reading environment) in a one-back task and they found significant differential activity between the two conditions on the N1 and P2/N2 components, but also on the P3 component (even if the effect was only marginally significant), suggesting that the influence of visual information would last longer than previously thought.

Following-up on these recent findings, the goal of the present study is to provide additional evidence on the time-course of visual influences during letter identification. To address this issue, the present experiment exploits a key feature of letters, i.e., their dual visual coding in uppercase and lowercase forms. For example, both the uppercase “A” and the lowercase “a” activate the same abstract shape-invariant letter representation, and the same phonological and articulatory representations. During letter naming, the same motor response (i.e., /a/) needs to be selected and once these articulatory-output codes are activated, we can assume that the output-production processes are exactly the same for naming “A” and “a”. As shown in Figure 1, the processing of “A” and “a” should therefore be the same once this processing is driven by abstract or phonological letter representations and is no longer

## VISUAL INFLUENCES IN LETTER RECOGNITION

influenced by visual factors. Therefore, any observed differences in the processing of uppercase and lowercase versions of the same letters can be taken as evidence that visual factors are still influencing processing.

< insert Figure 1 here >

Comparing the ERP signal of uppercase and lowercase letters from the presentation onset of these visual stimuli will therefore allow us to detect the early visual processing differences that will occur between these two visual categories. Previous studies suggest that these early differences should appear around 100 ms post-stimulus onset (e.g., Tarkiainen et al., 1999, 2002; Petit et al., 2006; Carreiras et al., 2013). Now, the logic of the present experiment is also to look at ERPs from the onset of response production and to move backward in time. Several recent studies have started to use this kind of response-locked analysis in the domain of word production in order to better specify response selection, response preparation, and response production processes (e.g., Riès, Janssen, Burle, & Alario, 2013 ; Van der Linden, Riès, Legou, Burle, Malfait, & Alario, 2014). In the present study, the idea is that by comparing ERPs locked on response onset for a group of matched uppercase *versus* lowercase letters and by moving backward in time, the first difference obtained between these ERPs should reflect the last influences of visual processing on letter identification. Response-locked ERPs should therefore provide new evidence about the contribution of visual codes to letter identification and response selection processes.

### Experiment

#### Participants

Twenty participants, 17 females and 3 males, with age ranging from 18 to 35 years, (mean age = 21.85,  $\sigma = 4.45$ ) participated in the experiment. All participants were right-handed native speakers of French with normal or corrected-to-normal vision.

## VISUAL INFLUENCES IN LETTER RECOGNITION

### Material

Stimuli consisted of uppercase and lowercase roman alphabetic letters that were displayed in the *Inconsolata* font (size 128, see Figure 2). Six letter pairs were selected on the basis of their visual dissimilarities between uppercase and lowercase shapes: a/A, b/B, d/D, e/E, n/N and r/R. We also selected the letter pair c/C as a visually similar control. The 19 remaining letters, both in uppercase and lowercase, were used as fillers to reduce anticipatory effects during the task. All stimuli were presented on a 17" cathode ray tube (CRT) monitor, with a refresh rate of 85 Hz, as white signs on an 800 x 600 pixels black background (32 x 24 cm). The experiment was controlled by a personal computer using E-Prime (Psychology Software Tools, Pittsburgh, PA).

< insert Figure 2 here >

### Procedure

After completing informed consent, participants seated comfortably in a sound-attenuated and dimly lit room. They were asked to read aloud the name of the target letter appearing in the middle of the screen, as quickly and accurately as possible. They were also asked to remain as relaxed as possible in order to avoid movements that could generate artifacts on the EEG recordings (e.g., eye blinks, frowning). Finally, they were asked to keep their mouth in resting position (semi-closed for all of them) between trials.

A trial started with a fixation cross (symbol '+') for 200 ms, followed by an empty screen during a randomized duration ranging from 500 to 700 ms. The target letter was then presented in the middle of the screen and remained until response or for a maximal duration of 1000 ms. An empty screen (black background) was finally presented with a randomized duration ranging from 1000 to 1300 ms.

The experiment started by a training session during which participants were randomly exposed to the 52 letters of the alphabet (26 in uppercase and 26 in lowercase) and were asked



## VISUAL INFLUENCES IN LETTER RECOGNITION

to perform the naming task. This was followed by the experimental session that was composed of 14 blocks of 125 trials. Each block started with 5 filler trials, followed by pseudo-randomized trials consisting of 100 target letters and 20 filler trials. The only constraint for the pseudo-randomization was to avoid name repetition of a target letter (e.g. no A -> A, A -> a, a -> A or a -> a). Filler trials were used during the blocks in order to minimize anticipation effects. Each of the 12 target letters (i.e., 6 uppercase and 6 lowercase) appeared randomly 100 times during the entire experiment, leading to a total of 1750 trials. The total duration of the recording time was approximately 90 minutes.

### Behavioral data recording and pre-processing

Reaction times (RTs) were not recorded from the voice-key triggering system given by the serial response box of E-Prime. Several studies have indeed shown that differences in microphone sensitivity can lead to important differences in the detection of the acoustic energy produced by the first and second phonemes (Rastle & Davis, 2002; Duyck, Anseel, Szmalec, Mestdagh, Tavernier, & Hartsuiker, 2008; Rey, Courrieu, Madec, & Grainger, 2013). Therefore, letter naming was completely digitized at 22040 Hz on a single channel in order to check for response accuracies and to determine RTs offline. On each digitized trial, we first employed a semi-automatic procedure by applying an algorithm based on Teager-Kaiser operator, which detect sudden variations of energy in the acoustic signal (Li, Zhou, & Aruin, 2007; see also Riès, Legou, Burle, Alario, & Malfait, 2012). Second, the results of this operator were convoluted through a moving average window, acting as a low-pass filter discarding artifactual noises unrelated to the participant's answer. Third, we visually checked the detected onset and manually corrected them when needed. Every trial was listened, and the ones associated with errors or hesitations were discarded. Finally, for every letter and every participant, we relied on robust estimators (Wilcox, 2005, 2012) by computing median naming RTs<sup>1</sup>, Median Absolute Deviation to the median (MAD), and discarded trials

## VISUAL INFLUENCES IN LETTER RECOGNITION

associated with outlier RTs as defined by the MAD-Median Rule (see Wilcox, 2012; Davies & Gather, 1993; Rousseeuw & Van Zomeren, 1990).

### EEG data recording

The EEG was recorded from 64 Ag/AgCl Active-2 pre-amplified electrodes (BIOSEMI, Amsterdam; 10–20 system positions). The vertical electro-oculogram (EOG) was recorded by mean of one electrode (Ag/AgCl) just below the right eye. The horizontal EOG was recorded with two electrodes (Ag/AgCl) positioned over the two outer canthi. Analog signal was digitized at 1024 Hz. Electrode offsets were kept below  $\pm 25 \mu\text{V}$ .

### EEG pre-processing

Offline, data were referenced on the average of the 64 scalp electrodes. Continuous signals were band-pass filtered by using a *butterworth* filter of order 4 between 1Hz and 100 Hz. Because the purpose of this experiment is to find onsets of differences between uppercase and lowercase letters, we relied on the property of causal filters (filters applied in only one direction, as opposed to non-causal filters applied in both forward and backward directions) to preserve onsets of differences (Rousselet, 2012; VanRullen, 2011; Widmann & Schroger, 2012). Filters were therefore applied in forward direction only for stimulus-locked analyses and in backward direction only for response-locked analyses.

### Stimulus-locked preprocessing

The resulting signal was then epoched between -200 ms and 1000 ms (before and after letter onset), and the epoch's baseline was computed from -200 to 0 ms. Epochs corresponding to incorrect or outlier trials (as identified by behavioral analysis) were rejected from further processing. We relied on an independent components analysis (Makeig, Bell, Jung, & Sejnowski, 1996), as implemented in the *runica* EEGLAB function (Delorme & Makeig, 2004; Delorme, Sejnowski, & Makeig, 2007), to identify artefactual ocular

## VISUAL INFLUENCES IN LETTER RECOGNITION

components related to blink activities. They were identified and removed by visual inspection of their scalp topographies, time-courses and activity spectra.

In order to reduce electromyographic (EMG) artifacts related to the articulation of the target letter on the EEG signal, we used a Blind Source Separation algorithm based on Canonical Correlation Analysis (BSS-CCA), that separate sources based on their degree of autocorrelation (De Vos, Riès, Vanderperren, Vanrumste, Alario, Huffel, & Burle, 2010; see also Riès, Janssen, Dufau, Alario, & Burle, 2011). BSS-CCA method was applied on non-overlapping consecutive windows of 1.2 seconds (corresponding to the maximum length of an epoch) enabling the targeting of local EMG bursts related to articulation (we used the EEGLAB plug-in Automatic Artifact Removal implemented by Gómez-Herrero available at <http://www.cs.tut.fi/~gomezher/projects/eeg/software.htm#aar>). EMG related components were selected according to their power spectral density. Components were considered to be EMG activity if their average power in the EMG frequency band (approximated by 15–30 Hz) was at least 1/5 of the average power in the EEG frequency band (approximated by 0–15 Hz) (see De Vos et al., 2010). Finally, all other artifacted epochs were rejected after a trial-by-trial visual inspection.

### Response-locked preprocessing

RTs corresponding to vocal responses (from behavioral processing) were added as triggers in the EEG signal, which was epoched between -500 and +200 ms before and after the onset of the vocal response. The epoch's baseline was computed from 0 (=onset of vocal response) to 200 ms (after the onset). We then excluded epochs using the same principles and procedures as in the stimulus-locked analysis, i.e., epochs corresponding to outliers or incorrect trials were excluded from further analysis. We then applied the same ICA algorithm to identify and exclude blinks, and the same BSS-CCA algorithm to exclude EMG activities related to articulation. Finally, epochs previously marked as artifacted during the stimulus-

## VISUAL INFLUENCES IN LETTER RECOGNITION

locked analysis were also excluded. Consequently, the same epochs were kept for the stimulus-locked analyses and the response-locked analyses.

### EEG data analysis (stimulus and response-locked)

Data from individual subjects were analyzed using the LIMO EEG toolbox, an extension to the EEGLAB environment (Pernet, Chauveau, Gaspar, & Rousselet, 2011). LIMO combines robust statistics and controls for multiple comparisons, allowing the testing of every time-frame (*tf*) and every electrode (*e*), while controlling for Type I error without sacrificing power. We give details hereafter about the rationale of our analysis, and more details can be found in Pernet et al. (2011).

At the individual level, trials corresponding to uppercase and lowercase letters were averaged separately. At the group level, we relied on a robust estimator of central tendency, the trimmed mean, to assess differences between uppercase and lowercase letters. For each pair of electrode/time-frame (*e, tf*), taken independently, amplitudes collected on the group were sorted, and the lowest 20% and the highest 20% of the distribution were trimmed. For each (*e, tf*) pair, the remaining amplitudes were then averaged. Since it preserves the central part of the distribution, the trimmed mean has been proved to be a robust and useful measure of location (see Wilcox, 2005; Wilcox & Keselman, 2003). Moreover, the trimmed mean has proven its utility in recent electrophysiological studies because of the robustness of this measure to the contamination by extreme values (Rousselet, Husk, Bennet and Sekuler, 2008; Desjardins & Segalowitz, 2013). Inferential results were computed by relying on the Yuen procedure, a robust counterpart to the paired t-test, with a threshold fixated at  $p < .05$  (see Wilcox, 2005, 2012). Because statistical tests were performed for every (*e, tf*) pair, we corrected for multiple comparison by using a bootstrap T approach at the cluster level (with  $p < .01$ ) (see Maris & Oostenveld, 2007; Pernet et al., 2011; Rousselet, Gaspar, Wiczorek, & Pernet, 2011).

## VISUAL INFLUENCES IN LETTER RECOGNITION

### Results

Due to noisy EEG signals, three participants were excluded from further analysis. Moreover, RTs corresponding to the vocal responses of C/c trials were not analyzed further because of major difficulties in determining response onsets. Indeed, it appeared that the onset of phoneme /s/ (corresponding to the first phoneme of the letter's name C/c, i.e., /se/ in French) was confounded with the baseline noise characterized by a frequency of 5000 Hz.

### Behavioral results

First, trials associated with errors or hesitations were excluded ( $M = 2.6\%$ ,  $\sigma = 2.3\%$ , range = 8%). Second, on the basis of the remaining trials, we identified and excluded outlier trials by relying on the MAD-Median Rule per letter and participant ( $M = 5.2\%$ ,  $\sigma = 0.9\%$ , range = 4%). Third, we excluded trials identified as artifactual epochs during EEG-preprocessing ( $M = 11.2\%$ ,  $\sigma = 8.6\%$ , range = 29%).

On the basis of the remaining trials, we computed median RTs and confidence intervals (CI) by using a percentile bootstrap approach (with 2000 bootstrap samples, and  $\alpha = .05$ ) corresponding to uppercase and lowercase letters by participant. *Figure 3* shows median RTs for uppercase and lowercase letters by participant and we found that uppercase letters were named slightly but significantly faster. We then compared reaction times for uppercase and lowercase letters by relying on the Yuen procedure<sup>2</sup>. The trimmed mean for uppercase letters was  $M_t = 408$  ms (SE = 10 ms, CI = [385 ; 431] ) and the trimmed mean for lowercase letters was  $M_t = 414$  ms (SE = 10 ms, CI = [391 ; 437]). The 6 ms difference between the two conditions (with CI = [3 ; 10]) was significant ( $T_y = 3.86$ ,  $p < .005$ )<sup>3</sup>. Despite this small mean difference, Cohen's effect size value reveals that it corresponds to a large effect ( $d = 1.51$ ). The mean overall RTs for naming uppercase and lowercase letter is estimated at 414 ms.

< insert Figure 3 around here >

### Stimulus-locked results

## VISUAL INFLUENCES IN LETTER RECOGNITION

Epochs corresponding to the same trials as the one used for the behavioral analysis were included in the stimulus-locked analysis. Mean ERPs corresponding to uppercase and lowercase letters were computed for every participant, electrode, and time-frame. *Figure 4a* and *Figure 4b* show significant  $T_y$  values, masked for significance ( $p < .01$  for the cluster statistic).

We observe 3 significant temporal windows. The first one, from 110 to 140 ms, appears bilaterally at occipital sites (P6, P8, PO8, PO3, PO7, O1) and fronto-central sites (FC1, C1, FCz, Cz). The second one, from 150 to 190 ms, is mostly localized at left occipital sites (PO7, P7, P9) and right fronto-central sites (FC6, FC4, C4). The third one, from 200 to 240 ms, is mostly localized at right occipital sites (PO7, P7, P9) and central sites (FC6, FC4, C4). *Figure 4c* and *Figure 4d* respectively represent the 20% trimmed mean ERPs to the uppercase and lowercase conditions, across participants, at electrodes C1 and P7. Confidence intervals at 95% are estimated by a bootstrap percentile approach.

< insert Figure 4 around here >

### Response-locked analysis

A similar statistical analysis as the one computed with stimulus-locked was performed. Based on the behavioral analysis, the mean RT over all letters and subjects is equal to 414 ms and is therefore taken as the average response onset. In *Figure 5* the results are displayed by going back in time from this value. *Figure 5a* and *Figure 5b* show a significant window of differences between +294 ms and +224 ms. This difference appears bilaterally at occipital sites, mostly at right sites (P4, P6, PO4), and fronto-central sites, mostly at left sites (FC1, C1, FCz, Cz). *Figure 5c* and *Figure 5d* respectively represent the trimmed mean ERPs related to the uppercase and lowercase conditions, across participants, on electrodes AF7 and O1. Confidence intervals at 95% are estimated by a bootstrap percentile approach.

< insert Figure 5 around here >

### Discussion

Three main results were obtained in this experiment. First, at a behavioral level, we found that uppercase letters are named faster than lowercase letters (6 ms, 95% CI [4 9]). Despite its small magnitude, this effect is large according to Cohen's  $d$  (1.51). Second, when the comparison between ERPs to uppercase and lowercase letters is made with a stimulus-locked approach, a first difference was obtained around 120 ms after stimulus onset. Third, when the same comparison is made with a response-locked approach then an initial difference is detected backward at 120 ms before response onset, which corresponds to 294 ms on average after stimulus onset, given that letter naming latencies were on average around 414 ms.

The faster responses to uppercase letters than to lowercase letters might seem counterintuitive since lowercase letters appear more frequently in our environment than uppercase letters (New & Grainger, 2011). However, in the present situation, stimuli were presented in isolation whereas in an ecological reading situation, lowercase letters are rarely presented in isolation but embedded within words. Therefore, context effects could account for the faster recognition of uppercase letters that may appear more frequently in isolation. This difference could also be due to more elementary visual properties, such as the relative luminance or contrast of the stimuli. Indeed, the amount of white pixels on a black background may explain the small but consistent advantage of uppercase letters and the speeded recognition.

The stimulus-locked ERP difference at 120 ms between uppercase and lowercase letters is consistent with the report of low-level visual processing differences within this time-window (Tarkiainen et al., 1999, 2002; Petit et al., 2006; Carreiras et al., 2013). This difference can simply be interpreted in terms of elementary visual differences between these

## VISUAL INFLUENCES IN LETTER RECOGNITION

two sets of letters, leading to a divergence in the evoked electrical response. Moreover, this result demonstrates that the selected uppercase and lowercase letters were sufficiently visually different to induce differential low-level visual processing, as revealed by these ERP differences. Although we did not rely on an analysis emphasizing on component latencies - since we tested every time point and every electrode in this study - the early difference at 120 ms on occipital sites (see *Figure 3d*) is consistent with a positive shift in time for lowercase N1 as compared to uppercase N1. Therefore, subsequent significant differences, around 150-190 ms, and around 200-240 ms are more difficult to interpret because they could simply result from the initial difference obtained at 120 ms that may have produced a processing advantage for uppercase letters (and later on, faster overall response times).

More crucially for the purpose of the present study, by comparing ERPs to uppercase and lowercase letters locked on vocal responses, the difference found around 120 ms before the onset of the vocal response (that is made on average around 414 ms) suggests that the offset of visual influences would take place, on average, around 294 ms. This result is consistent with recent findings on letters that used the priming paradigm (i.e., Mitra & Coch, 2009; Carreiras et al., 2013) and that suggested an influence of visual information as late as 300 ms after stimulus onset (for a similar result, see also Keage et al., 2014). Moreover, since we tested for statistical significance on every time point and every electrode from the vocal response, our methodology provides a mean to assess more precisely the offset of visual influences that is therefore estimated on average at 290-300 ms.

This result provides additional constraints for models of letter perception processes (Grainger et al., 2008). Indeed, the fact that visual information still influence letter processing until 294 ms post-stimulus onset and that participants start producing letter names on average around 414 ms, would leave 120 ms (i.e., 414-294 ms) for processing non-visual information (i.e., abstract and phonological representations) and generating the output articulatory



## VISUAL INFLUENCES IN LETTER RECOGNITION

response. This small time-window (i.e., 120 ms) is certainly computationally too short to encompass all these non-visual processes, suggesting that visual and non-visual processes cannot be encapsulated and have to interact earlier in time (Carreiras et al., 2014). Similarly, the fact that abstract or phonological effects have been reported much earlier than 290-300 ms (e.g., Madec et al., 2012; Petit et al., 2006) also indicates that visual and non-visual levels of processing are co-activated at some point in time during letter identification and would therefore interact following a cascaded interactive-activation framework (McClelland & Rumelhart, 1981).

Before concluding, one can note that the logic of the present study rests on the assumption that the end product of processing is the same for uppercase and lowercase letters before producing the vocal response. However, one could argue that even if response selection is completed and the motor program corresponding to the letter's name has been activated, there could still be some kind of visual processing occurring in parallel, sustaining the visual representation of the just-processed letter in a short term memory buffer. This possibility cannot be excluded even though it would not seem to have any major consequences on the present results. Indeed, this potentially sustained visual activity is certainly independent of the vocal response that we used as a trigger in the present response-locked analyses. By averaging the EEG signal on the onset of the vocal responses, we eliminate any activity that is not specifically related to the generation of this response (like any potentially sustained visual activity). The remaining difference that we observe is therefore likely due to differences in visual processing that contributes towards letter identification and response selection.

To summarize, the present study was mainly concerned with the time-course of letter perception and by determining the offset of visual influences that, according to our data, would end around 290-300 ms after stimulus presentation. Our results and previous empirical

## VISUAL INFLUENCES IN LETTER RECOGNITION

findings therefore suggest that visual information is processed in a time-window starting around 100 ms after stimulus onset and lasting around 190-200 ms. This long-lasting time-window (i.e., 200 ms) is consistent with a cascaded interactive-activation model of letter perception in which visual information feeds forward information to abstract and phonological letter representations well before the processing of such visual information has terminated. The end product of this cascaded interactive process would be the selection of the output motor response.

### Footnote

1. Due to the large number of data points per condition and per participant, the median or the mean give substantially equivalent results.
2. The Yuen procedure compares marginal trimmed means (noted  $M_t$ ) for each condition. The statistical test produced by this procedure, which is a robust analog to the t-value, will be subsequently referred as to  $T_y$ .
3. Note that similar results are obtained with a standard computation of the mean, i.e., the mean for uppercase letters being  $M_{upper} = 410$  ms, and the mean for lowercase letters being  $M_{lower} = 417$  ms. Consistent with our robust analysis, a classical paired t-test indicates a significant difference between these two conditions:  $t(16) = 6.21, p < .005$ .

## VISUAL INFLUENCES IN LETTER RECOGNITION

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## VISUAL INFLUENCES IN LETTER RECOGNITION

### Figure captions

Figure 1: Differences and similarities in the processing of uppercase and lowercase letters that have dissimilar letter shapes (like “A” and “a”). Gray boxes correspond to processes that should differ (i.e., involving different visual information) and white boxes reflect processes that should be the same (i.e., involving abstract (A), phonological (P) and output (Out) letter representations).

Figure 2: Uppercase and lowercase letters displayed in the Inconsolata font. Encircled letters correspond to the six critical pairs of uppercase/lowercase letters used in the experiment.

Figure 3: Median RTs for lowercase and uppercase letters for each participant. Blue and red lines represent 95% bootstrap confidence intervals respectively for uppercase and lowercase letters.

Figure 4: Stimulus-locked analysis for the lowercase vs. uppercase comparison. a)  $T_y$  values masked for significance based on a cluster test ( $p < 0.01$ ). The y-axis represents the 64 recording electrodes of the scalp, with electrodes 1 to 7: FP1, AF7, AF3, F1, F3, F5, F7; electrodes 8 to 19: FT7, FC5, FC3, FC1, C1, C3, C5, T7, TP7, CP5, CP3, CP1; electrodes 20 to 27: P1, P3, P5, P7, P9, PO7, PO3, O1; electrodes 28 to 32: Iz, Oz, POz, Pz, CPz; electrodes 33 to 42: FPz, FP2, AF8, AF4, AFz, Fz, F2, F4, F6, F8; electrodes 43 to 56: FT8, FC6, FC4, FC2, FCz, Cz, C2, C4, C6, T8, TP8, CP6, CP4, CP2; electrodes 57 to 64: P2, P4, P6, P8, P10, PO8, PO4, O2. b) Topographic maps of  $T_y$  values, masked for significance, from 120 to 240 ms. c) Trimmed-means and 95% confidence interval of the ERPs corresponding to lowercase and uppercase letters, for the electrode C1, between -200 ms to 500 ms (0 corresponding to letter onset). d) Same as c) for electrode P7.

Figure 5: Response-locked analysis for the lowercase vs. uppercase comparison. a)  $T_y$  values masked for significance based on a cluster test ( $p < 0.01$ ). See Figure 2 for the correspondence between numbers of the y-axis and electrodes. b) Topographic maps of  $T_y$  values, masked for

## VISUAL INFLUENCES IN LETTER RECOGNITION

significance, from +275 to +235 ms. c) Trimmed-means and 95% confidence interval of the ERPs corresponding to lowercase and uppercase letters, for the electrode O1, from +600 ms to -100 ms (+414 ms being the mean response onset, 0 corresponding to letter onset). d) Same as c) for electrode AF7.

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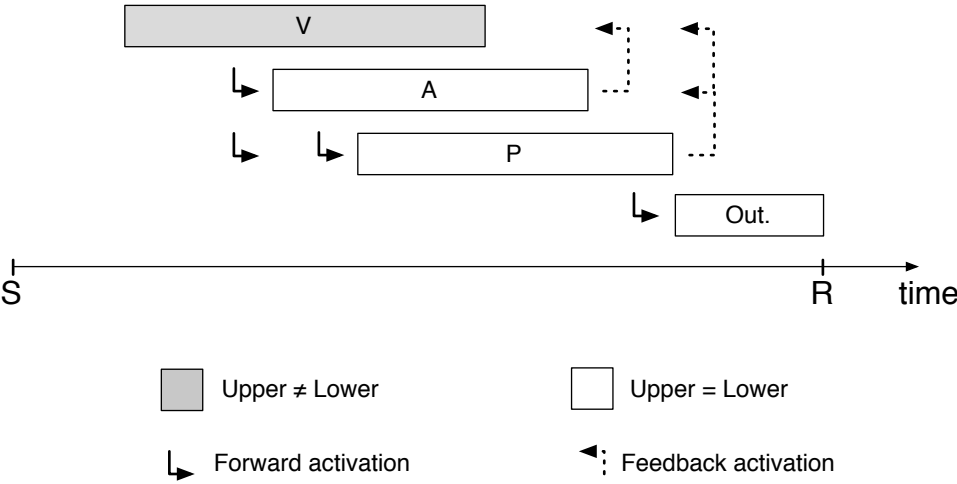


Figure 1

VISUAL INFLUENCES IN LETTER RECOGNITION

A	B	C	D	E	F	G
H	I	J	K	L	M	N
O	P	Q	R	S	T	U
V	X	Y	Z			
a	b	c	d	e	f	g
h	i	j	k	l	m	n
o	p	q	r	s	t	u
v	x	y	z			

Figure 2

VISUAL INFLUENCES IN LETTER RECOGNITION

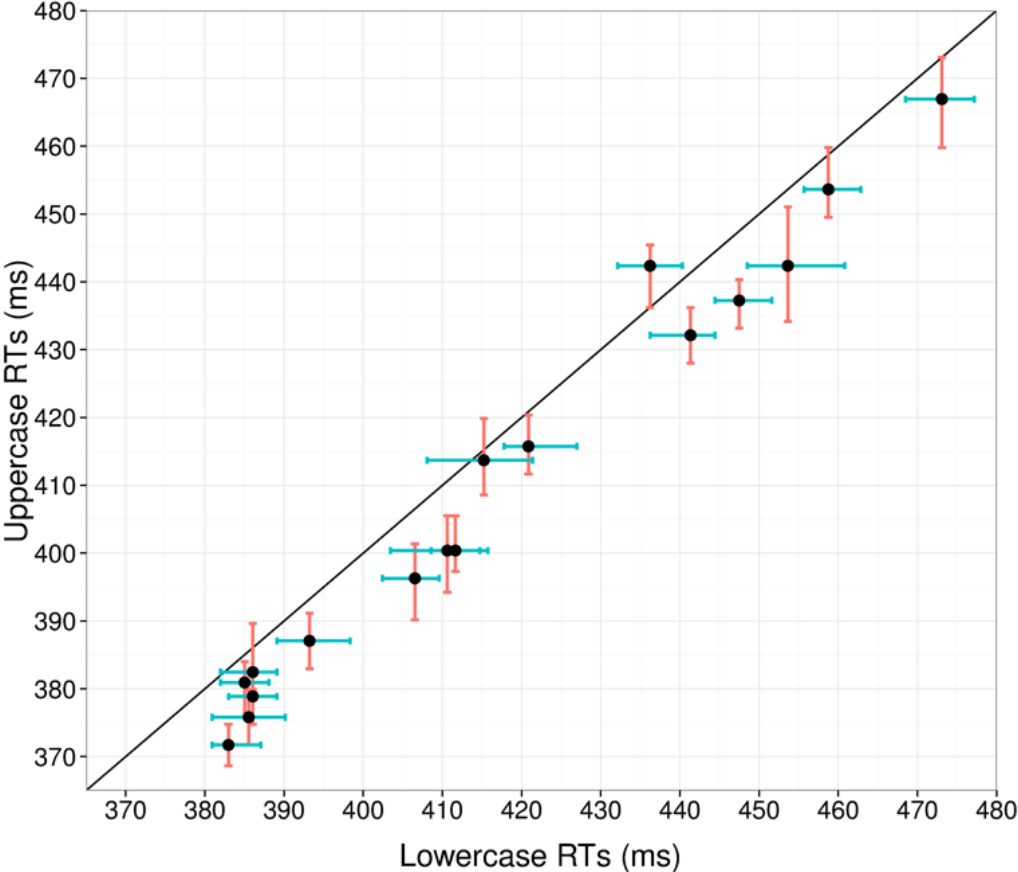


Figure 3

VISUAL INFLUENCES IN LETTER RECOGNITION

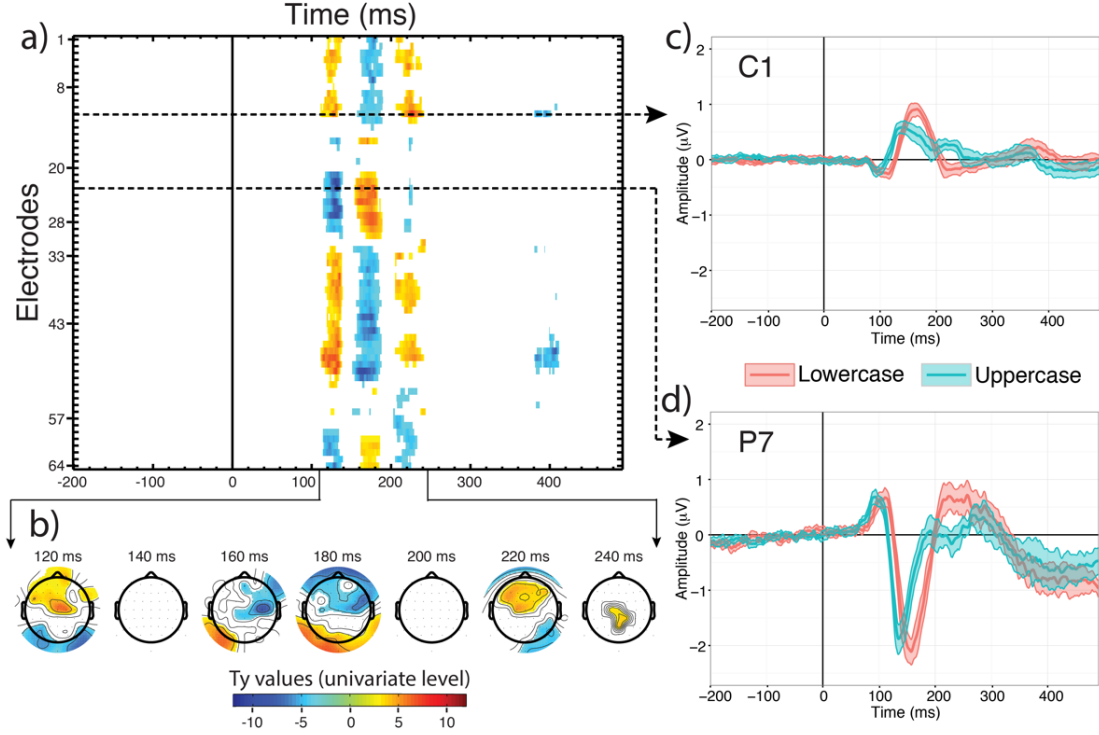


Figure 4



VISUAL INFLUENCES IN LETTER RECOGNITION

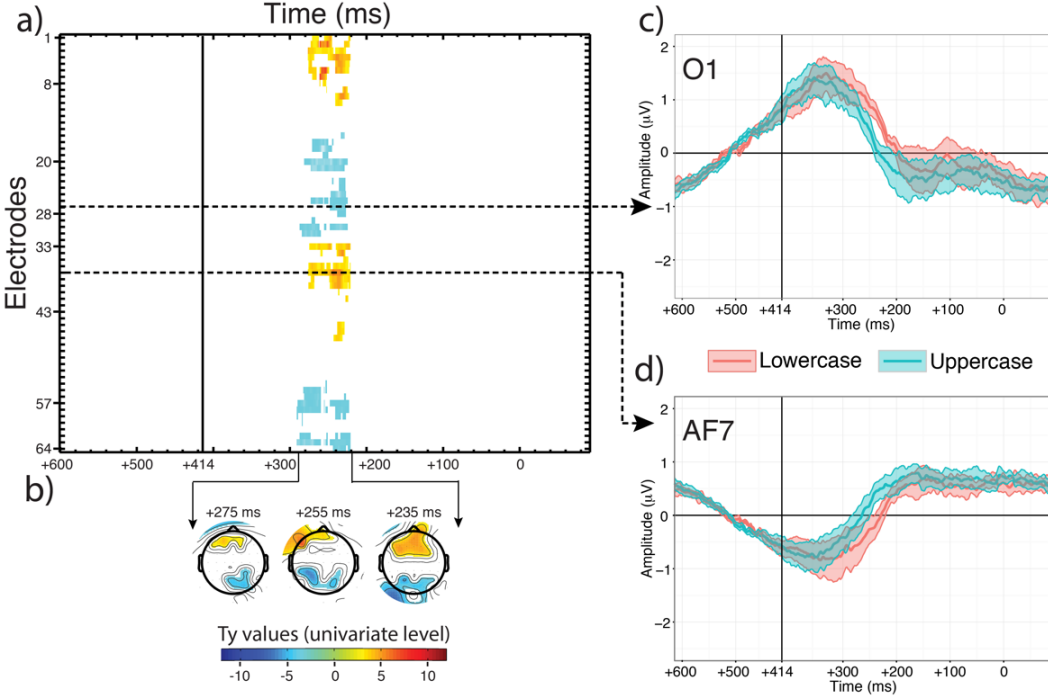


Figure 5