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ORIGINAL PAPER

Comparison of Electrophysiological Correlates of Writing and Speaking: A Topographic ERP Analysis

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Abstract Behavioral and neuropsychological studies on written production suggested that some cognitive processes are common with spoken production. In this study, we attempted to specify the time course of common processes between the two modalities with event-related brain potentials (ERPs). High density EEG was recorded on twenty two healthy participants during a handwritten and an oral picture naming task on the same 120 stimuli. Waveform analyses and topographical pattern analyses were combined on stimulus- and response-aligned ERPs in order to cover the whole word encoding processing. Similar electrophysiological correlates between writing and speaking appeared until about 260 ms. According to previous estimations of the time course of spoken production, the time period of identical electrophysiological activity corresponds to visual (0–150 ms) semantic (150–190 ms) and lexical-semantic (190–275 ms) processes. Then, spoken and handwritten picture naming starts diverging and display different and modality specific topographical configurations from around 260 ms, i.e., at the beginning of the time-window associated to the encoding of the surface phonological form in spoken production. These results suggested shared conceptual and lexical-semantic processes between speaking and writing and different neurophysiological activity during word-form (phonological or orthographic) encoding.

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Introduction

Although speaking and writing are both used in daily communication in highly literate societies, much less is known about cognitive and neurophysiological processes involved in writing than in speaking. The main processes underlying spoken production have been largely investigated using picture naming paradigms, at least at single word level. Most models (e.g., Dell 1986; Levelt 1989; Caramazza 1997; Levelt et al. 1999) suggest the following processing levels: a conceptual preparation during which the speaker decides what he wants to produce in a specific communicative situation or from object recognition processes; the lexical level is assumed to involve both the retrieval of a lexical-semantic entry (lemma) from a semantic representation and the encoding of phonological codes to build up the form of the sentence. Finally, phonetic plans are encoded to address muscle commands (or "gestural scores", Levelt et al. 1999).

Such detailed proposition is not available for handwritten conceptually driven production. Neurolinguistic studies (e.g., Basso et al. 1978; Roeltgen and Heilman 1984; Caramazza and Miceli 1990; McCloskey et al. 1994; Badecker 1996; Rapcsak and Beeson 2002; Henry et al. 2007), functional magnetic resonance imaging investigations (e.g., Katanoda et al. 2001; Sugihara et al. 2006; Roux et al. 2009) and/or cortical electrical stimulation mapping studies (e.g., Lubrano et al. 2004; Roux et al. 2009) provided information on the representations involved during the written word-form retrieval processes and at graphomotor levels (e.g., Baxter and Warrington 1986;

van Galen 1991; Forbes and Vinneri 2003) and the their neural substrates. By contrast, the time-course of the mental operations involved in writing from concept to motor execution has not been systematically investigated.

The continuous measure of brain activity of event-related brain potentials (ERPs) allows investigating the time-course of activation and the interplay between different neuro-functional subsystems involved in writing. To the best of our knowledge, the time-course of writing has not been explored in previous studies (some ERP studies have used grapheme-monitoring tasks, but were aimed at studying phonological encoding involved in oral production, e.g. Hauk et al. 2001). By contrast, the time course of mental operations has been largely investigated with ERPs for (single word) speech production (e.g., van Turennout et al. 1998, 1999; Eulitz et al. 2000; Jescheniak et al. 2002; Maess et al. 2002; Rodriguez-Fornells et al. 2002; Cornelissen et al. 2003; Jescheniak et al. 2003; Vihla et al. 2006; Koester and Schiller 2008; Laganaro et al. 2009; Strijkers et al. 2010; Zhang and Damian 2009; Laganaro and Perret 2011; Riès et al. 2011; see Indefrey and Levelt 2004 for a review). The comparison between speaking and writing seems then the best way of investigating the time-course of activation involved in single word writing. It is worth noting that comparison between written and oral modalities has already been carried out in psycholinguistic behavioral studies (e.g., Bonin et al. 1998, 2002) and in a neuroimaging study using positron emission tomography (Brownsett and Wise 2010).

The present study investigates the time course of activation involved in writing with high density EEG recordings during handwritten picture naming, using spoken picture naming as a comparison point. In addition, we combined waveform analyses and topographical pattern analyses on stimulus-aligned and response-aligned ERPs (Laganaro and Perret 2011). This method allows capturing the whole production processes (from picture presentation to motor execution) independently of inter-individual variations in production latencies. A systematic comparison between spoken and handwritten picture naming allows us to specify which electrophysiological patterns are shared by the two language modalities and which ones are specific to the written modality.

Method

Subjects

The participants were 22 students (five men), native French speakers, aged 20–36 (mean: 25.55). All were right-handed as determined by the Edinburgh Handedness Scales (Oldfield 1971; lateralization quotient index range: 80–100%, mean: 95; SD: 11). They reported having normal or corrected-to-normal vision and did not suffer from any neurological or motor problem. All participants gave their informed consent to participate in the study and were paid for their participation. The study procedure obtained approval from the local research ethical committee at Geneva University.

Material

A total of 120 words and their corresponding pictures were selected from French databases (Alario and Ferrand 1999; Bonin et al. 2003). Pictures had high name agreement (*h*-statistic mean 0.17) and the associated words were of high frequency (mean 17.96 per million).

Procedure

The participants were tested individually in a soundproof dimly light room, sat 60 cm in front of the screen. There were two experimental tasks: a spoken picture naming and a handwritten picture naming using exactly the same stimuli. All participants underwent the two conditions either in Handwritten-Spoken or in Spoken-Handwritten order, with an interval filled with an unrelated task in between. Before the experiment the participants were familiarized with the experimental pictures and their corresponding names. In each condition, the 120 pictures were presented randomly, preceded by four warming-up items. A short break was given after every 40 trials, which allowed the experimenter to change the sheet on the graphic tablet in the written condition. Each spoken and handwritten session lasted about half an hour.

The software E-Prime (E-Studio) presented the trials and recorded the response latencies (reaction times: RTs hereafter). In both conditions an experimental trial had the following structure: first, a warning signal (an asterisk) was presented for 500 ms. Then, the drawing appeared on the screen, presented on reverse video mode (white lines on grey screen) in constant size of 9.5 × 9.5 cm (approximately 4.52 degree of visual angle). A grey screen was used to avoid extreme light exposition. The participants had to produce the (spoken or written) word corresponding to the picture immediately when the stimulus appeared on the screen. In both conditions the picture remained on the screen during 3,000 ms and a next trial began 2,000 ms after the drawing offset.

In the *spoken picture naming* task participants were told that they would see a picture and they had to say aloud the name corresponding to the picture as rapidly and as accurately as possible. The spoken responses were digitized and recorded for later response latency and accuracy check.

In the *handwritten picture naming* task they had to write down the name corresponding to the picture as rapidly and as accurately as possible on a graphic tablet (WACOM UltradPad A4) with inking contact pen (SP-401). The white sheet on the graphic tablet allowed collecting the handwritten productions in order to check responses. The participants could not see and monitor their production, as a box hided their hand and the graphic tablet. This procedure was used to avoid head movement during the change of eye fixation point from the screen to the sheet and has been previously tested in a behavioral study comparing masked (non visible) writing to standard (visible) handwriting (Perret and Laganaro, subm). Participants were instructed to try to follow an imaginary line and to write down as accurately as they can. Additionally, the sentence "lift the pen" appeared for 1,000 ms on the screen right before the ready signal, reminding the participants to stop any movement and sat the pen right above the tablet in a new position in order to avoid random variability in the initial positioning.

EEG Acquisition and Pre-Analyses

EEG was recorded continuously using the Active-Two Biosemi EEG system (Biosemi V.O.F. Amsterdam, Netherlands) with 128 channels covering the entire scalp. Signals were sampled at 512 Hz with band-pass filters set between 0.16 and 100 Hz.

Two averaging procedures were combined in each language modality: one on stimulus-aligned (forward) epochs of 460 ms starting at the moment the picture appeared on screen; one on response-aligned (backward) epochs of 460 ms starting 100 ms before the production latency of each individual trial. The exact same trials were averaged in the stimulus-aligned and response-aligned ERPs (when an epoch had to be excluded in the response-aligned analysis, the corresponding stimulus-aligned trial was also excluded). This procedure allows stimulus-aligned and response-aligned merged ERPs to completely match. For the topographical pattern analysis (see "Topographic pattern analysis" section) the stimulus- aligned and response-aligned data from each subject were merged according to each individual subject's RT in each condition. The combination of stimulus- and response-aligned data was introduced by Laganaro and Perret (2011) on spoken picture naming: here it allows the individual averaged data (and the group grand-average) to cover the actual time form onset (picture on screen) to 100 ms before oral or written production.

In addition to an automated selection criterion rejecting epochs with amplitudes reaching ±100 µV, each trial was visually inspected, and epochs contaminated by eye blinking, movements or other noise were rejected and excluded from averaging. ERPs were then bandpass-filtered to 0.2–30 Hz and recalculated against the average reference.[1] After rejection of errors and of contaminated epochs a minimum of 72 epochs (60%) were averaged per subject for each language modality condition. The spoken and handwritten reaction times were computed after exclusion of production errors and rejected epochs.

RT Analyses

Data Elimination

After elimination of errors, latencies of vocal responses (ms separating the onset of the picture and articulation onset) were systematically checked with speech analysis software (Praat: Boersma and Weenik 2007), thanks to an inaudible acoustic click at the onset of the picture recorded on the second track of the recording system. Based on the examination of the graphic productions words that were misspelled or written down with an uppercase initial letter were discarded. Finally, spoken and handwritten RTs corresponding to excluded epochs during ERP pre-analysis were also discarded.

Data Analysis

ANOVAs using mixed-effect analysis (Baayen et al. 2008) using the R-software (R-project, R-development core team 2007; Bates and Sarkar 2007) were run on RTs with Items and Participants as random-effect variables and Type of task (Handwriting vs. Speaking) as fixed-effects variable. Error rates were fitted with logit mixed-effects models (Jaeger 2008) with same random- and fixed-effects factors.

Waveform and Global Field Power Analyses

The ERPs were first subjected to standard waveform analysis to determine the time periods where amplitude differences were found between conditions. This analysis was performed on all electrodes and data-points. Waveform analysis was carried out in the following way: paired *t*-tests were computed on amplitudes of the evoked potentials between conditions (handwritten versus spoken naming) at each electrode and time point over the entire analysed periods (stimulus-aligned and response-aligned).

[1] Baseline correction was not applied for the following reasons. First, it is difficult to establish a good time window to be used as baseline for both stimulus- and response-aligned data. One can imagine using a pre-stimulus period. Nevertheless, we cannot exclude different recruitment of preparatory neural resources across conditions, specially because the sentence "lift the pen" appeared on the screen before the ready signal in the handwritten condition, which may induce differences in the pre-stimulus period across conditions. A discussion of possible consequences of pre-stimulus baseline correction on ERPs when different tasks are compared can be found in Michel et al. (2009, p. 43).

Only differences over at least five electrodes from the same region out of six regions at scalp (left and right anterior, central, and posterior) extending over at least 30 ms were retained with an alpha criterion of 0.05. For differences in *global field power* (GFP, or standard deviation of all electrodes at a given time, see Lehmann and Skrandies 1984), paired *t*-test were computed on the GFP between conditions at each time-frame, with an alpha criterion of 0.01 and a time-window of 30 ms of consecutive significant difference.

Topographic Pattern Analysis

Significant variations of ERP waveforms can follow from a modulation in the strength of the electric field, from a topographic change of the electric field (revealing distinguishable brain generators), or from latency shifts of similar brain processes. To differentiate these effects, we applied topographic analyses (spatiotemporal segmentation analysis, Brunet et al. 2011). This approach allows summarizing ERP data into a limited number of topographical map configurations (Lehmann and Skrandies 1984) and identifying time periods during which different conditions (handwritten and spoken production) evoke different electric fields at scalp.

This topographic (map) pattern analysis is independent of the reference electrode (Michel et al. 2001, 2004) and insensitive to pure amplitude modulations across conditions (topographies of normalized maps are compared). A modified hierarchical clustering analysis (Pascual-Marqui et al. 1995; Michel et al. 2001)—the agglomerative hierarchical clustering (Murray et al. 2008)—was used to determine the most dominant map configurations. A modified cross-validation criterion was used to determine the optimal number of maps that explained the best the group-averaged data sets across conditions. Statistical smoothing was used to eliminate temporally isolated maps with low strength. This procedure is described in detail in Pascual-Marqui et al. (1995). Additionally, a given topography had to be present for at least 15 time frames (30 ms).

We first applied a spatio-temporal segmentation on the two grand average data (handwritten and spoken word production). Then, the pattern of map templates observed in the averaged data was statistically tested by comparing each of these map templates with the moment-by-moment scalp topography of individual subjects' ERPs from each condition. Each time point was labelled according to the map with which it best correlated spatially, yielding a measure of map presence. This procedure referred to as 'fitting' allowed to establish how well a cluster map explained individual patterns of activity (GEV: Global Explained Variance) and its duration. The "fitting" procedure was applied on the merged stimulus- and response-aligned ERPs of each individual subject in each condition.

Two series of statistical analyses were run. First, in order to analyse whether one map is more representative of one condition, GEV and the presence of map observed in each subject's data were used for statistical analysis. In other words, we tested whether a map is specific to one language modality. Second, if a spatial configuration appeared in both language modalities, we compared the duration of this electrophysiological map across conditions. Non-parametric tests (Friedman rank sum test) were applied to these measures with subjects as random variable and language modality conditions as fixed factors. This approach has been regularly used in other cognitive domains (Murray et al. 2006; Schnider et al. 2007; Britz et al. 2009) as well as with language data (Laganaro et al. 2009; Camen et al. 2010; Laganaro and Perret 2011) and the procedure has been described in detail in Murray et al. 2008 (see also Michel et al. 2009; Brunet et al. 2011).

Results

Behavioral Results

For the spoken modality, incorrect responses (3.04%) and outliers (mean RT ± 3 SD, 2.35%) were excluded from the RTs analysis. Excluded epochs corresponded to 5.57% of data. Incorrect responses (5.09%), outliers (mean RT ± 3 SD, 2.08%) and excluded epochs (5.8%) were also excluded from handwritten production data.

Handwritten RTs did not significantly differ from spoken RTs ($t < 1$) and there was no difference on the number of excluded epochs between the two conditions ($z < 1$). Only the error rate was higher in the handwritten condition ($z = -2.444$, $P = 0.0145$) Table 1.

ERP

Figure 1 shows time points of significant amplitude differences between handwritten and spoken picture naming. In the stimulus-aligned ERPs analysis amplitude differences appeared between the two modalities at around 100–140 ms on electrodes from left anterior and left and right posterior regions and more systematically from

Table 1 Production latencies in the two modalities

Conditions	Means	Standard deviation
Handwritten production	778 ms	185.88
Spoken production	772 ms	159.19

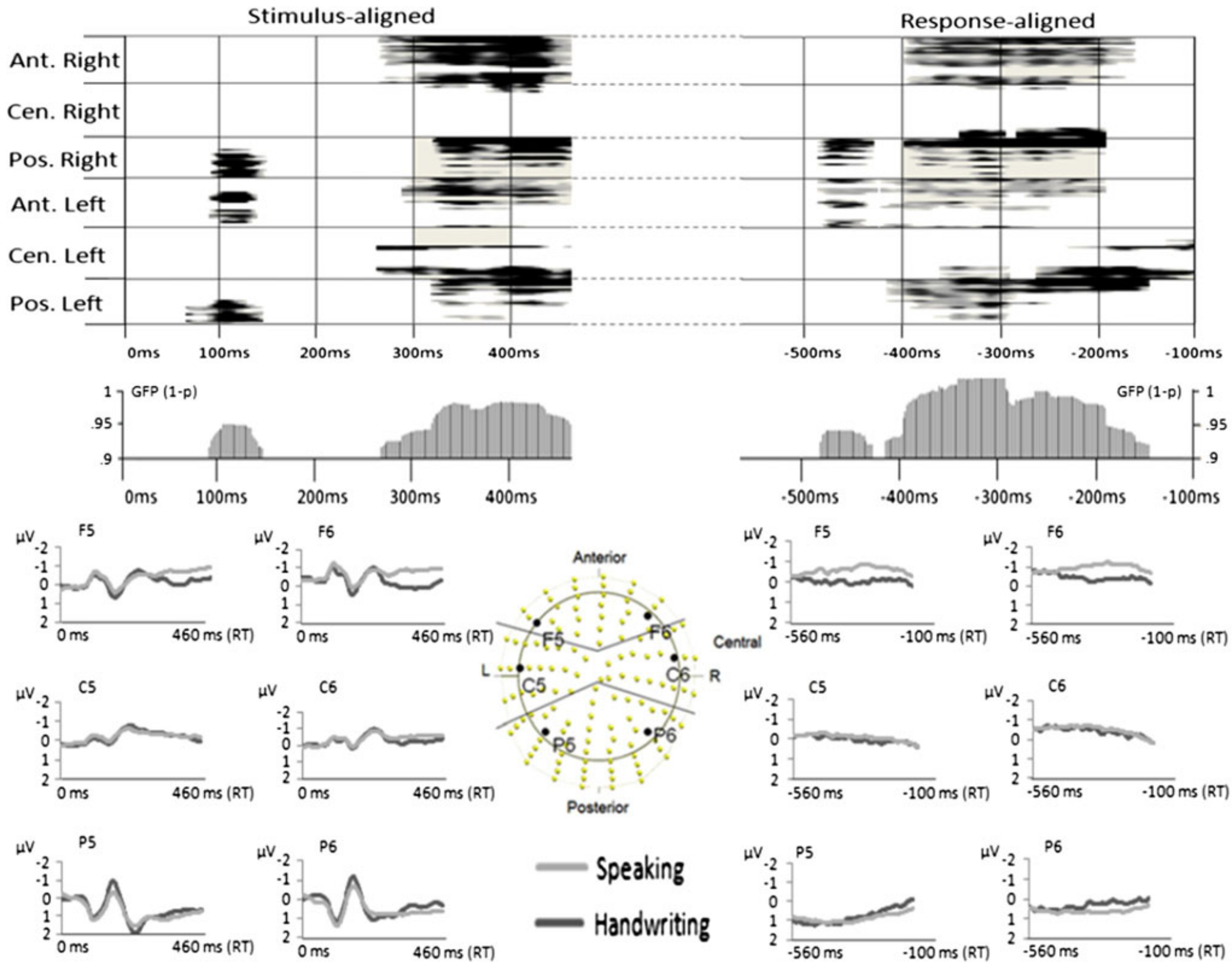

Fig. 1 Waveform and global field power analyses. Top: Significant differences (*P*-values from *gray*, $P < 0.05$ to *black*, $P < 0.001$) on ERP waveform amplitude on each electrode (*Y* axes) and time point (*X* axes) between handwritten and spoken picture naming (only differences over at least five electrodes from the same region extending over at least 20 ms are displayed) and results of statistical analysis ($1 - P$-values) on global field power (GFP). Bottom: Group averaged ERP waveforms in handwritten and spoken picture naming. Negative amplitudes are plotted in the upward direction. In the lower right corner of the figure, the arrangement of the 128 electrodes with the electrode position of the displayed waveforms is presented

around 270–460 ms on all regions at scalp. Different GFP between the two languages modalities were observed in approximately the same time-windows. In the response-aligned ERPs, a first group of amplitude differences observed on posterior right and anterior left regions appeared around 480–430 ms before motor production (articulation or handwritten production) and more systematically on all scalp regions from around 410–150 ms before production. Differences in this time-window also appeared on GFP. Finally, amplitude differences appeared on a few electrodes from central and posterior left region around 150–100 ms before motor execution.

The spatio-temporal segmentation applied on the average data of handwritten and spoken picture naming conditions revealed eight different electrophysiological template maps (see Fig. 2) accounting for 94.22% of the variance. The same sequence of topographical maps appeared in both conditions until about 260 ms (maps labeled "A", "B", and "C" in Fig. 2). From 260 to 600 ms, different electrophysiological spatial configurations were observed in the two language production modalities (Fig. 2). Finally, a common map labeled "H" appeared in both language modalities during the last 80 ms.

These observations were validated by the results of the fitting procedure applied to individual handwritten and spoken picture naming data in three time-windows: from 0 to 260 ms, from 260 to 600 ms and from 600 to 680 ms. Three maps ("A", "B" and "C") were included in the fitting in the first time-window. For maps "A" (from about 70–140 ms) and "C" (from about 180–260 ms), there was no difference on map presence or duration across the 22 participants ($\chi^2 < 1$). GEV was higher for handwriting

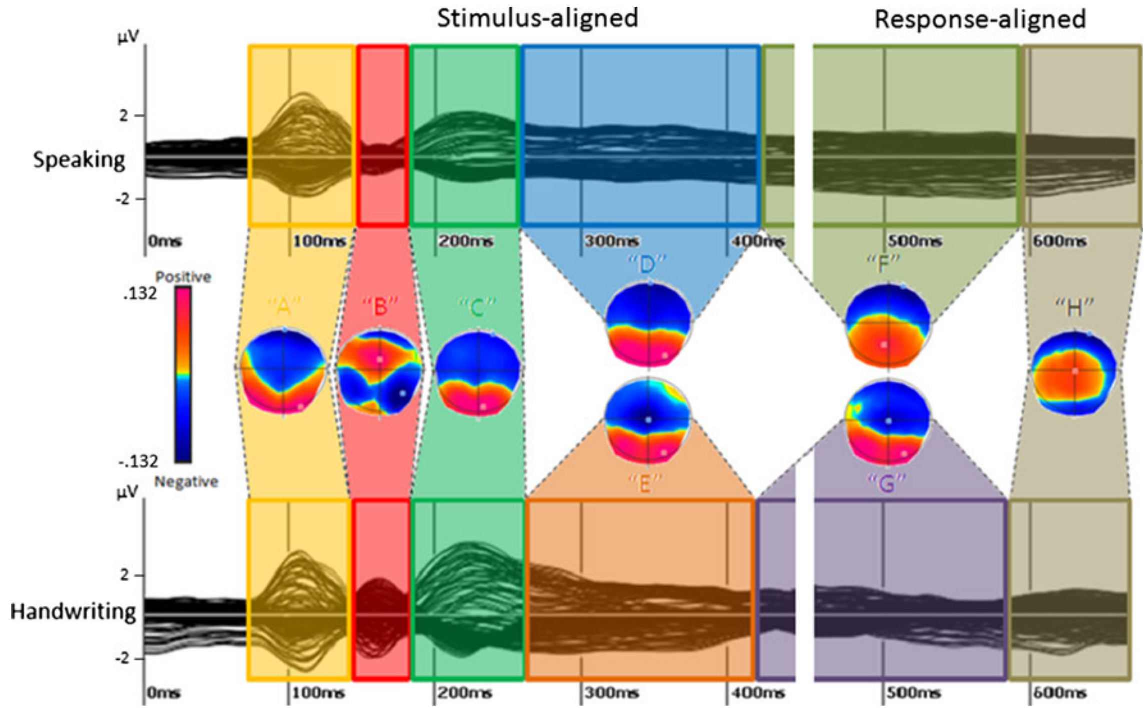

Fig. 2 Grand average ERPs (128 electrodes) from each language modality (speaking and handwriting) and temporal distribution of the topographic maps revealed by the spatio-temporal segmentation analysis in each data. Topographic maps and their specific time-windows are showed by each rectangle. Map templates were associated with corresponding stable topographies

(63%) than for speaking on map "A" (52%, $\chi^2 = 5.76$, $P = 0.016$) with no further difference for map "C" ($\chi^2 < 1$).

For map "B" (from about 140–180 ms) the fitting procedure indicated that it characterized handwritten production better than spoken production (respectively 77% of presence versus 45%, $\chi^2 = 7$, $P = 0.008$; 36% of GEV vs. 12%, $\chi^2 = 13.23$, $P = 0.001$), but without difference on map duration across the two language modalities ($\chi^2 < 1$).

During the second time-window, distinct electrophysiological configurations at scalp were observed for each language modality (see Fig. 2). The fitting procedure confirmed that maps "D" and "F" appeared specifically during spoken word production while maps "E" and "G" were more specific to handwriting ERPs (see Table 2). Finally, the last time-window of fitting procedure confirmed that the last electrophysiological map (map "H", Fig. 2) was observed in spoken as well as in handwritten picture naming (Map presence, $\chi^2 = 3.26$, n.s.; GEV, $\chi^2 < 1$), with similar duration ($\chi^2 < 1$).

Discussion

Systematic comparison between handwriting and spoken picture naming suggested similar electrophysiological correlates until about 260 ms and different electrophysiological activations from around 260–200 ms before production. As several previous ERP studies have analyzed the ERP correlates and time course in spoken picture naming (see "Introduction" section), we will base our comparison on these previous results. Before any further discussion, it is worthy to note that RTs were similar in spoken and handwritten production. Previous behavioural studies comparing spoken and handwritten picture naming systematically reported longer latencies for writing than for speaking. However, in the present study the participants could not see their production as the sheet and their hand were masked. The similar RTs between oral and handwritten production are in line with Perret and Laganaro (subm)'s hypothesis according to which longer RTs are only observed in "standard" (visible) written picture naming, due to the change of eye fixation point from the screen to the sheet. Finally, the difference in accuracy between handwriting and speaking is due to higher rate of spelling errors (inaccurate orthographic knowledge, Bonin et al. 2001).

Until Around 260 ms after Stimulus Presentation

No differences were observed on the sequence of stable electrophysiological activity (topographic maps) across

Table 2 Comparisons on map presence and GEV in each modality across the 22 participants for the time-period from 260 to 600 ms

	Map presence			GEV		
	Speak.	Hand.	χ^2	Speak	Hand.	χ^2
Map "D"	91%	8%	16***	60%	2%	20***
Map "E"	13%	86%	14***	3%	44%	19***
Map "F"	86%	14%	11***	62%	3%	16***
Map "G"	14%	86%	15***	4%	38%	14***

Speak. Spoken picture naming; *Hand.* handwritten picture naming; χ^2 Friedman rank sum test

*** $P < 0.001$

conditions in a first time-period from 0 to 260 ms. Three different stable topographical configurations appeared in the same sequence in both conditions. According to previous estimations of processes involved in spoken picture naming (Indefrey and Levelt 2004), this time-period corresponds to the visual perception processes, (until about 140 ms), conceptual preparation (until about 190 ms) and lexical-semantic encoding (until about 260 ms). Therefore, the present results suggest that the electrophysiological activity involved in visual treatment (picture recognition) and conceptual preparation are common to both language modalities, which is in line with results from behavioral studies pointing to shared cognitive processes between speaking and writing at these processing levels (Bonin et al. 2002; Caramazza 1997). However, a difference was observed on amplitudes at around 100–140 ms, associated to lower GEV for speaking than for writing for the stable topographical patterns in this time-window. This suggests higher electrophysiological variability in the spoken production.

A stable electrophysiological activity also appeared in both language modalities with virtually the same duration from around 190–260 ms. Indefrey and Levelt (2004) associated this time-period with lexical-semantic processing in spoken picture naming, i.e., lemma retrieval in some models of speech production (Levelt 1989; Levelt et al. 1999). This observation is crucial for the comprehension of processes involved in handwritten and spoken conceptually driven production. It suggests that both spoken and handwritten picture naming involve a lemma retrieval process and that this treatment seems to be common to the two production modes.

From 260 to 600 ms after Stimulus Presentation

The main differences between handwriting and speaking appeared on amplitudes, on GEV (Fig. 1) and on stable electrophysiological configurations (Fig. 2) in the time-period from 260 to 600 ms. Crucially, different stable electrophysiological activities were observed in this time window, suggesting different underlying cognitive processes across language modalities. In the spoken production literature the time-window between 275 and 400–450 ms has been associated to phonological encoding process, followed by phonetic encoding and motor planning/execution (Indefrey and Levelt 2004). The sequence of stable topographical configurations in the spoken naming data (Maps "D" and "F", Fig. 2) corresponded closely to this sequence of processes. Two different stable electrophysiological configurations (maps "E" and "G", Fig. 2) were observed in this time-period in the written data. We can infer from this comparison that different cognitive processes underlie word-form encoding in the spoken and written modalities, both having approximately the same duration.

Finally, an unexpected result appeared with the common electrophysiological pattern at the end of the analyzed period, i.e. close to motor execution (labeled "H" in Fig. 2). According to estimations made for oral production (Indefrey and Levelt 2004), phonetic encoding processes start around 450 ms in picture naming, but no further specification is available so far. We can assume that this late electrophysiological activity can be associated with motor programming, i.e., a process during which abstract motor codes are translated into motor execution. Whether similar electrophysiological activity underscores both production modalities just before motor execution should be replicated before any serious interpretation can be drawn.

In sum, spoken and handwritten picture naming start diverging around 260 ms, i.e. at the beginning of the time-window associated to the encoding of the phonological form in spoken production. These results suggest similar processes up to lexical selection and different networks underlying the encoding of surface forms (respectively phonological and orthographic).

Conclusion

Systematic comparisons between electrophysiological activity form spoken and handwritten picture naming recordings with high density EEG suggested two time-windows of processes. During the first time-window (from the presentation of picture to 260 ms), no differences appeared across modalities, suggesting that visual picture treatment, conceptual preparation and lexical (lemma) selection are shared by spoken and handwritten production. ERP divergences across modalities both in the waveform analysis and topographical pattern analysis were reported during the second time-window from 260 to 600 ms. As different topographies characterized spoken and written production in this second time-period, two distinct electrophysiological processes underlie the two production modalities during the encoding of the surface form.

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