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Exploring the multiple-level hypothesis of AoA effects in spoken and written object naming using a topographic ERP analysis

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ABSTRACT

Here we tested the multiple-loci hypothesis of age-of-acquisition effects in both spoken and handwritten object naming using Event-Related Potentials (ERPs) and spatiotemporal segmentation analysis. Participants had to say aloud or write down picture names that varied on frequency trajectory (age-of-acquisition). Early-acquired words yielded shorter naming times than late-acquired words in both spoken and written naming. More importantly, AoA modulated ERPs only during a later time-window in both output modalities: waveforms started to diverge around 400 ms, which corresponded to the end of a period of topographic stability starting at around 260 ms in both conditions. These stable electrophysiological maps lasted longer in the late than in the early-acquired condition and shifted the onset of the following periods of stable electrophysiological activity. Taken together, the findings are at odds with the multiple loci hypothesis, but support the hypothesis that AoA affects a single encoding level, namely the word-form encoding process.

1. Introduction

Identifying the factors that affect the speed and the accuracy of lexical processing has long been a critical issue in psycholinguistics, cognitive neuropsychology and cognitive neurosciences. As far as object naming, which is the focus of the current study, is concerned a number of variables have been investigated as potential determinants of the naming performance in the spoken (e.g., Alario et al., 2004), and, also to a lesser extent, in the written modality (Bonin, Chalard, Méot, & Fayol, 2002). Among these factors is the age at which words are learned (henceforth AoA). Indeed, AoA effects have been found in a wide variety of lexical tasks in the performance of both healthy (see Johnston & Barry, 2006; Juhasz, 2005 for reviews). AoA is also one of the most influential factor affecting the performance of patients with Alzheimer's disease (Herrera, Rodriguez-Ferreiro, & Cuetos, 2012), with semantic dementia (Woollams, 2012) and of aphasic patients (e.g., Catling, South, & Dent, 2013; Cuetos, Aguado, Izura, & Ellis, 2002; Kittredge, Dell, Verkuilen, & Schwartz, 2008). However, even though the existence of AoA effects is well-established at an empirical level, the locus and the functional dynamics of AoA effects in object naming are far from being fully understood (Juhasz & Yap, 2013). As we shall argue, this situation is due to the fact that a strategy of logical elimination of the different levels at which AoA effect takes place has been used. The aim of this study was to address the issue of which mental operation is affected by AoA in object naming. To this aim we analyzed AoA effects in both spoken and written modalities using Event-Related Potentials (ERPs) covering the entire encoding period, from picture onset to articulation and spatiotemporal segmentation analyses (Brunet, Murray, & Michel, 2011; Michel, Koenig, Gianotti, & Wackermann, 2009; Murray, Brunet, & Michel, 2008). In the following, we shall first briefly address the issue of the measurement of the AoA of the words. Then we will review the issue of the locus(i) of AoA effects in object naming and spell out the approach we have pursued to address this issue.

The best way of evaluating and conceptualizing the AoA of words has long been, and remains, a subject of debate (see Bonin, Méot, Mermillod, Ferrand, & Barry, 2009; Mermillod, Bonin, Méot, Ferrand, & Paindavoine, 2012). The most frequently used measures of word AoA are subjective estimations. Adults are given a list of words and are required to provide an estimation of the age at which they think they learned each of the words using

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Likert scales with different age-bands (e.g., Alario & Ferrand, 1999; Barry, Morrison, & Ellis, 1997; Bonin, Peereman, Malardier, Méot, & Chalard, 2003; Marques, Fonseca, Morais, & Pinto, 2007). Zevin and Seidenberg (2002) adopted a different perspective to account for AoA effects, using *frequency trajectory (FT)*. FT is operationally defined as by the difference between the "adult" frequency and the "child" frequency. Among other things, this measure is less highly correlated with other lexical variables than the standard AoA measures (Bonin, Barry, Méot, & Chalard, 2004; Bonin et al., 2009). Although, certain aspects of frequency trajectory can be criticized (e.g., the fact that only two points in time are generally taken into account, e.g., Bonin et al., 2004), we believe that this measure is certainly a reliable alternative to investigate AoA effects (Mermillod et al., 2012).[1] We then have opted for these measures in the present study which have not as yet been used to explore the locus of AoA effects.

1.1. Locus(i) of AoA effects in object naming

In the literature, several potential loci of AoA effects have been proposed in object naming. Fig. 1 provides a theoretical framework for understanding the processes and the representations underpinning spoken and written object naming and the potential loci of AoA effects. It is generally assumed that object naming involves four main processing levels (e.g., Humphreys, Riddoch, & Quinlan, 1988; Levelt, Roelofs, & Meyer, 1999). First, a visual representation of the object is generated from the visual image, leading to the retrieval of structural representations (i.e., visual object recognition). The associative and functional properties of the to-be-named object (i.e., conceptual/semantic activation) are then accessed. The third processing level is lexical access, which involves the retrieval of a lexical entry specifying the word's gender and grammatical category (lemma retrieval in Fig. 1, but see Caramazza, 1997) and the access to the word-form (L-level in Fig. 1). Finally, the abstract (individual phonemes in speaking or individual graphemes in writing) codes are passed on to a set of processing stages, which lead to the planning of motor movements.

The most often cited locus for AoA effects in spoken object naming is still the word-form level (e.g., Morrison, Ellis, & Quinlam, 1992; Navarrete, Scaltritti, Mulatti, & Peressotti, 2012) albeit not within the framework of the phonological completeness hypothesis.[2] As far as written naming is concerned, the locus of AoA effects has also been ascribed to the word-form level (the L-level in Fig. 1). Nevertheless, the hypothesis that the phonological level is the sole locus of AoA effects in object naming and in other lexical tasks has been criticized mainly because it cannot account for the fact that AoA effects are found in tasks in which lexical representations do not seem to be required such as face recognition/face familiarity decision tasks, (e.g., Lewis, 1999; Moore & Valentine, 1999; Valentine, Hollis, & Moore, 1998).

One hypothesis is that AoA effects in object naming do not originate solely at the word-form level but can potentially take place at other processing levels (i.e., the multiple loci hypothesis of AoA

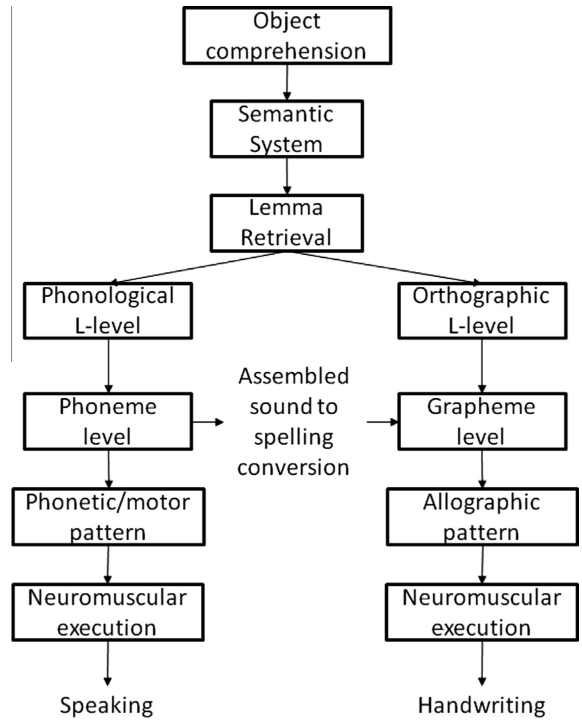

Fig. 1. Processing levels of spoken and handwritten object naming.

effects). More precisely, two other loci have been put forward: the object recognition level (e.g., Catling, Dent, & Williamson, 2008; Dent, Calting, & Johnston, 2007) and the semantic/conceptual level (e.g., Belke, Brysbaert, Meyer, & Ghyselinck, 2005; Johnston & Barry, 2005; Morrison & Gibbons, 2006). The object recognition level has been proposed as a candidate locus for AoA effects in object naming for two reasons. The first reason is methodological (Levelt, 2002). Levelt (2002) claimed that in certain object naming studies reporting AoA effects (e.g., Barry et al., 1997; Bonin, Fayol, & Chalard, 2001; Bonin, Peereman, & Fayol, 2001), the speed of object recognition was not controlled for. However, strong AoA effects in object naming latencies have been found when the ease of the perceptual processing of the objects was controlled for Bonin, Chalard, Méot, and Barry (2006). The second reason is that AoA effects have been observed in object recognition tasks (e.g., Catling et al., 2008; Dent et al., 2007). Since object naming involves object recognition (Bonin, Roux, Barry, & Canell, 2012), a logical consequence would seem to be that AoA effects in object naming can arise at this level.

Another plausible locus for AoA effects in object naming is the semantic level. According to Brysbaert, van Wijnendaele, and de Deyne (2000), AoA effects arise as a result of the organization of the semantic information in the mental lexicon. The order of acquisition is thought to be an important organizational principle of the semantic system (Steyvers & Tenenbaum, 2005), with the result that late-acquired concepts are built on earlier-acquired concepts. Indeed, AoA effects have been found in semantic tasks such as categorization (e.g., Brysbaert et al., 2000; Johnston & Barry, 2005; Morrison & Gibbons, 2006 but see Morrison et al., 1992). In object naming, it is assumed that access to semantic codes is obligatory for the retrieval of object names (e.g., Bonin et al., 2012) and this assumption is consistent with the findings that AoA effects are stronger in picture naming than in word reading since it is sometimes thought that word reading does not require (or requires less) semantic code activation (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Although the hypothesis that AoA effects have a semantic locus is still discussed in the literature, there is also

[1] It is worth noting that the issue of the best AoA measures to use is unsettled. Actually, Pérez (2007) has shown for instance that there was no reliable effect of frequency trajectory beyond AoA ratings in his regression analyses of naming times. As far as object or face naming is concerned, maybe both rated AoA and frequency trajectory variables will contribute to research by providing complementary

[2] In accordance with a phonological locus of AoA effects, Brown and Watson (1987) put forward an account of AoA effects referred to as the phonological completeness hypothesis. According to this hypothesis, phonological representations of Early Acquired words are holistic in nature, whereas those of Late Acquired words are more fragmented. Therefore, the former are quicker to retrieve than the latter. Often cited in the past, the phonological completeness hypothesis of AoA effects has been since discarded by Monaghan and Ellis (2002) who reported strong evidence against it.

evidence that challenges it (Chalard, Bonin, Méot, Boyer, & Fayol, 2003; Izura & Ellis, 2004, 2002; Izura et al., 2011).

Finally, Ellis and Lambon Ralph (2000) have put forward the view that AoA effects are a general property of cognitive systems in which the learning of the items is cumulative and interleaved. By means of a series of simulations, they showed that AoA effects emerged as a result of a gradual loss of plasticity in neural networks, with the result that it is more difficult for late-acquired items to become represented than early-acquired items (see also Lambon Ralph & Ehsan, 2006; Mermillod et al., 2012). This view is commonly referred to as the mapping hypothesis that localizes the AoA effect at different connecting-points in the system. Their view is compatible with the idea that AoA effects can have multiple loci in mature cognitive systems.

As reviewed above, no clear-cut evidence has been found in support of a single locus in picture naming. In our opinion, the situation is obscured by the fact that the various hypotheses concerning the locus of AoA effects in object naming are based on the comparison of AoA effects on behavioral measures in object naming with other different lexical tasks. We refer to this logic as the elimination strategy. Likewise, the single 'word-form locus' hypothesis of AoA effects in object naming is supported by the observation that AoA affects tasks requiring access to word-forms, such as picture naming, but it does not affect tasks in which word form encoding is not required, such as object recognition tasks. This latter task, as object naming, requires access to the level of structural representations and of semantic codes but does not require access to the level of word-forms. Insofar as AoA effects are reliable in object naming latencies but are not reliable in other tasks (e.g., object recognition), which are assumed to involve only some of the components involved in object naming (structural, semantic) these effects can only be attributed, by elimination, to the level at which they reliably occur (Morrison et al., 1992). In contrast, the multiple-level hypothesis of AoA effects in object naming is supported by the fact that AoA effects have been found in a number of different tasks, including object recognition and semantic categorization tasks, which share some but not all processing levels with object naming, namely the structural and the semantic levels.

Recently, neuro-imaging techniques have allowed a different approach to the exploration of the issue of the processing level(s) affected by the age at which words are learned in a single task. AoA effects have been found in fMRI studies (e.g., de Zubicaray, Miozzo, Johnson, Schiller, & McMahon, 2011; Ellis, Burani, Izura, Bromiley, & Venneri, 2006; Fiebach, Friederici, Müller, von Cramon, & Hernandez, 2003; Urooj et al., 2014; Weekes, Shu, Hao, Liu, & Tan, 2004). In covert picture naming, Ellis et al. (2006) found an increase in activity in the fusiform gyrus for late-acquired words and in the most inferior portions of the temporal lobe for early-acquired words suggesting a visual and semantic locus of AoA effects (see also Urooj et al., 2014). According to Ellis et al. (2006), early items are characterized by richer semantic interconnections than late items whereas the latter require more visual-form processing than early items. As far as Event-Related Potentials (ERP) studies are concerned, research addressing a methodological issue concerning the use of immediate picture naming in comparison to delayed production, conducted by Laganaro and Perret (2011) found that AoA effects appeared only in immediate naming, when the analyses were performed from picture onset to the onset of articulation. The locus of AoA effects was not the main purpose of this study, and the early and late acquired items were not properly matched on several important psycholinguistic variables (e.g., Image Variability). Nevertheless, AoA effects in the immediate naming condition appeared in the time-window typically associated with the phonological word-form level (275–450 ms, see Indefrey, 2011).

1.2. The current study

In the current study, we tested the multiple-level hypothesis of age-of-acquisition effects in object naming with ERPs and spatio-temporal segmentation analyses. As explained in the Introduction, we chose to use *frequency trajectory* (FT) measures to index AoA effects. A semi-factorial design was used in combination with highly controlled material. Two sets of high-to-low (i.e., early-acquired) items and low-to-high (i.e., late-acquired) items were matched on sixteen psycholinguistic variables. Moreover, we used only one task, namely object naming, in two different modalities, namely spoken (Experiment 1) and handwritten (Experiment 2) production. ERP studies have led to estimate of the activity of main processes underlying single word production during spoken picture naming (Indefrey, 2011; Indefrey & Levelt, 2004; Riès, Janssen, Burle, & Alario, 2013; Strijkers & Costa, 2011). For instance, in their review of the ERP literature, Strijkers and Costa (2011) suggested that lexical/lemma processing occurs within 200 ms after stimulus presentation.

Written naming can be thought as another instance of object naming. It shares some processing levels with spoken naming but also involves other specific processing levels (Bonin & Fayol, 2000). In a recent study comparing spoken and written object naming, Perret and Laganaro (2012) found that electrophysiological correlates diverged around 260 ms after picture presentation. They suggested that the two modalities involved similar processes until the retrieval of modality specific word form which started around 260 ms. Given that the word-form level (i.e., orthographic and phonological word form) has been proposed as the main locus of AoA effects in object naming in both production modes (Bonin, Fayol, et al., 2001; Bonin, Peereman, et al., 2001), we expect to find AoA effects in a similar time-window in written naming and in spoken naming. The ERP and spatiotemporal segmentation methodologies were employed to specify the time-window(s) during which differences in electrophysiological activities were observed between the two AoA conditions in each modality (oral and written).

2. Spoken picture naming

2.1. Participants

The participants were 21 (4 men) native French speakers (aged 20–36, mean: 25.14). All were right-handed as determined by the Edinburgh Handedness Scales (Oldfield, 1971; lateralization quotient index range: 80–100%, mean: 95.24; SD: 8.51). All reported having normal or corrected-to-normal vision and did not suffer from any neurological or motor problem. They gave their informed consent to participate in the study and were paid for their participation. The study procedure was approved by the local ethical research committee at Geneva University.

2.2. Material

A total of 120 words and their corresponding black-and-white pictures were selected from French databases (Alario & Ferrand, 1999; Bonin et al., 2003). We used a dual criterion to select our material: adult rated AoA measures on a 5-point scale and Frequency Trajectory. Half of the items were early-acquired words (EARLY, mean = 1.86, SD = .23) and the other half late-acquired word (LATE, mean = 2.67, SD = .38, $t(97.346) = -13.9418$, $p < .0001$). EARLY also had a significantly smaller mean frequency trajectory than LATE (see Table 1). To obtain the frequency trajectory and the cumulative frequency, we used the "adult" measure of frequency taken from LEXIQUE2 (New, Pallier, Brysbaert, &

Table 1
Characteristics of early and late acquired words.

	EAW		LAW		*p* values
	Mean	SD	mean	SD	
h-NA	.14	.2	.19	.26	n.s.
IA	3.53	.73	3.73	.68	n.s.
Fam	3.02	.88	2.96	.87	n.s.
VC	2.92	1.06	3.1	.80	n.s.
Ivar	2.93	.53	2.79	.5	n.s.
Freq-traj	-.27	0.79	.27	0.57	.0012
logFreq	1.10	.40	.99	.44	n.s.
Cumul-freq	.09	2.37	-.09	2.87	n.s.
LET-length	6.13	1.73	6.22	1.68	n.s.
PHO-length	4.45	.133	4.65	1.44	n.s.
Ortho-Neig	6.1	5.44	6.48	6.81	n.s.
Phono-Neig	12.72	10.32	11.2	11.18	n.s.
logFreqsyllphon	2.65	.93	2.48	1.00	n.s.
logFreqsyllortho	2.28	.75	2.21	.78	n.s.
logFgraph	4.58	.14	4.59	.15	n.s.
logFphon	4.42	.14	4.42	.15	n.s.
Sono-value	3.58	2.72	3.43	2.69	n.s.

Notes: H-NA: Name Agreement (h statistic); IA: Image Agreement; Fam: conceptual Familiarity; VC: Visual Complexity; Ivar: Image Variability; Freq-traj: Frequency Trajectory; logFreq: lexical frequency in log; Freq-Cumu-freq: cumulate frequency; LET-length: number of letters; PHO-length: number of phonemes; Ortho-Neig: number of Orthographic neighbors; Phono-Neig: number of phonological neighbors; logFreqsyllphon: logarithm of phonological syllable frequency; logFreqsyllortho: logarithm of orthographic syllable frequency; logFgraph: logarithm of grapheme frequency; lofFphon: logarithm of phoneme frequency; Sono-value: sonority value of the first phoneme.

Ferrand, 2004) and the "child" measure of frequency (*U* values) taken from MANULEX (Lété, Sprenger-Charolles, & Colé, 2004). The frequency trajectory values were computed as the difference between the *z*-scores associated with the two measures of frequency (LEXIQUE2 minus MANULEX) and the cumulative frequency measures were calculated by adding *z*-scores (LEXIQUE2 plus MANULEX).

Early- and late-acquired words were matched on sixteen pictorial, lexical and sublexical variables (Table 1). Name Agreement, Image Agreement, Conceptual Familiarity, Visual Complexity and Image Variability values were taken from the two French normative databases (Alario & Ferrand, 1999; Bonin et al., 2003). The following lexical and sublexical properties were taken from the French data-base LEXIQUE2 (New et al., 2004): lexical frequency, densities of orthographic and phonological neighborhood, the phonological and orthographic lengths, phonological syllable frequency and phoneme and grapheme frequencies (Table 1). Orthographic syllable frequency was taken from Chetail and Mathey (2010). Finally, EA and LA items were matched on the sonority values of the first phoneme.

2.3. Procedure

The participants were tested individually in a soundproof dimly light room and sat 60 cm in front of the screen. Before the experiment the participants were familiarized with the experimental pictures and their corresponding names. This is a usual procedure in object naming experiments which has the potential to diminish the number of spoiled naming trials. In each modality, the 120 pictures were presented randomly, preceded by 4 warming-up items. A short break was given after every 40 trials. The E-Prime software (E-Studio) presented the trials and recorded the response latencies. The experimental session lasted about 20 min.

An experimental trial had the following structure: first, a warning signal (an asterisk) was presented for 500 ms. Next, the drawing appeared on the screen, in inverse video (white lines on gray screen) at a constant size of 9.5 * 9.5 cm (approximately 4.52° of visual angle). A gray screen was used to avoid exposure to extreme lighting. The participants were told that they would see a picture and 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 a subsequent examination of the response latency and accuracy. The picture remained on the screen for 3000 ms and the next trial began 2000 ms after the drawing offset.

2.4. EEG acquisition and pre-analyses

The 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: 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. Exactly the 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 permits full matching between stimulus-aligned and response-aligned ERPs. For the topographical pattern analysis (see Section 2.7), the stimulus-aligned and response-aligned data obtained from each participant were merged based on each individual subject's RT in each condition by removing the overlapping ERP from the response-aligned signal. The combination of stimulus- and response-aligned data was introduced by Laganaro and Perret (2011) in spoken picture naming, to enable the individual averaged data (and the group grand-average) to cover the actual time from onset (picture on screen) to 100 ms before oral production.

In addition to an automated selection criterion which led to the rejection of epochs with amplitudes reaching ±100 μV, each trial was visually inspected, and epochs contaminated by 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. After rejection of errors and of contaminated epochs, a minimum of 72 epochs (60%) were averaged per subject. The spoken reaction times were computed after exclusion of production errors and rejected epochs.

2.5. RT analyses

2.5.1. Data elimination

After elimination of errors, vocal response latencies (ms between picture onset and articulation onset) were systematically checked using speech analysis software (Praat: Boersma & Weenik, 2007). This was possible thanks to an inaudible acoustic click at the onset of the picture recorded on the second track of the recording system. Finally, spoken RTs corresponding to excluded epochs during ERP pre-analysis were also discarded.

2.5.2. Data analysis

ANOVAs using a mixed-effect analysis (Baayen, Davidson, & Bates, 2008) based on the R-software (R-project, R-development core team, 2010) were run on RTs with AoA conditions (EARLY versus LATE) as fixed-effect variable. Items and Participants were included as random-effect factors with adjustments on slope and on intercept for each factor.

Likelihood ratio tests were used to choose the most appropriate model (Baayen et al., 2008). The more complex model (the adjustment on both slopes and intercept) never displayed a better random structure than the simpler model with adjustment on intercept. Error rates and the number of excluded epochs were fitted using logit mixed-effects models (Jaeger, 2008) with the same random- and fixed-effect factors.

2.6. Waveform and global field power analyses

The ERPs were first subjected to a standard waveform analysis to determine the time periods at which the ERPs of the two AoA conditions started to diverge significantly from one another. We adopted a method suggested by Guthric and Buchwald (1991). 2-Tailed paired *t*-tests were computed on the amplitudes of the evoked potentials between conditions (Early-acquired-word versus Late-Acquired-Word) at each electrode and time point over the entire analyzed periods (stimulus-aligned and response-aligned, Laganaro & Perret, 2011). Only differences over at least 5 electrodes from the same region out of 6 regions on the scalp (left and right anterior, central, and posterior) extending over a sequence of at least 12 consecutive *t*-test samples exceeding the 0.05 significance level were retained.

Moreover, to avoid influence of reference choice (Murray et al., 2008), we compared the standard deviation of all electrodes at a given time at each time point over the entire analyzed periods (Lehmann & Skrandies, 1984). For differences in this *global field power* (GFP), 2-tailed paired *t*-tests were computed on the GFP between conditions at each time-frame, with an alpha criterion of 0.05 and a time-window of 24 ms (12 *t*-tests) of consecutive significant difference.

2.7. Topographic pattern analyses

Significant variations of ERP can follow from a modulation in the strength of the electric field, from a topographic change in the electric field (revealing distinguishable brain generators) to latency shifts in similar brain processes. To differentiate these effects, we applied topographic analyses (spatiotemporal segmentation analysis, Brunet et al., 2011). This approach allows us to summarize ERP data into a limited number of electrophysiological stable periods (topographical map configurations, Lehmann & Skrandies, 1984). We applied a spatiotemporal segmentation to the three grand average data sets (All words; EARLY; LATE). A modified hierarchical clustering analysis (Michel et al., 2001; Pascual-Marqui, Michel, & Lehmann, 1995) – the agglomerative hierarchical clustering method (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 best explained the group-averaged data sets across conditions. Statistical smoothing was used to eliminate low-strength temporally isolated maps. This procedure is described in more detail in Pascual-Marqui et al. (1995). Additionally, a given topography had to be present for at least 12 time frames (24 ms). This analysis is independent of the reference electrode (Michel et al., 2004) and insensitive to pure amplitude modulations across conditions (topographies of normalized maps are compared).

The pattern of map templates resulting from the spatiotemporal segmentation on the grand averages was statistically tested by comparing each of these map templates with the moment-by-moment scalp topography of individual subjects' ERPs in each condition. Each time point was labeled according to the map with which had the best spatial correlation, thus 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), its onset point in time (FTF: First Time Frame) and its duration. The "fitting" procedure was applied to the merged stimulus- and response-aligned ERPs of each individual subject in each condition. Non-parametric tests (Friedman rank sum test) were applied to these three measures (i.e., FTF, GEV and duration) with subjects as random variable and AoA as fixed factor. This approach has been regularly used with language data (Laganaro, Morand, & Schnider, 2009; Laganaro & Perret, 2011; Laganaro, Valente, & Perret, 2012; Perret & Laganaro, 2012) and the procedure has been described in detail in Murray et al. (2008; see also Brunet et al., 2011; Michel et al., 2009).

3. Results

3.1. Behavioral results

Incorrect responses (4.40%) and outliers (mean RT ± 3 SD, 0.56%) were excluded from the RT analysis. Excluded epochs corresponded to 4.33% of data.

AoA influenced spoken production latencies ($t(2285) = 3.756$, $p = .0002$): early-acquired words were initiated significantly shorter than late acquired words (Table 2). Also, AoA influenced error rates with less errors on early acquired words in the spoken modality (*Wald* $z = 2.911$, $p = .0036$). Finally, there was no difference in the number of excluded epochs (*Wald* $z < 1$).

3.2. Waveform and global field power analyses

Fig. 2 presents the time points corresponding to significant amplitude differences between EARLY and LATE for Spoken picture naming. *t*-Tests conducted on each sampling rate for spoken picture naming (Fig. 2) indicated that the ERPs for Early-Acquired Words started to diverge significantly from those for Late-Acquired Words 382 ms after stimulus presentation.

These amplitude differences appeared continuously up to 414 ms at the electrodes in the left anterior and right and left central regions. Sparse amplitude differences were also observed at the electrodes from same regions at about 460 ms. Different GFPs were observed across the AoA conditions in approximately the same time-windows. In the case of the response-aligned ERPs, a first group of amplitude differences, which were observed in all

Table 2
Production latencies in spoken picture naming for each AoA/FT conditions.

	Early acquired words (HL)			Late acquired words (LH)		
	Means	SD	Errors	Means	SD	Errors
Spoken production	748	152.46	2.77%	795	165.24	6.04%

Notes: HL = high-to-low frequency trajectory words; LH = low-to-high frequency trajectory words.

scalp regions (excepted on right anterior region), appeared from 342 ms to 260 ms before articulation. A second group of amplitude differences at similar scalp regions was observed from 246 ms to 212 ms before spoken production (Fig. 2). GFP differences were also observed in these time-windows.

3.3. Topographic pattern analyses

The spatiotemporal segmentation applied to the 3 grand averages (i.e., all-word, EARLY and LATE conditions) from 70 ms after picture presentation to 100 ms before articulation revealed 6 different electrophysiological template maps accounting for 96.32% of the variance. The same sequence of topographical maps appeared in both AoA conditions (Fig. 3). The stable map "D" was shorter for EARLY than LATE, and shifted the first onset of the next two maps "E" and F". These two stable maps seemed to have an indistinguishable duration.

These observations were validated by the results of the fitting procedure applied to individual EARLY and LATE spoken picture naming data in two time-windows: from 0 to 260 ms and from 260 ms to 695 ms. In the first fitting period, the same durations, FTF and GEV of the stable maps "A", "B" and "C" were observed across AoA conditions (all $\chi^2 < 1.33$, $ps > .2482$). The second fitting period revealed a 42 ms difference in duration for stable map "D" between Early- and Late-acquired words (EARLY: 168 ms, LATE: 210 ms; $\chi^2 = 9.80$, $p = .0017$). GEV also differed across AoA conditions (EARLY: 40%, LATE: 50%; $\chi^2 = 8.08$, $p = .0045$) while FTF was virtually the same ($\chi^2 s < 1$). Finally, the shift of FTF was significant for the stable electrophysiological maps "E" (EARLY: 418 ms, LATE: 464 ms; $\chi^2 = 10.71$, $p = .0011$) and "F" (EARLY: 549 ms, LATE: 592 ms; $\chi^2 = 8.537$, $p = .0116$) while these stable maps did not differ on duration and GEV (all $\chi^2 < 1.47$, $ps > .2253$).

3.4. Discussion

According to the multiple-level hypothesis of AoA effects in object naming, differences in electrophysiological activity should be observed during the time period from around 0 ms to around 455 ms. The results of the spoken picture naming task were not consistent with this hypothesis. The ERPs for Early-Acquired

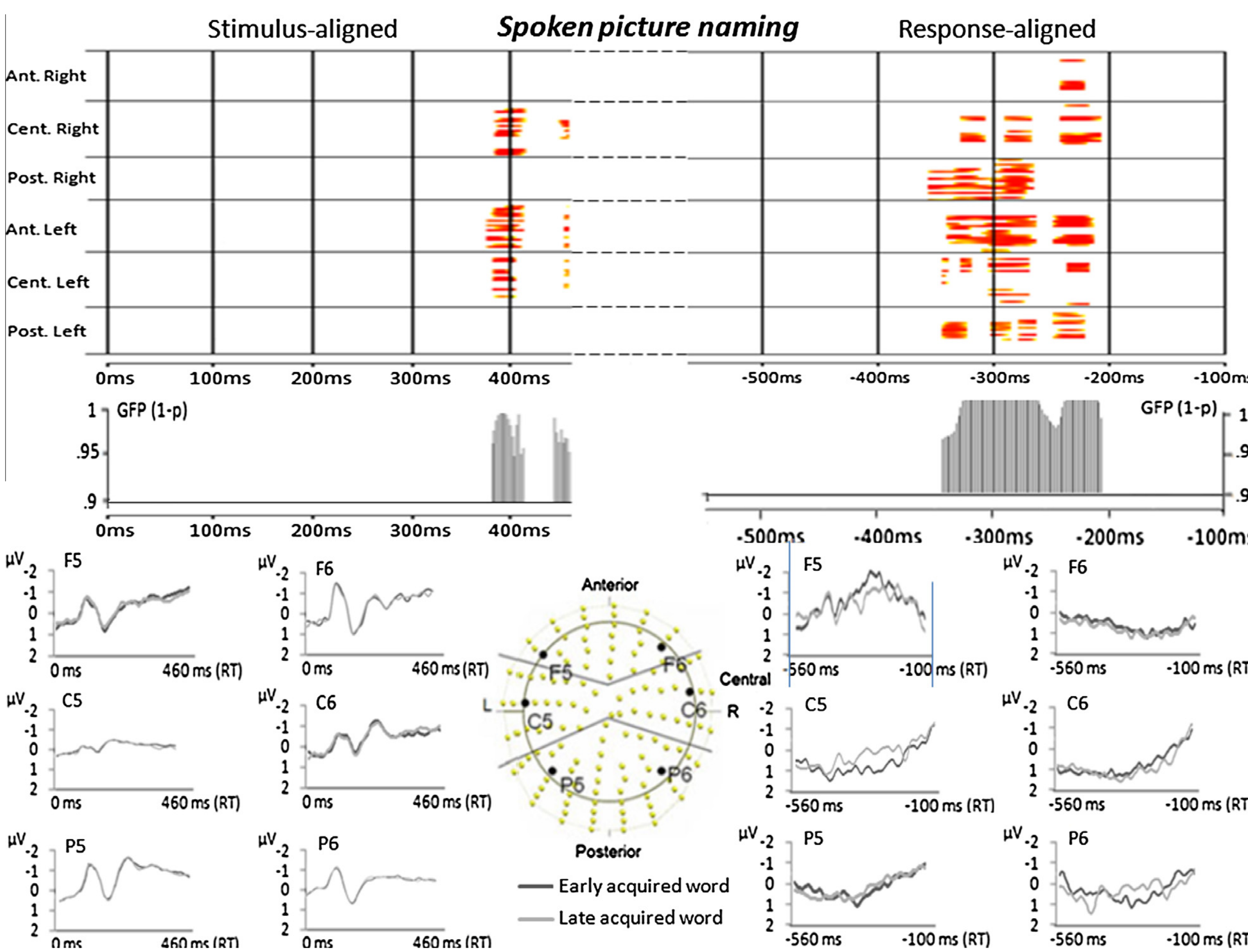

Fig. 2. Waveform and global field power analyses. Top: Significant differences (*P*-values from gray, $P < 0.05$ to black, $P < 0.001$) in ERP waveform amplitude at each electrode (*Y* axes) and time point (*X* axes) between EARLY and LATE (only differences over at least six electrodes from the same region extending over at least 20 ms are shown) and results of statistical analysis ($1 - P$-values) of global field power (GFP). Bottom: Group-averaged ERP waveforms in EARLY and LATE conditions. Negative amplitudes are plotted in the upward direction. The arrangement of the 128 electrodes with the electrode position of the displayed waveforms is presented at the bottom of the central part of the figure.

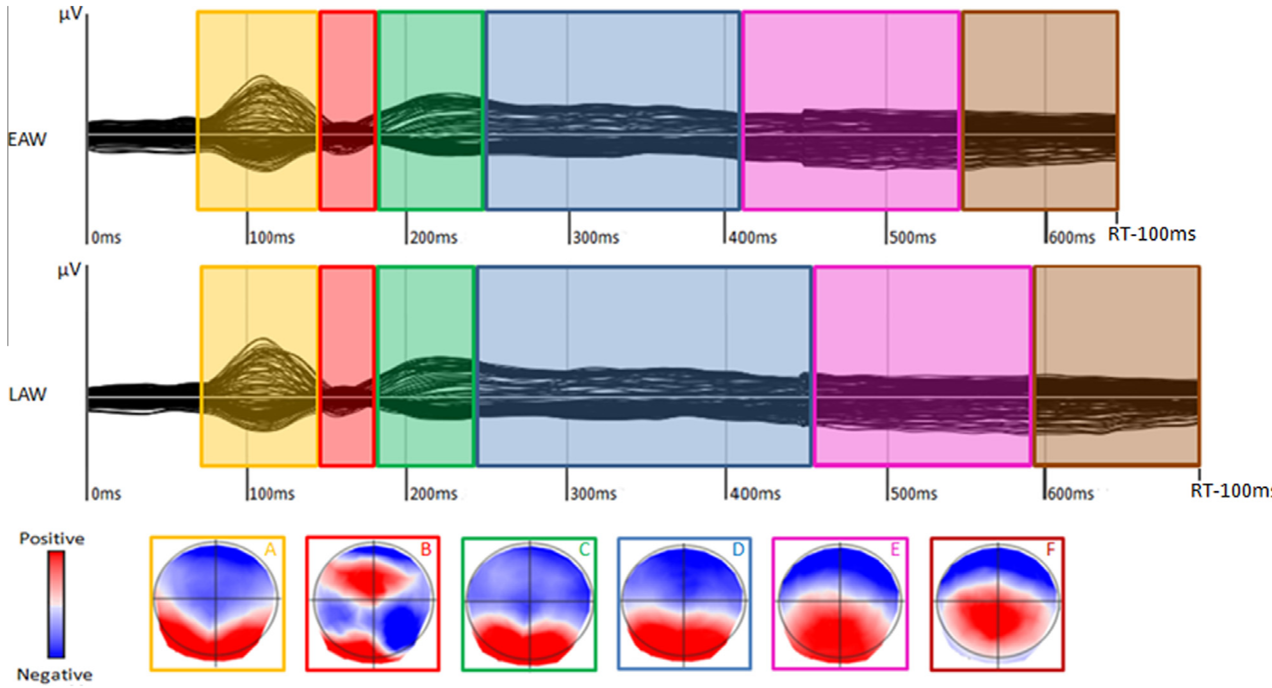

Fig. 3. Grand-average ERPs (128 electrodes) from each AoA condition from onset to 100 ms before RT and temporal distribution of the topographic maps revealed by the spatio-temporal segmentation analysis for each data set. Bottom: map templates for the six stable topographies observed from 70 ms after picture presentation to 100 ms before articulation (positive values in red and negative values in blue with display of maximal and minimal scalp field potentials).

Words started to diverge significantly from those for Late-Acquired Words around 380 ms after stimulus presentation up to 100 ms before articulation. In the spatiotemporal analysis, a longer period of stable topography ("D" in Fig. 3) characterized the data for the late-acquired words compared to that observed for the early-acquired words. The corresponding time-window has been associated with the lexeme access, (L-level) in previous studied (Indefrey, 2011). Nevertheless, before reaching a conclusion, it seems crucial to explore the time-course of AoA effects in a different word production modality, namely with a handwritten picture naming task. As explained in Section 1, handwritten naming shares some encoding processes with spoken object naming, which have been estimated to last until approximately 260 ms (Perret & Laganaro, 2012). Electrophysiological differences between early- and late-acquired words observed after the period of common spoken and handwritten processes (after 260 ms) would represent a further argument in favor of the word-form level hypothesis (L-level in Fig. 1) as the main locus of AoA effects in object naming.

4. Handwritten picture naming

4.1. Participants

The participants in the handwritten picture naming task were 20 right-handed (lateralization quotient index range: 80–100%, mean: 95; SD: 8.66) undergraduate native French students (aged 20–36, mean: 25.55). All reported having normal or corrected-to-normal vision and did not suffer from any neurological or motor problem. They gave their informed consent to participate in the study and were paid for their participation. The study procedure was approved by the local ethical research committee at Geneva University.

4.2. Material

The experimental stimuli were the same 120 pictures used in the spoken picture naming task.

4.3. Procedure

The procedure was the same as that used for spoken picture naming, except that the participants had to write down the picture names (in lowercase) as rapidly and as accurately as possible on a graphic tablet (WACOM UltradPad A4) using an inking contact pen (SP-401). The white sheet on the graphic tablet made it possible to collect the handwritten productions in order to check the responses. The short break after every 40 trials allowed the experimenter to change the sheet on the graphic tablet. The participants could not see and monitor their production since a box hid their hand and the graphic tablet. This procedure was used to prevent head movements during the change of eye fixation point from the screen to the sheet (Perret & Laganaro, 2012). The participants were instructed to try to follow an imaginary line and to write as accurately as they could. In addition, the sentence "lift the pen" appeared for 1000 ms on the screen immediately before the ready signal to remind the participants to stop moving and reposition the pen directly above the tablet in order to avoid any random variability in initial positioning.

4.4. EEG acquisition and pre-analyses

The same EEG recordings and pre-analyses were performed as in the spoken picture naming task. The combination of stimulus- and response-aligned data was introduced by Perret and Laganaro (2012) in a handwritten picture naming task to make it possible for the individual averaged data (and the group grand average) to cover the entire time from onset (picture on screen) to 100 ms before handwritten production.

4.5. Analyses

Based on an examination of the graphic productions, words that were misspelled or written with an uppercase initial letter were discarded. Handwriting RTs corresponding to excluded epochs during ERP pre-analysis were also discarded.

Table 3
Production latencies in handwritten picture naming for each AoA/FT conditions.

	Early acquired words (HL)			Late acquired words (LH)		
	Means	SD	Errors	Means	SD	Errors
Handwritten production	742	176.47	3.92%	787	183.71	7.25%

Notes: HL = high-to-low frequency trajectory words; LH = low-to-high frequency trajectory words.

All analyses were the same as those used in spoken picture naming.

5. Results

5.1. Behavioral results

Incorrect responses (5.58%), outliers (mean RT ± 3 SD, 0.92%) and excluded epochs (6.5%) were excluded from the handwritten production data.

AoA influenced handwritten production latencies ($t(2087) = 3.527$, $p = .0004$): early-acquired words were produced significantly faster than late-acquired words (Table 3). Furthermore, AoA influenced error rates with fewer errors being made on early-acquired words during handwritten production (*Wald* $z = 5.311$, $p < .0001$). Finally, there was no difference in the number of excluded epochs (*Wald* $z < 1$).

5.2. Waveform and global field power analyses

Fig. 4 indicates the time points at which there were significant amplitude differences between EARLY and LATE for handwritten picture naming. The ERP for Early-Acquired words started to diverge significantly from those for Late-Acquired words 356 ms after stimulus presentation, with amplitude differences persisting until 426 ms (Fig. 4).

These differences appeared continuously at the electrodes in all scalp regions. Different GFPs between the two AoA conditions were also observed in approximately the same time-windows. In the case of the response-aligned ERPs, a first group of amplitude differences was observed on electrodes from the anterior, central and posterior left regions from 334 ms to 240 ms before handwriting. Different GFPs were also observed across the AoA conditions during this time-window. A second group of amplitude differences was observed from 158 to 124 ms before articulation at the electrodes in the left and right anterior regions and left and right posterior regions (Fig. 4). Nevertheless, the difference in GFP was not significant for this time-window.

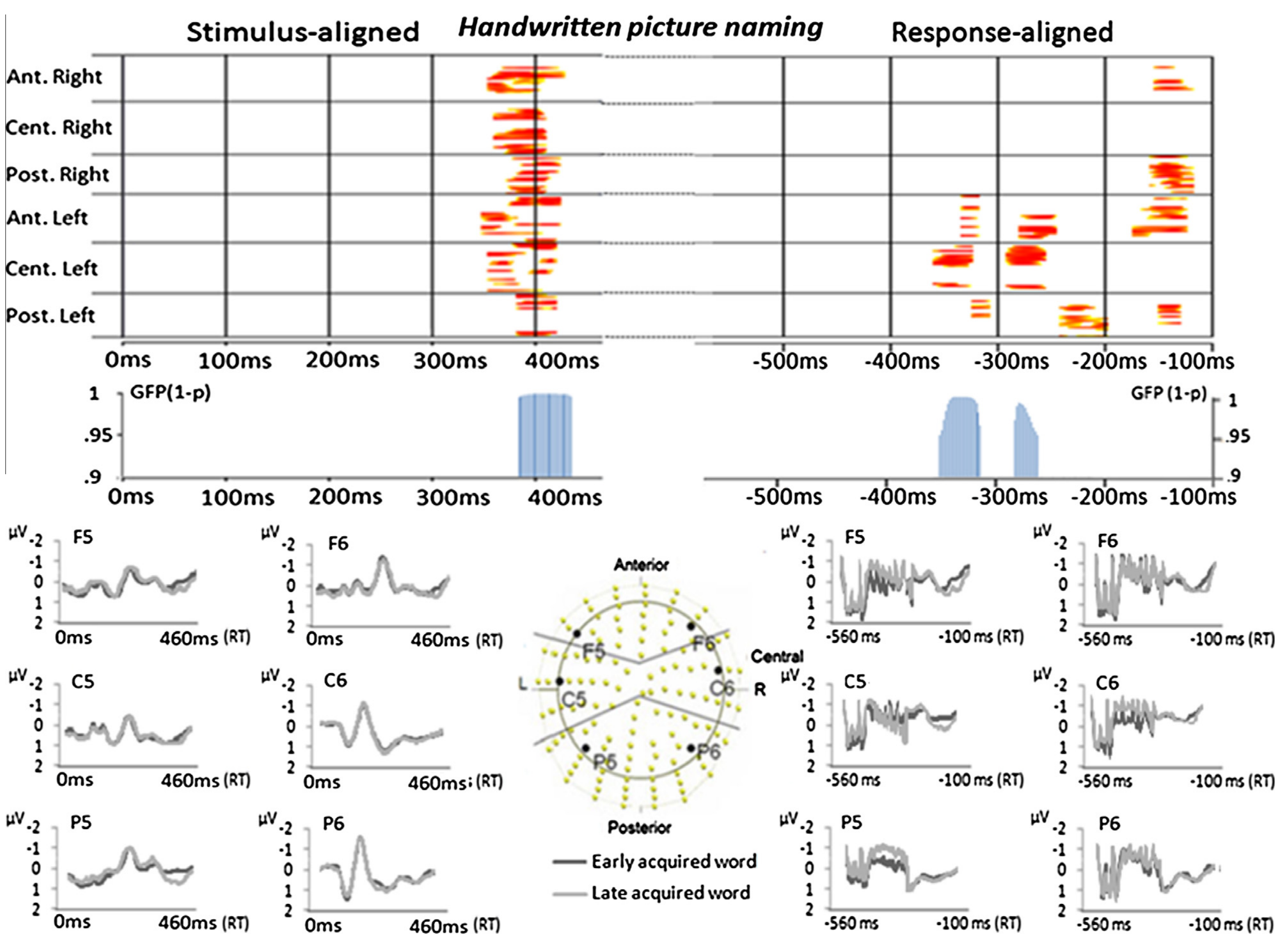

Fig. 4. Waveform and global field power analyses. Top: Significant differences (P-values from gray, $P < 0.05$ to black, $P < 0.001$) in ERP waveform amplitude at each electrode (Y axes) and time point (X axes) between EARLY and LATE (only differences over at least six electrodes from the same region extending over at least 20 ms are shown) and results of statistical analysis ($1 - P$-values) of global field power (GFP). Bottom: Group-averaged ERP waveforms in EARLY and LATE conditions. Negative amplitudes are plotted in the upward direction. The arrangement of the 128 electrodes with the electrode position of the displayed waveforms is presented at the bottom of the central part of the figure.

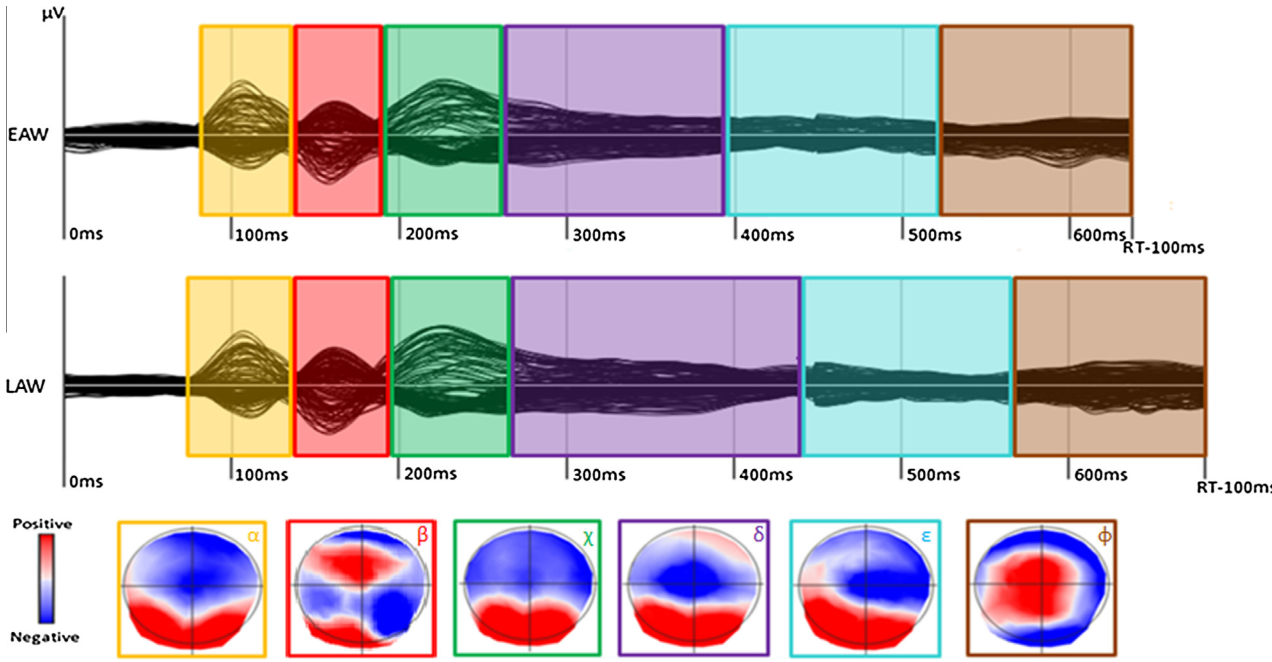

Fig. 5. Grand-average ERPs (128 electrodes) from each AoA condition from onset to 100 ms before RT and temporal distribution of the topographic maps revealed by the spatio-temporal segmentation analysis for each data set. Bottom: map templates for the six stable topographies observed from 70 ms after picture presentation to 100 ms before articulation (positive values in red and negative values in blue with display of maximal and minimal scalp field potentials).

5.3. Topographic pattern analyses

The spatiotemporal segmentation applied to the three grand-average data sets (i.e., all-word, EARLY and LATE conditions) from 70 ms after picture presentation to 100 ms before articulation revealed 6 different electrophysiological template maps which accounted for 94.26% of the variance. This map pattern was virtually the same in both AoA conditions. In the same way as for spoken picture naming, the only difference seemed to be the longer map "δ" in the late-acquired word condition (Fig. 5). The next two maps ("ε" and "φ") seemed to have a same duration, with the initial onset being shifted.

These observations were validated by the results of the fitting procedure. The following fitting periods were applied to verify map characteristics (i.e., duration, FTF and GEV) in the individual data: from 0 to 260 ms and from 260 ms to 695 ms. The maps labeled "α", "β" and "χ" did not differ between conditions (all $\chi^2 < 1$). The mean duration of stable electrophysiological activity "δ" was 114 ms for the EARLY and 154 ms for the LATE subgroups. This difference (40 ms) was significant, $\chi^2 = 11.84$, $p = .0017$. The first onset was virtually the same ($\chi^2 < 1$). A marginal difference on GEV for this stable map "δ" (EARLY: 62.24%, LATE: 52.25%; $\chi^2 = 3.2$, $p = .0736$) was observed. The longer duration of the map "δ" was confirmed by the difference on FTF for maps "ε" (EARLY: 492 ms, LATE: 533 ms; $\chi^2 = 5.56$, $p = .0182$) and "φ" (EARLY: 523 ms, LATE: 566 ms; $\chi^2 = 4.26$, $p = .0389$). No differences appeared on GEV and on durations for these two stable electrophysiological maps (all $\chi^2 < 1$).

The results were the same as those found in spoken picture naming. ERPs for Early-Acquired Words started to diverge significantly from those of Late-Acquired Words at around 350 ms after stimulus presentation. In the spatiotemporal analysis, a longer period of stable topography "δ" (from 260 to 400–450 ms) characterized the data for the late-acquired words data compared to early-acquired words. Taken together, the findings of the spoken and handwritten picture naming studies suggest that the lexeme retrieval process (L-level, Fig. 1) is the single locus of age-of-acquisition effects.

6. General discussion

As reviewed in Section 1, there is now robust evidence that AoA is one of the most important factors affecting word production of both healthy and brain-damaged speakers (Johnston & Barry, 2006). However, how and when these effects arise in the brain remain important issues (Juhasz & Yap, 2013). The findings of our two object naming experiments were clear-cut. AoA had a reliable impact on both spoken and handwritten picture naming latencies (and error rates) and it affected ERPs in a unique and late time-window in both spoken and handwritten production. In both experiments, waveform amplitudes and GFP differences between early- and late-acquired words appeared starting around 360–380 ms in the stimulus-aligned ERPs, and from 330–340 ms to 240–210 ms before articulation or before the onset of handwriting in the response-aligned ERPs. In addition the spatiotemporal analysis disclosed the same scalp topographies in the two AoA conditions in both tasks, but with different time distribution after 260 ms: a longer period of stable topography characterized late-acquired words in both tasks (respectively map "D" in Fig. 3, and map "δ" in Fig. 5). Crucially, the fitting procedure indicated that the duration of the electrophysiological map observed between 270 and 400–450 ms after picture onset was about 40 ms shorter for early-acquired than for late-acquired words in both experiments.

It seems not straightforward to associate this unique and late electrophysiological effect of AoA with specific cognitive processes. Nevertheless, a meta-analysis on the time-course of word planning in picture naming (Indefrey, 2011; Indefrey & Levelt, 2004) as well as several recent ERP studies using overt picture naming (see Strijkers, Costa, & Theirry, 2010) tasks provide some evidence on the time-windows likely associated with specific word encoding processes at least for the spoken modality. In Indefrey's (2011) estimates, lexical selection is engaged around 190 ms and word form encoding after 270 ms. Results of several recent ERP investigations using overt picture naming paradigms converge with the view that lexical selection is engaged at about 200 ms after picture presentation (Aristei, Melinger, & Abdel-Rahman, 2011; Costa, Strijkers, Martin, & Thierry, 2009; Maess, Friederici, Damian, Meyer, & Levelt, 2002), whereas phonological processes are engaged after 260–300 ms (Vihla, Laine, & Salmelin, 2006). Thus, the time-period corresponding to the ERP modulation by AoA has been associated, in previous studies on spoken picture naming, with phonological (from 275 ms to 455 ms) and phonetic/motor encoding (after 450 ms).

Unlike in the case of spoken picture naming, the literature provides no direct insight into the dynamics of word writing in picture naming. However, the systematic comparison of handwritten and spoken picture naming reported by Perret and Laganaro (2012) indicated similar electrophysiological correlates from 0 to 260 ms. This period of similar ERPs between speaking and writing likely corresponded to the common processes preceding word-form (phonological versus orthographic) encoding. Here, the differences between early- and late-acquired words in both handwritten and spoken naming tasks fell after this time-period of common electrophysiological patters to the two production modalities, suggesting an orthographic and phonological word form locus for AoA effects.

Taken together, these findings suggested that, when many correlated variables of Age of Acquisition are controlled in the stimuli, AoA modulates ERPs in a unique and late time-window. Indeed, if AoA effects in object naming were localized at the object recognition level or/and at the semantic level, we should have observed differences during the first 260 ms in the time-windows common to the processes underpinning both spoken and written picture-naming. The question then is why there are some reports in the literature pointing to an AoA effect in recognition tasks, i.e., in tasks that do not require naming, but require processing stages that are needed for naming? It would be somewhat premature to definitively rule out a pre-lexical locus of AoA effects in object naming, it should be highlighted that some studies reporting AoA effects in object recognition level (e.g., Vitkovitch & Tyrell, 1995) did not control for important factors that are assumed to play a role at this level (e.g., Image Agreement or Image Variability). Importantly, using the same set of items that varied on AoA but were controlled for a high number of relevant dimensions pertaining to the pre-lexical levels involved in object naming, Chalard et al. (2003) found reliable effects of AoA only in object naming The current findings thus fit better with the hypothesis that in object naming AoA affects a specific encoding period which probably corresponds to the word-form encoding level. It is worthy to note that similar conclusions have been reached with de Zubicaray et al. (2011) study. They observed increased activity for late acquired words in pMTG and mid-MTG and pSTG, suggesting that AoA effects take place at the level of word form retrieval in object naming.

One remaining issue, which we could not test in the current study, is whether the same representations underlie these effects in both spoken and written naming. Currently, while not completely ruling out a phonological influence in orthographic encoding (Bonin, Peereman, et al., 2001), there is also good evidence in support of the hypothesis that in written word naming, orthographic encoding can proceed directly on the basis of semantic codes and is therefore not obligatorily phonologically mediated (Roux & Bonin, 2012). Thus, while AoA effects are localized at the word-form level in both production modes, they could be orthographic in written naming and phonological in nature in spoken naming. Our study was not intended to address this specific issue which therefore calls for further investigation.

6.1. Methodological issues

It is worth mentioning the novelty of our approach to the study of the question of the locus of AoA effects. First of all, we used *frequency trajectory (FT)* to index AoA effects instead of the traditional rated or objective AoA measures. As claimed in the Introduction, although we cannot ascertain that FT is the best measure, it represents an interesting alternative to the classical rated AoA measures. One advantage of FT measures is that, contrary to rated AoA measures, they are less correlated to other psycholinguistic variables which also play a major role in object naming (e.g., word frequency). A second methodological issue lies in the advantage EEG/ERPs over reaction time measures. Likewise, the spatiotemporal segmentation approach allowed us a direct insight into the unfolding cognitive processes by tracking the periods of stable electrophysiological activity influenced by AoA manipulation. Third, we used the *same* material to investigate AoA effects in the two output modalities which provided a double test of the time-window affected by AoA. One final methodological consideration concerns the multiple level approach. As explained in Section 1, advocates of the single locus hypothesis of AoA effects in object naming have generally relied on a multiple level approach and made use of a logical strategy of elimination. This mode of reasoning has often been employed in psycholinguistics to determine the locus of several other important effects (e.g., word frequency effects, Jescheniak & Levelt, 1994; semantic interference effects, Schriefers, Meyer, & Levelt, 1990). Nevertheless, the issue of identifying tasks which genuinely index specific components of the cognitive skill under investigation is both complex and important. It is not our intention to undermine the multiple task approach and the elimination logic because this is certainly a useful way of addressing the locus of effects by means of RT measures. Nevertheless, EEG/ERP approaches represent an interesting alternative when addressing this kind of questions in particular because they permit the on-line exploration of the issue of the processing level(s) affected by a specific factor using only the main task.

7. Conclusion

Psycholinguistic research has endeavored to localize the effects of AoA in lexical processing tasks by means of different behavioral approaches. The current systematic ERP comparison between early-acquired (i.e., high-to-low frequency) words and late-acquired (i.e., low-to-high frequency) words suggests that AoA effects in object naming originated at a single locus, namely the word-form level.

Acknowledgments

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