



Article scientifique

Article

2015

Published version

Open Access

This is the published version of the publication, made available in accordance with the publisher's policy.

---

Functional and time-course changes in single word production from  
childhood to adulthood

---

Laganaro, Marina; Tzieropoulos, Hélène; Frauenfelder, Ulrich Hans; Zesiger, Pascal Eric

**How to cite**

LAGANARO, Marina et al. Functional and time-course changes in single word production from childhood to adulthood. In: NeuroImage, 2015, vol. 111, p. 204–214. doi: 10.1016/j.neuroimage.2015.02.027

This publication URL: <https://archive-ouverte.unige.ch/unige:80455>

Publication DOI: [10.1016/j.neuroimage.2015.02.027](https://doi.org/10.1016/j.neuroimage.2015.02.027)

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/272750635>

# Functional and time-course changes in single word production from childhood to adulthood

ARTICLE *in* NEUROIMAGE · FEBRUARY 2015

Impact Factor: 6.36 · DOI: 10.1016/j.neuroimage.2015.02.027 · Source: PubMed

---

READS

70

4 AUTHORS, INCLUDING:



[Marina Laganaro](#)

University of Geneva

62 PUBLICATIONS 708 CITATIONS

[SEE PROFILE](#)

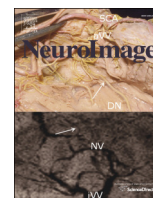


[Pascal Zesiger](#)

University of Geneva

58 PUBLICATIONS 539 CITATIONS

[SEE PROFILE](#)



## Functional and time-course changes in single word production from childhood to adulthood



Marina Laganaro\*, H el ene Tzieropoulos, Ulrich H. Frauenfelder, Pascal Zesiger

Faculty of Psychology, University of Geneva, Switzerland

### ARTICLE INFO

#### Article history:

Accepted 11 February 2015

Available online 19 February 2015

#### Keywords:

Development

Language

Picture naming

ERP

### ABSTRACT

Picture naming tasks are widely used both in children and adults to investigate language production for research and for assessment purposes. The main theoretical models of single word production based on the investigation of picture naming in adults provide a detailed account of the principal mental operations involved in the transformation of an abstract concept into articulated speech and their temporal dynamics. These models and in particular their time-course do not apply directly to children who display much longer production latencies than adults. Here we investigate the functional processes and the temporal dynamics of word encoding in school-age children and adults. ERPs were analysed from picture onset to the onset of articulation in 32 children and 32 adults performing the same overt picture naming task. Waveform analyses were not informative since differences appeared throughout the entire period, due to an early shift of waveform morphology and to larger amplitudes in children. However, when the sequences of periods of topographic stability were considered, different patterns of electric fields at scalp only appeared in approximately the first third of the analysed period, corresponding to the P1–N1 complex. From about 200 ms in adults and from 300 ms in children to articulation onset similar patterns of global topography were observed across groups but with a different time distribution. These results indicate qualitative changes in an early time-window, likely corresponding to pre-linguistic processes, and only quantitative changes in later time-windows, suggesting similar mental operations underlying lexical processes between age-school children and adults, with temporal dynamic changes during development.

  2015 Elsevier Inc. All rights reserved.

### Introduction

Both adults and children can produce a familiar word corresponding to the concept they wish to communicate fluently and effortlessly. Such a transformation of a pre-linguistic concept into articulated speech sounds requires a series of cognitive and neurophysiological processes which have been investigated widely with picture naming tasks in psycholinguistic (Levitt et al., 1999; Dell, 1986) and neuroimaging studies (Indefrey and Levelt, 2004; Price et al., 2005) on (young) adult speakers. Although the sequential or parallel nature of the processes underlying word production is still under debate, there is a general agreement on the necessity and existence of a minimal set of mental operations involved in such tasks. When speakers produce a word corresponding to a depicted object, they first analyse the picture visually and recognize it before beginning linguistic planning. Word encoding then entails lexical–semantic processes, that is, the lexical selection or the retrieval of the word – the lemma – in the mental lexicon and lexical–phonological processes or the encoding of the phonological form – lexeme –, which constitutes the input to the preparation of motor plans (phonetic

encoding) for articulation. The time-course of these processes has been estimated in a meta-analysis of behavioural and event-related potential (ERP) studies by Indefrey and Levelt (2004), and then updated on the basis of more recent evidence (Indefrey, 2011). In picture naming tasks, visual and conceptual processes are estimated to take place during the first 190–200 ms after picture presentation, followed by lexical–semantic processes (lemma retrieval) until about 275 ms. Word form (lexeme) retrieval and phonological encoding processes are thought to be engaged until 400–500 ms followed by phonetic encoding and motor execution.

These estimates of the timing of the different cognitive processes have been made for adult word production. They provide a general framework for studying the dynamics of word production in adults, although mean production latencies vary considerably across experiments, raising the question of rescaling the duration of processing stages. Indefrey (2011) suggested that linear rescaling in the case of faster or longer response latencies is probably not the correct approach as, depending on the experimental conditions, specific processes may take less or more time. Laganaro et al. (2012) suggested that variation in object naming speed in a group of young adults is attributable to a single underlying electrophysiological process starting around 200 ms that lasts longer in slower participants. The question of rescaling the durations of processing stages is all the more relevant when populations

\* Corresponding author at: FPSE, University of Geneva, 40, Bd Pont d'Arve, CH-1211 Geneva 4, Switzerland.

E-mail address: [marina.laganaro@unige.ch](mailto:marina.laganaro@unige.ch) (M. Laganaro).

with longer response times are considered, such as children. Here, the core question we are interested in is how these encoding processes and their timing change during development. School-age children have a vocabulary of approximately 10,000 words (Clark, 1993), and they are able to name the picture of many objects (Cycowicz et al., 1997; D'amico et al., 2001). However, even on items they can correctly name, children show longer production latencies than adults (e.g., 7 year-olds are 330 ms slower than adults in D'amico et al., 2001), and picture naming latencies speed up considerably during school-age (e.g., from ~1860 ms in 7 year-olds to ~1500 ms in 12 year-olds in Bragard et al., 2010).

Despite lower accuracy and longer production latencies (RTs) in children relative to adults, most behavioural studies point to the fact that globally the same psycholinguistic variables predict accuracy (Cycowicz et al., 1997) and production speed (D'amico et al., 2001; Bragard et al., 2010) in school-age children and adults. Other studies focusing on specific task manipulations known to influence word planning in adults (e.g., semantic interference and phonological facilitation) also observed the same effects on RTs in school-age children (Brooks and McWhinney, 2000; Jerger et al., 2002). Adult models also seem to account for picture naming errors in school-age children. Budd et al. (2011) fitted picture naming errors produced by children with a model previously used to simulate errors produced by aphasic adults and reported a good fit after the age of eight. Taken together, these behavioural studies suggest that, at least after the age of seven years, the same encoding processes underlie single word production in children and adults despite fairly different production latencies (see also Brooks and McWhinney, 2000, for differences on a rhyme phonological priming task in younger children).

Neuroimaging studies using functional magnetic resonance to compare language production in children and adults have shown largely overlapping activated brain regions between these two groups but also areas with higher haemodynamic response in children than in adults as well as the opposite (Brown et al., 2005; Krishnan et al., 2014). These differences in the activation patterns observed in children and adults may reflect qualitative changes in underlying processes (as for instance differences in task monitoring as suggested by Krishnan et al., 2014) and/or quantitative changes across age groups related to the cognitive demand affecting the duration and strength of the activation of specific brain regions. Qualitative and timing differences between children and adults have been tracked with magnetoencephalographic (MEG) or electroencephalographic (EEG) evoked potential studies. Most ERP studies on language development have focused on speech perception and comprehension in infants and on written word processing in school-age children. Perception studies have shown that already very early in their development children display the same electrophysiological components as adults; changes are mainly in timing, with later peaks in children than in adults (Friederici, 2006). The very few ERP studies investigating language production with picture naming tasks in school-age children have led essentially to the same conclusions. For instance, Budd et al. (2013) reported ERP latency shifts in 12 year-old children relative to adults in a verb production (conjugation) task. Greenham and Stelmack (2001) used a picture naming task in the context of a reading study with 9 to 13 year-old children and adults and reported similar waveforms in children and adults with enhanced amplitudes in children.

In sum, most behavioural and neuroimaging studies suggest that the cognitive processes and ERP components underlying language processing are similar for children and adults. Indeed, it seems that it is the time-course of the underlying processes rather than the processes themselves that are subject to developmental changes. The former changes are suggested in particular by longer latencies of waveform components in children's ERPs. Such shifts have been reported on both early ERP components associated with auditory or visual perception (e.g., at P50 and P100 peaks for auditory and visual stimuli respectively, Holcomb et al., 1992) and on later components associated with

language processing (prolonged N400 in a semantic task in Friedrich and Friederici, 2005; shifted component at 300–550 ms in the verb conjugation task in Budd et al., 2013). Given that these results focused on specific ERP components in various experimental paradigms and ages, it is not possible to conclude whether only specific word planning processes speed up from childhood to adulthood or if the increases in processing speed are distributed across all processing stages.

In the present study we take advantage of local waveform analyses combined with global topographic analyses to investigate the functional and temporal dynamics of changes in word production from childhood to adulthood. We will analyse periods of stable electric field (topographies) in the ERP signal, which can be associated with specific periods of information processing (Changeux and Michel, 2004; Koukou and Lehmann, 1987), from picture onset to the individual onset of articulation in children and adults. The combination of stimulus-aligned and response-aligned ERPs enables to cover the entire planning period for each participant and to account for differences in production latencies across individuals and groups (Laganaro and Perret, 2011, see Laganaro, 2014 for the rationale and the description of the method). The analysis of periods of stable electric fields (topographic analysis) allows us to disentangle functional changes (different topographies) between age-groups from changes in the temporal dynamics (same periods of stable electric field which are differently distributed). If only processing speed increases from children to adults, the same functional microstates should be observed in the two groups but with different durations. Such changes in the duration of processing stages may be distributed throughout the processes underlying word production in picture naming (simple rescaling) or be limited to specific time-windows, corresponding to specific encoding processes.

## Method

### Participants

Thirty-three school-age children and 32 adults (undergraduate students) participated in the study. The data of one child was removed from the data set due to excessive noise in the EEG signal. The children were recruited from two age-groups, namely "7–8 year-old" children (16 participants, age range: 7–8 year-old, average: 7.2, 8 females) and "10–12 year-old" children (16 participants, age range: 10–12 year-old, average: 11.6, 5 females). Adults were recruited among undergraduate students (aged 20–30) and were divided a posteriori into two sub-groups: 16 adults aged 20 to 22 (average: 20.8, 13 females) and 16 adults aged 24–29 (average: 26, 12 females). They were all right-handed but one ambidextrous in each children group and native French speakers without diagnosed reading impairment or neurological disease. Adults were recruited through announcements posted at the university whereas children were recruited through Geneva public schools. This study was approved by the local ethics committee; adults gave their written informed consent and parents' approvals were collected for their children. Children were offered a small present and a voucher whereas adults were paid for their participation.

### Stimuli

120 black and white drawings and their corresponding modal names were selected from two French databases (Alario and Ferrand, 1999; Bonin et al., 2003). The stimuli corresponded to words with an age of acquisition range of 1.19–3.55 on a five-point scale (1: learned between 0 and 3 years; 4: learned between 9 and 12 years) and high name agreement (mean = 92.5%) to ensure that participants give the same name for a same picture. A preliminary test carried out with two 7-year-old children without previous familiarisation allowed to make sure that the majority of the words were named correctly by the

youngest children in our group. The size of the pictures was set at  $9.5 \times 9.5$  cm.

### Procedure

Half of the children from both age groups underwent the experiment in their school, and the other half and adults in a laboratory at the University. Participants were installed either in a dimly lit sound-attenuated room or in a schoolroom and seated at approximately 60 cm of a computer screen.

A familiarisation with all pictures and their corresponding modal names was run before the experiment. Adults were familiarised on a paper sheet containing all pictures and their printed modal name. They were asked to go once through all items. As written presentations of modal names could not be used with our children, modal names were presented auditorily. To ensure that the child paid attention to the modal name, a simple word–picture matching task was used: each picture of the experiment was presented paired with another image from the experimental dataset and the child had to click on the picture corresponding to the name delivered through loudspeakers. If the choice was not correct, the name was repeated until the right image was selected.

The presentation of the stimuli was controlled by the E-Prime software (E-Studio). An experimental trial had the following structure: first, a fixation cross was presented for 500 ms on the screen. Then, the picture appeared for 3000 ms. Participants had to overtly produce the word corresponding to the picture as fast and accurately as possible. For adults, inter-stimulus interval was set at 2000 ms. For children, the fixation cross–picture sequence was manually triggered by an experimenter sitting behind the child and in contact with another experimenter monitoring the EEG online signal. This procedure allowed longer pauses when the signal became noisy due to the children's movements.

All items were presented in a pseudo-random order, which was different for each participant, with a break after 60 stimuli. The pseudo-randomisation was preferred to a complete randomisation to avoid succession of stimuli from the same semantic category or with high phonological overlap. Four warm-up filler trials corresponding to easy-to-name stimuli were set at the beginning of the experiment and after the break. Pictures were presented in a constant size ( $9.5 \times 9.5$  cm) on a grey screen.

Word productions were digitized and production latencies (RTs in ms, i.e. the time separating the onset of the picture and the onset of the speech wave) were systematically checked with a speech analysis software (Check-Vocal, [Protopapas, 2007](#)).

### EEG acquisition and pre-processing

EEG was recorded continuously using the Active-Two Biosemi EEG system (Biosemi V.O.F. Amsterdam, Netherlands) with a 128 electrode cap for the adults and a 64 electrode cap for the children. Sampling frequency was set at 512 Hz, the signal band-pass filtered between 0.16 and 100 Hz and stored on a computer for off-line analysis. The custom online reference of the system is the common mode sense (CMS active electrode) – driven right leg (CMS–DRL) which drives the average potentials as close as possible to the amplifier zero (for details on this setup see: <http://www.biosemi.com>).

Adults' data were then down-sampled to 64 electrodes to be compared with children data. Only trials with correct productions and valid RTs were retained. Trials were visually inspected to reject artefact-contaminated epochs and extract stimulus-aligned and response-aligned epochs. Stimulus-aligned epochs started at picture onset and covered 684 ms (350 time frames, tf) for children, 508 ms (260 tf) for adults. Response-aligned epochs started 100 ms before articulation and covered the preceding 684 ms (children) or 508 ms (adults). Data was high-pass filtered at 0.2 Hz and low-pass filtered at 30 Hz and averaged for each participant.

### Behavioural data analyses

Outliers (reaction times shorter than 350 ms or longer than 3000 ms) and response errors were removed from the dataset. RT data were fitted with a linear regression mixed model ([Baayen, 2008](#)) and accuracy data were fitted with a generalized linear mixed-effects model for binomially distributed outcomes ([Jaeger, 2008](#)) with the R-software (R-project, R-development core team 2005), including participants and items as random effect variables and groups as fixed variable.

### EEG data analyses

All analyses were run on average-referenced data. The ERPs were first subjected to a sampling point-wise ERP waveform analysis to determine the time periods presenting local differences in ERP amplitudes between age-groups. Then, a spatio-temporal segmentation was performed on the group-averaged ERPs of each sub-group to determine topographic differences across groups, i.e. differences in periods of stable global electric fields, likely corresponding to particular periods in mental information processing ([Changeux and Michel, 2004](#); [Koukou and Lehmann, 1987](#); [Lehmann and Skrandies, 1984](#); [Lehmann et al., 1998](#)), and statistically validated in the responses of single subjects as described below.

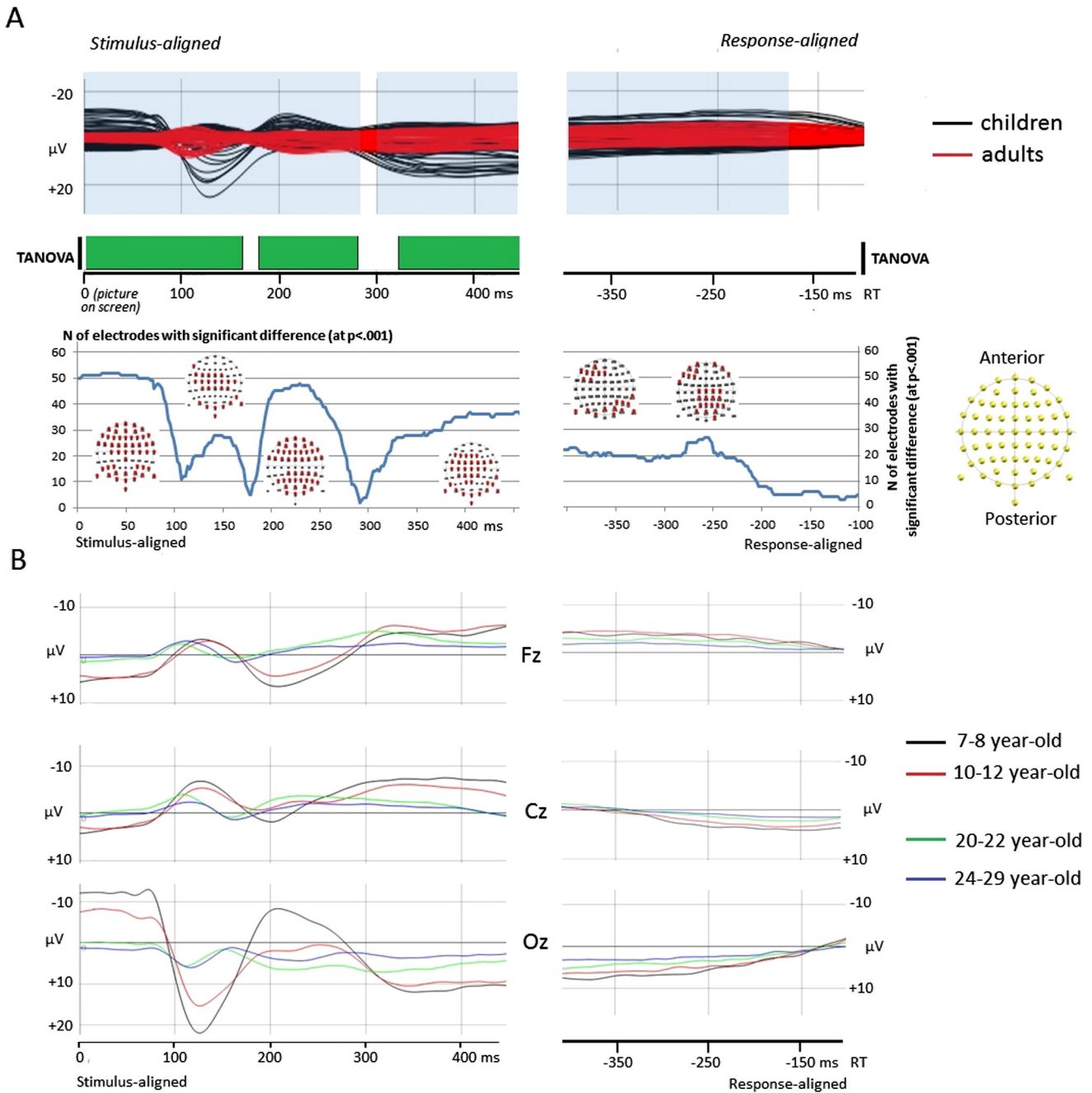
To assess group differences on amplitude, comparisons on each electrode and for each time point across were run separately on stimulus-aligned and response-aligned ERPs using unpaired t-tests as implemented in the Cartool software ([Brunet et al., 2011](#)). To correct for multiple tests, a time-constraint of 20 ms was applied and the level of significance at 0.01; finally, results were taken into account only when significant over a cluster of 5 electrodes. Waveform amplitude analysis was not informative about the children vs. adult comparison due to a large latency shift starting in the early P100 potential and due to the larger amplitudes in children throughout the analysed periods (see [Fig. 1](#)). As a result, waveform amplitude comparisons were made separately for the two children groups and for the two adult groups; only the global topographic analysis was applied to compare children and adults (see below). To validate the visually observed latency shift, the latency of the P1 component was also extracted for each age group based on the latency of maximal GFP value in the 80–160 ms time-window.

### Global topographic ERP pattern analysis (spatio-temporal segmentation)

First, a topographic analysis (called “TANOVA”) was run on each sampling point on stimulus- and response-aligned ERPs to identify periods of significant topographic modulation between children and adults and between the two children and the two adult sub-groups. This procedure involves a non-parametric randomization test to the global dissimilarity measures – a measure of the topographic differences between two electric fields independent of their strength – between conditions ([Murray et al., 2008](#)). The permutation of the data is accomplished by re-assigning randomly the topographic maps of single subjects to the different groups. The global dissimilarity of these random group-averaged ERPs is compared time-point by time-point with the values of topographic dissimilarity of the actual groups. The same time-period criterion of 20 consecutive ms and an alpha criterion of 0.01 were applied.

Before running the topographic analysis we performed a topographic consistency tests (TCT, [Koenig and Melie-García, 2010](#)) on stimulus-aligned and response-aligned ERPs to ensure that different topographies were not driven by random noise in the within group data. This analysis allowed us to determine that topographic patterns were indeed consistent across subjects from each subgroup throughout the analysed periods, except for a short period of topographic inconsistency which appeared in one adult group between 150 and 175 ms in the stimulus-aligned ERPs (see Supplementary material S1).





**Fig. 1.** A. Children and adult group-averaged stimulus-aligned and response-aligned ERPs (64 electrodes) with periods of significant differences in amplitudes highlighted in blue. Periods of significant differences in the TANOVA analysis (at  $p < .01$ ) are displayed in green. The blue line represents the number of electrodes (out of 64) with significant differences in amplitudes at each time-point with display of the electrodes yielding significant differences at 50 ms, 150 ms, 230 ms and 400 ms in the stimulus-aligned ERPs and 350 and 250 ms before the onset of articulation in the response-locked ERPs. B. Exemplar group-averaged ERP waveforms (Fz, Cz, Oz) for the 4 groups plotted in microvolts as a function of time.

For the common topographic analysis of stimulus- and response-aligned ERPs, the “overlap” between stimulus-aligned and response-aligned ERPs was removed based on average reaction times of each group, following the procedure described in Laganaro and Perret (2011) and Laganaro (2014). The same procedure was applied to each individual ERP and used in the fitting procedure (see below). As a result, the combination of stimulus- and response-aligned ERPs covered the exact time interval from picture onset to 100 ms before articulation onset for each group and for each participant. Common microstate segmentation was then applied to the four group-averaged ERP data sets from picture onset to 100 ms before articulation. This analysis entails a spatio-temporal segmentation of the ERPs over periods of

electrophysiological stability (i.e. topographic maps or ERP microstates). The spatio-temporal segmentation procedure compresses the variability of ERPs in a series of template maps which summarize the data and serve to determine which topographic template best explains ERPs in each group. In extension, it provides insights into how groups differ in terms of likely underlying neurophysiologic mechanisms (Murray et al., 2008; Michel and Murray, 2012), in addition to the temporal information about ERP differences. This method is independent of the reference electrode (Michel et al., 2009; Michel and Murray, 2012) and insensitive to pure amplitude modulations across conditions (since topographies of normalized maps are compared). Here a topographic atomize and agglomerate hierarchical clustering (T-AAHC)

method was used, merging clusters correlating above 95% and rejecting segments shorter than 20 ms. The Krzanovski–Lai criterion combined with a cross-validation was used to select the model which best represents the dataset. This procedure is described in detail in Pascual-Marqui et al. (1995, see also Brunet et al., 2011; Murray et al., 2008).

The sequence of template maps characterising the four group grand-averages was then compared to the individual data in order to determine if differences observed on the grand means were actually representative of differences across groups at the subject's level. This procedure, referred to as 'fitting', allows one to establish how well a topographic template map explains single participant responses. Each map template observed in a specific time-window in the group-averaged data was compared with the moment-by-moment scalp topography of each individual ERP from each group. In other words, when two (or more) different microstates characterised the different group-averaged ERPs in a specific time-period, these template maps were fitted back to all the individuals from all groups. The "fitting" time-periods were determined on the basis of the distribution of the topographic maps issued from the microstate segmentation on the group averaged data (see Results section). Each data sampling point was labelled according to the template map with which it best correlated spatially, yielding a measure of map presence, of duration in milliseconds and of global explained variance (GEV). These measures are then used to test topographic differences across groups using non-parametric statistical tests.

#### Source estimation

Estimation of the location of intracranial generators was carried out using a linear distributed inverse solution (LAURA, Grave de Peralta et al., 2001) only for specific time windows when the results of the topographic pattern analysis identified different and consistent topographies between children and adults. This source imaging method is based on the physical law that the strength of a source regresses regularly with distance. Using a regular grid of solution points, the method incorporates this law in terms of a local autoregressive average with coefficients depending on the distance between solution points (Michel et al., 2001). The solution space included 5000 solution points, equally distributed within the grey matter of the averaged brain of a standard MRI for the adult group and to the 7–11 year-old children MNI (Fonov et al., 2009; 2011) for the two children groups. A spherical head model with an anatomical constraint was used, applying the SMAC transformation method (Spinelli et al., 2000) with the solution space restricted to grey matter subspace. To correct for bone properties affecting conductivity in children, skull relative conductivity was reduced to .01 (.05 in adults).

## Results

#### Behavioural results

Mean production accuracy and latencies for each experimental group are presented in Table 1.

Production accuracy was lower in children relative to the adults ( $z(5888) = -7.25, p < .0001$ ), and it was lower in 7–8 year-old relative to the 10–12 year-old children ( $z(3904) = -5.3, p < .0001$ ). There was no significant difference in accuracy between the two adult sub-groups

**Table 1**  
Mean production accuracy and RTs for each group (SD in brackets).

	Accuracy	Response latencies in ms (RT)
7–8 year-old	85% (8%)	1146 (99)
10–12 year-old	95% (3%)	1000 (104)
Adults (20–22)	97% (1.7%)	834 (96)
Adults (24–29)	96% (2%)	816 (109)

( $z(4216) = -1.05, p = .3$ ). Production latencies also differed across children and adults ( $F(1, 7557) = 103.46, p < .0001$ ). Contrasts are significant between the two children sub-groups ( $t(3494) = 4.32, p < .001$ ), but not between the two adult sub-groups ( $t < 1$ ).

#### ERP results

##### Waveforms

The comparison between children and adults revealed differences in amplitudes on most electrodes throughout the analysed time windows, except for the last 80 ms and a short time-window around 280 ms (Fig. 1A). This is due to larger amplitudes and to latency shifts in children relative to adults (see displayed waveforms in Fig. 1B). Due to this early occurring latency shift and extended amplitude differences, no further comparisons were run on waveforms between adults and children. The TANOVA analysis also revealed differences across groups throughout the stimulus-aligned ERPs, but not on the response-aligned ERPs (see Fig. 1A).

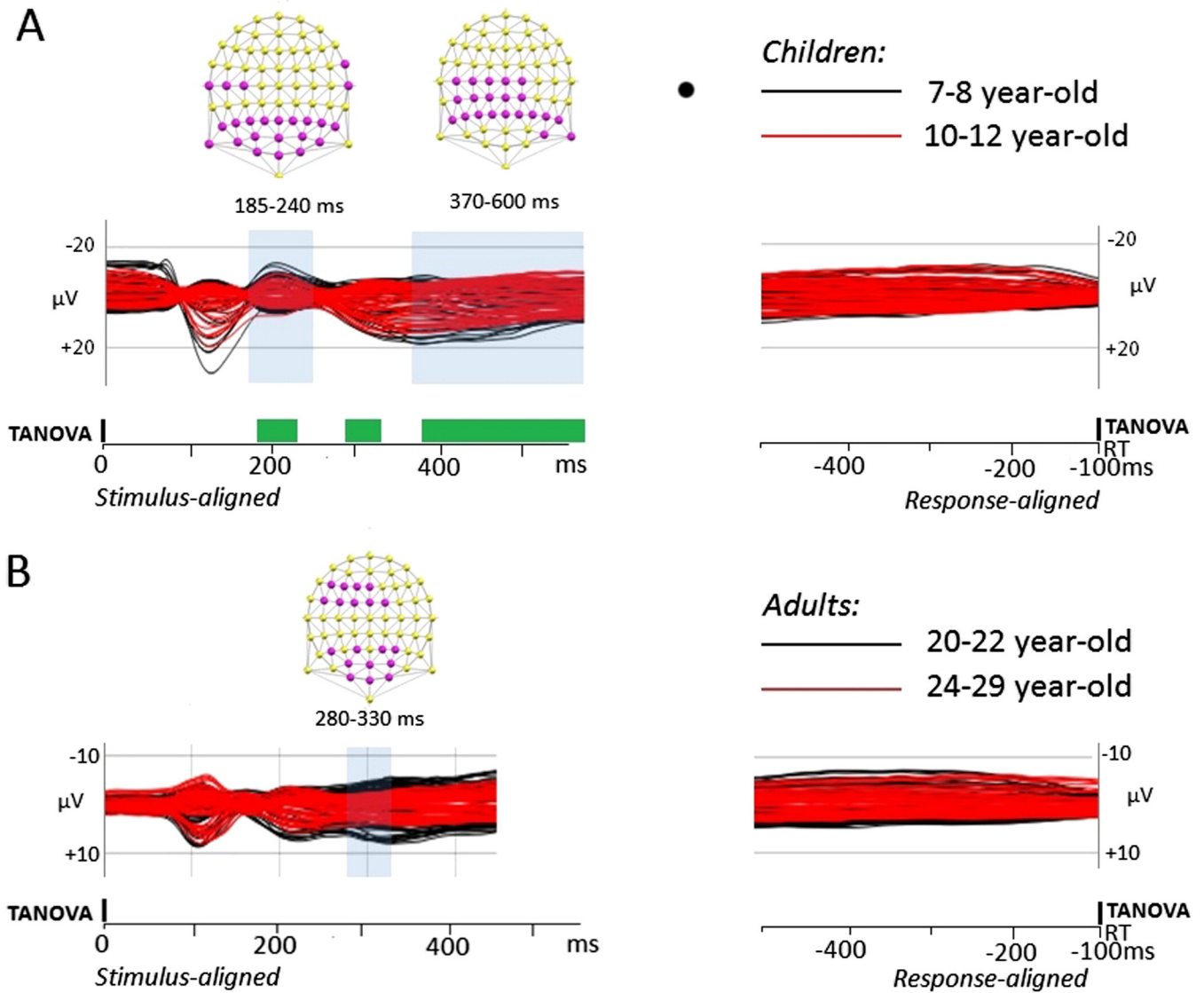
The comparison of 7–8 year-old versus 10–12 year-old children groups (Fig. 2A) yielded significant differences in two time windows on a large set of electrodes: between 185 and 240 ms postonset corresponding to the N1/N200 component mainly on posterior electrodes bilaterally with larger amplitudes in the younger than in the older group (see Fig. 2A and waveforms in Fig. 1B); in a later time-interval between 370 and 600 ms on central and parietal electrodes, mostly showing greater amplitudes for the 7–8 year-old children. The TANOVA also revealed different topographic distributions across age groups in approximately the same time-windows in the stimulus-aligned ERPs. No differences appeared in the response-aligned ERPs. The comparison between the two adult sub-groups (Fig. 2B) indicated different amplitudes between 280 and 330 ms on posterior and anterior channels in the stimulus-aligned ERPs without significant difference in the TANOVA analysis and no differences in the response-aligned ERPs (see Fig. 2B).

##### Global field pattern analysis

The microstate segmentation applied on the four grand means revealed a best model explaining 96.5% of variance with 12 different topographic maps from picture onset to 100 ms before articulation (Fig. 3). On the grand means, the same template maps appeared in both children's groups with different time-distribution. Different periods of topographic stability appeared for children and adults in early time windows (maps A, D, E, H in children, maps B, C, F, G in adults), whereas the same topographic maps characterised ERPs after 300 ms in children and after ~200 ms in adults (maps I, J, K and L), although shifted in time.

Based on the distribution of the periods of topographic stability on the group averaged ERPs (see Fig. 3), three fitting periods were applied to the individual combined stimulus- and response-aligned ERPs in order to statistically assess the differences observed on the grand-means: from 0 to 150 ms (maps A, B, C, D); from 150 to 500 ms (with maps E, F, G, H, I, J, K), and from 500 to the end of the individual ERPs (maps J, K, L).

In the first fitting period, whereas map A was present in 31 out of 32 children with high GEV (47% in the younger and 41% in the older group), much more variability was observed in adults: 18 subjects (9 from each sub-group) also displayed map A (GEV = 19% in each group), whereas map B was observed in about one third of the individual ERPs (respectively, 12, and 11 in each subgroup and 2 children). Hence, map A was significantly more present in children than in adults ( $\chi^2(1) = 14.7, p < .0001$ , on GEV: Mann–Whitney  $z = -4.0, p < .0001$ ) and map B characterised adults' ERPs better than those of children ( $\chi^2(1) = 7.8, p < .01$ ). Although more variability in adults than in children appeared in the microstates observed in the very first period following picture onset, there was no significant differences across the two adult groups on the presence of maps A or B in the 0–150 ms fitting period



**Fig. 2.** A. Group averaged ERPs for the 7–8 and 10–12 year-old children. Periods of significant differences in amplitudes are highlighted in blue on the group-averaged ERPs with display of the electrodes yielding significant differences in amplitudes in the 185–240 ms and 370–600 ms time-windows. Periods of significant topographic differences in the TANOVA analysis at  $p < .01$  are plotted in green over the time-line. B Group averaged ERPs for the two adult groups with significant differences in amplitudes highlighted in blue and display of the electrodes yielding significant differences in amplitudes in the 280–330 ms time-window. No topographic differences appeared across the two adult sub-groups in the TANOVA analysis.

(map A: GEV = 19% in both groups, map B: GEV = 18% and 14%,  $z = -1.25$ ,  $p = .22$ ).

The fitting in the first 150 ms also revealed that the two different P100 maps observed on the group averaged ERPs (maps C and D) were specific to adults and children respectively. These two map templates were fitted back in the individual ERPs to the 80–160 ms period, revealing the presence of map D in 30 children (16 younger and 14 older, GEV: 69% and 56% respectively), while 31 adults displayed map C in the P100 interval (with 52% of GEV in the 20–22 year-olds and 62% of GEV in the 24–29 year-old adults). Hence, two distinct P100 topographies characterised children and adults ERPs ( $\chi^2(1) = 27.9$ ,  $p < .0001$  on map presence). Source localisation on these two different P1 topographic maps observed in children and adults disclosed larger bilateral activation of the occipital lobe including the occipital pole and the lingual occipital region in children. In adults activation was limited to occipital lobe and to the cuneus with an additional source in the left middle and inferior left temporal lobe.

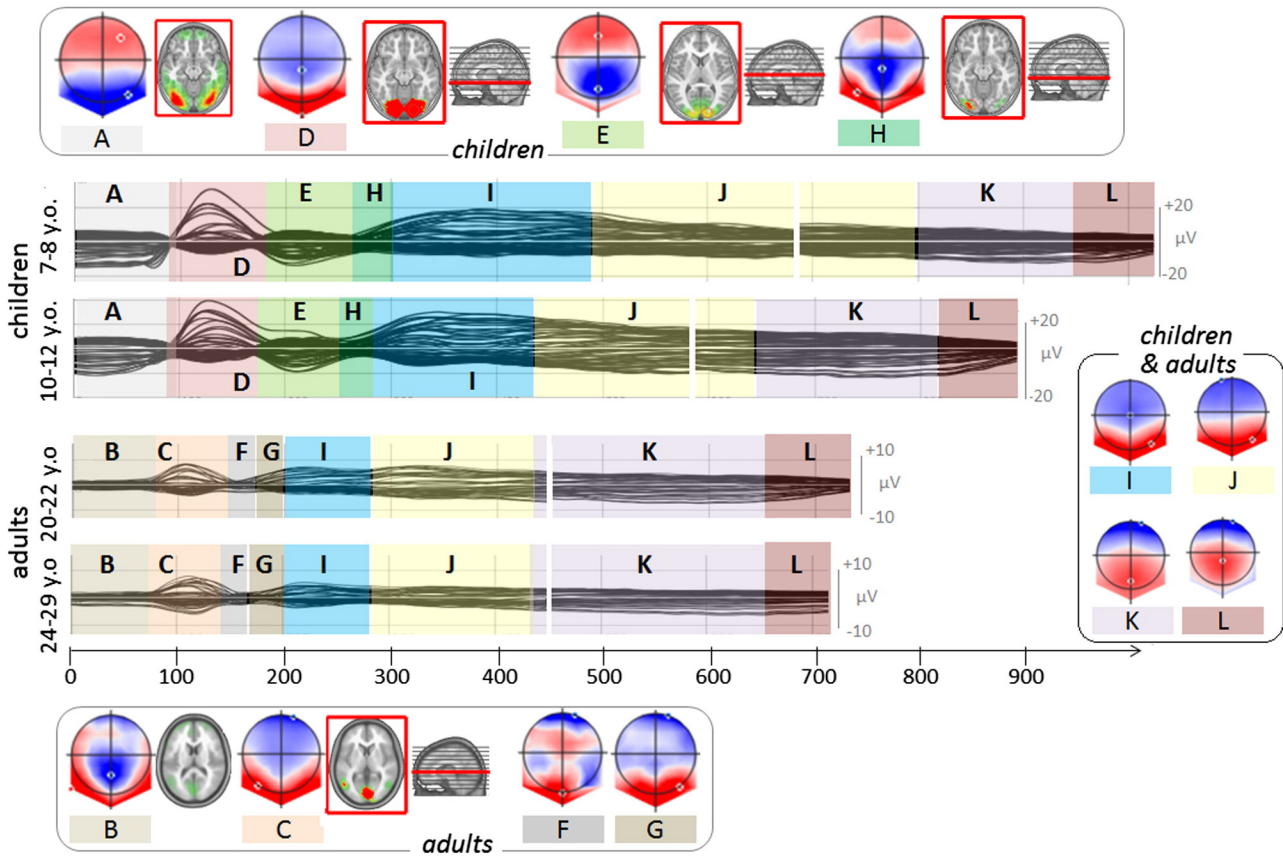
The analysis of the maximum GFP confirmed the difference in the P100 peak visible on the waveforms in Fig. 1, which was earlier in adults

(115 ms) than in children (128 ms, Mann-Whitney  $z = -3.9$ ,  $p < .0001$ ), with no differences between children or adults sub-groups (both  $z < 1$ ).

In the second fitting period (150–500 ms), the topographic map immediately following the P100 labelled “E” in Fig. 3, characterised children’s ERPs better than those of the adults: it was observed in 25 children (fifteen 7–8 year-old children and ten 10–12 year-old children) and in 9 adults (presence of map “E” in children versus adults:  $\chi^2(1) = 16.1$ ,  $p < .0001$ ; GEV:  $z = -3.3$ ,  $p < .01$ ). There was no difference on GEV between the two children sub-groups (28% in both groups), but this stable period of topographic stability lasted ~40 ms longer in the younger group than in the older children ( $z = -1.8$ ,  $p = .059$ ).

The two map templates F and G observed on the adult groups averaged ERPs were not systematically present in the individual ERPs: map F appeared only in 3 adults with very low GEV (2%) and map G in 11 individual ERPs (GEV = 11%); these two topographic maps were almost never observed in children ERPs. Note that this period corresponds to the period of topographic instability revealed by the TCT in adults (see Supplementary 1).





**Fig. 3.** Group-averaged ERPs for each children and adult sub-group from stimulus onset to 100 ms before articulation (after removing the overlap between stimulus-aligned and response-aligned ERPs according to each group average response latencies) and temporal distribution of the topographic maps in each data set revealed by the spatio-temporal segmentation analysis. Template maps for the 12 stable topographies are displayed with positive values in red and negative values in blue and with indication of the maxima and minima of scalp field potentials. LAURA source estimations are displayed for the topographies observed consistently in children but not in adults (maps A, D, E and H) and for those appearing consistently in adults but not in children (maps B and C).

The period of stable electric field labelled “H” in Fig. 3 also appeared more systematically in children than in adults ( $\chi^2(1) = 5.1, p = .02$ ): it was observed in 21 children (9 from the youngest (GEV = 39%) and 12 from the older group (GEV = 47%)) and only in 6 participants from each adult group. Source localisation for the two periods of stable electric fields which characterised children ERPs in the N1/N200 time-window (E and H) revealed activation of the occipital lobe bilaterally around the cuneus for map E and predominant left inferior occipital–temporal activation for map H.

From here on, the four different periods of topographic stability labelled I, J, K and L in Fig. 3 appeared in all group averaged ERPs, although with different temporal distributions. Map I appeared in virtually all children (31) and in most adults (28) but with earlier onsets in adults (~210 ms versus ~280 in children) and on average 60 ms longer duration in children than in adults (difference across groups on first onset:  $z = -2.7, p < .01$ ; on duration:  $z = -3.6, p < .001$ ). This period of stable electric field at scalp lasted longer in the 7–8 years old than in the older children (on duration:  $z = -2.1, p < .05$ ; GEV  $z = -1.4, p = .14$ ); no differences were observed across the two adult groups ( $z < 1$ ). The two consecutive fitting periods were considered to track presence of map J in all groups. This period of topographic stability was present in all children and in 28 adults: its onset was later (due to shifts in preceding maps) and its absolute duration was ~80 ms longer in children than in adults (onset:  $z = -2.5, p = .01$ ; duration:  $z = -2.6, p < .01$ ). Onset was also shifted across children sub-groups, confirming the longer lasting preceding period of stable topography ( $z = -3.5, p < .001$ ) and the absolute duration of map J was also longer in the youngest group ( $z = -2.6, p < .01$ ). No differences appeared on

onset or duration across adult sub-groups (both  $z < 1$ ). Map K appeared in the individual ERPs of 63 out of the 64 participants, with only marginal differences in duration across the main age-groups ( $z = -1.8, p = .065$ ). The very last period of topographic stability (map L) was observed in 28 children (15 younger and 13 older) and 23 adults (11 and 12), and lasted about 80 ms in all groups (all  $z < 1$ ).

Correlations were computed between production latencies and the durations of the periods of stable scalp topographies which were present in virtually all individual ERPs (maps I, J, K and L) across all participants and separately for children and adults. The duration of map “I” presented the strongest positive correlation with RTs ( $r = .580, z = 4.8, p < .0001$ ; in children:  $r = .512, z = 3.0, p < .003$ ; in adults:  $r = .305, p = .12$ ), followed by the duration of map “J” ( $r = .494, z = 4.1, p < .0001$ ; children:  $r = .387, z = 2.2, p = .03$ ; adults:  $r = .343, p = .07$ ), all other correlations being non-significant or marginal (max  $r = .185$  for map “L”).

To summarise, children and adults displayed different amplitudes during the entire analysed period and an early shift of waveform morphology. However, when the sequence of periods of stable electric fields was considered independently of time periods, functional differences were only observed in approximately the first third of the analysed period, corresponding to the P1–N1 complex. From about 200 ms in adults and about 300 ms in children to articulation, the same sequence of stable global electric field at scalp was observed but with different time distribution. The two children groups presented different amplitudes but similar sequences of periods of topographic stability although shifted in time for maps “I” and “J”. No significant differences appeared between the two adult sub-groups.

## Discussion

The present study aimed to investigate ERP differences in single word production in school-age children and adults. In particular, we aimed to determine whether the commonly observed slower naming times in children is accounted for by functional changes, indicating different underlying encoding processes, or by similar processes distributed differently in time and in the latter case to identify the time-course of such changes.

Reaction times were indeed ~180 ms faster in adults than in the 10–12 year-old group and ~150 ms faster in the older (10–12 year-old) relative to the younger (7–8 year-old) children but did not differ between 20–22 and 24–29 year old adults. Due to an early shift in the waveform morphology of the visual component (P100) and to overall larger amplitudes in children, later waveform comparisons were not informative, but a topographic analysis taking into account different processing times and map shifts was run. Interestingly, despite the very early ERP difference, a sequence of similar ERP activities appeared for children and adults on more than half of the word planning period. In fact, different periods of electrophysiological stability only appeared in the first third of the analysed data corresponding to the P1–N1 complex. From here on, similar patterns of global electrophysiological activity at scalp but different durations were observed across the age groups.

Thus, a first rough response to the question of qualitative versus quantitative changes in word encoding from childhood to adulthood is that both changes in functional microstates (topographies) and changes in the time-course of similar EEG global fields are involved, in addition to a general decrease of waveform amplitudes. These two types of patterns of change are observed for different time-periods of the word planning process: topographic differences appeared exclusively in the earliest time-window and changes in the temporal distribution of similar functional microstates were observed in later time-periods. For the two groups of children (7–8 vs. 10–12 years old) a decrease of amplitudes along with shortening of common periods of stable topographic patterns is observed, but no functional differences.

In the following we will discuss step by step the differences and similarities identified between groups from picture onset to articulation.

### *P1–N1 range: pre-linguistic processes*

The earliest topographic differences appeared on the averaged ERPs from the beginning of the analysed time-window, i.e., at the moment pictures appeared on screen. However, whereas the scalp topography corresponding to map “A” in Fig. 3 clearly characterised individual ERPs in children, it was only observed in half of the adults, with the presence of a different configuration of the electric field at scalp in the other half. This very early processing in the ERP period preceding the P100 component reveals more variability in adults than in children. Importantly, despite these early differences across groups, topographic similarities were observed at later time points for all groups, which suggest that these initial differences did not affect later ERPs.

The first reliable differences across age groups appeared in the P1 time range of the visual evoked potentials (VEP): different topographies appeared in the ERPs of children and adults (map “D” and map “C” in Fig. 3), along with higher amplitudes and a shift of the P100 peak for children. A decrease in the amplitudes of VEP with age has been repeatedly described using different kinds of visual stimuli (Allison et al., 1984; Breclj et al., 2002; Hoffmann et al., 2001; Holcomb, Coffey and Neville, 1992; Mahajan and McArthur, 2012; Taylor et al., 2004). Larger amplitudes in children have been attributed to less thick skulls or to generators being closer to the surface electrode in smaller brains (Chauveau et al., 2004; Picton and Taylor, 2007). Alternatively, amplitude decreases may result from increasing automaticity; the same processes require fewer resources, leading to a decrease in cerebral activation, a phenomenon that has been described in many developmental brain imaging studies (Durstun and Casey, 2006).

Latency changes across age have also been described (Allison et al., 1984; Zemon et al., 1995). Shorter P1 peak latency in adults than in children may reflect the increase in processing speed due to myelination (Picton and Taylor, 2007). Several studies have reported that P100 latency stabilizes around 20 years of age (Shaw and Cant, 1981; Allison et al., 1984; Emmerson-Hanover et al., 1994). Here, the P1 peak was ~20 ms later in children than in adults, without differences between the two children groups or between the two adult groups. Finally, source localisation of the different periods of global topographic activity in the P1 range displayed activation of occipital areas in both groups, with more extended bilateral activation in children and a left lateralised temporal–occipital source in adults. Changes from symmetrical to more lateralised activation for visual stimuli in adults have also been reported previously with written stimuli (Holcomb et al., 1992, see also Shaywitz et al., 2007).

The peak in the N1 range was also clearly shifted in children relative to adults. Once again, more stable electrophysiological patterns were observed for children (maps E and H in Fig. 3), extending up to 280–300 ms, whereas much more variability appeared in adults, who showed a period of topographic inconsistency in the 150–175 ms period.

Thus, differences observed in this early time-window between children and adults are largely in line with previously reported changes in visual processes. Here, the first 200 ms period most likely corresponds to visuo–conceptual processes (recognition of the depicted object, see also Indefrey and Levelt, 2004; Indefrey, 2011); the P1–N1 complex seems to be shifted in children up to 300 ms. Two converging results suggest that the processing observed in the first 200 ms in adults extends to 280–300 ms in children. First, the P1–N1 peaks are clearly shifted in children with respect to adults. Second, the same period of stable global electrophysiological activity (map “I” in Fig. 3) appeared after around 200 ms in adults (corresponding in adults to a P200/N200 component, see below), after about 290 ms in the 10–12 year-old children and after around 300 ms in the 7–8 year-old children. Hence, we will argue that changes in functional microstates observed from childhood to adulthood in this first early time-window in picture naming tasks are related to visual–cognitive processes, i.e., to pre-linguistic processes.

The first differences between the two children groups also appeared in the N1 time-period, with larger amplitudes in the youngest group around 200 ms but similar periods of topographic stability. The differences appearing in the TANOVA in this time window reflect greater variability in the older group (map E was less present in the older children) and longer durations of this period of electrophysiological stability in the younger group. Although ERP correlates in the 10–12 year-olds are closer to those of the youngest than to the adult group, the shorter periods of stable topographic activity reflect a speeding up of visual and conceptual processes from 7–8 to 10–12 year-old children. The two adult groups had very similar ERP patterns.

### *After the P1–N1 complex: word encoding processes*

After the P1–N1 complex, namely after 300 ms in children and 200 ms in adults, the same sequence of global electrophysiological patterns was observed across all groups.

A P200/N200 like component is observed in both adult groups peaking around 220 ms (see Fig. 1B). This component has been associated with lexical (lemma) selection in several ERP studies using overt picture naming with adult participants (Aristei et al., 2011; Costa et al., 2009; Maess et al., 2002; Laganaro et al., 2012). In the present study this time-period corresponds in adults to the onset of the period of stable scalp topography labelled “map I” in Fig. 3. This global topography starting around 200 ms has been reported very consistently across several picture naming studies in adults using topographic analyses approaches (Laganaro et al., 2012; Laganaro, 2014; Perret and Laganaro, 2012). Here it was present in the individual ERPs of most subjects

from all age groups, but its onset was delayed in children. If we attribute the first 280–300 ms to pre-linguistic processes in children, then it appears that children engage in lexical–semantic processing (lexical selection) from about 290–300 ms after picture onset. The duration of this period of stable global scalp topography decreased significantly between children and adults and between 7–8 and 10–12 year-old children, whereas it was similar across the two adult groups.

The following period of stable scalp topography (map “J”) was also consistently observed in most individuals, with different durations in children and adults and in the younger and older children. Thus, in the time-window we associate to word planning, children and adults presented similar global ERP activity, despite different waveforms due to shifted components and to different amplitudes. Along with faster visual and conceptual processes, the common periods of stable electrophysiological activity underlying lexical processes in adults accounted for a large part of the changes in word production speed across ages.

The two last periods of topographic stability consistently appeared in most participants, with only marginal differences in duration across groups. There is not enough insight from previous studies using high temporal resolution paradigms to infer about the processes involved during the last hundreds of milliseconds. The time-period after 400–500 ms has been associated in adults with phonological–phonetic encoding, i.e. the transformation of an abstract phonological form into articulatory plans (Indefrey, 2011; Laganaro et al., 2013; Möller et al., 2007), but it likely involves also pre-motor control and monitoring (Möller et al., 2007). These processes do not seem to vary consistently between children and adults.

#### *The dynamics of development in single word planning*

The comparison of the processes underlying word production in picture naming in children and adults yielded three different patterns corresponding to three different time-periods from picture onset to articulation: a) qualitative differences (different functional microstates corresponding to different underlying processes), b) quantitative differences (differences in timing) and c) neither qualitative nor quantitative differences but very similar ERPs. In the early time-period (from 0 to 200 ms in adults and to 300 ms in children), most likely corresponding to pre-linguistic processes, qualitative differences appeared between children and adults, with only quantitative differences among the two children groups and no differences between the two adult groups. In a second time-period, probably corresponding to lexical processes, quantitative differences were observed between children and adults and between the two children groups. In the final 250 ms of the response-aligned analysed time-window, associated with articulatory planning and monitoring, similar patterns were observed in the ERPs of all groups. These results suggest that different brain mechanisms underlie pre-linguistic processes in picture naming in children and adults, while language processes are mostly similar between school-age children and adults, only their temporal dynamics changes during development.

It is somewhat paradoxical that, within the developmental periods studied here, visual processes, which are usually considered to develop quite rapidly from birth on, undergo a qualitative change, while language production processes, which appear later and take years to automatize, are simply characterised by a decrease in processing time. The development of the electrophysiological patterns in the P1–N1 time-window from school-age children to adolescence or to early adulthood is not specific to picture naming, as it has been reported in picture categorisation tasks (Batty and Taylor, 2002) as well as with other visual stimuli, such as faces (Taylor et al., 2004) and words (Brem et al., 2006, 2010). Changes have been associated with expertise and the automatization of the identification of visual stimuli and their corresponding concepts as well as with the maturation of occipital areas. In particular, in reading studies changes in the N1 component have been associated with expertise with printed stimuli (Brem et al., 2006, 2010). Hence, the reorganization observed in these early components

may also be related to literacy acquisition. Obviously, learning to read and write is a major achievement of the early school years. Literacy acquisition has been shown to affect the brain connectivity and morphology, phenomena that have been reported in comparisons of beginning and more proficient reading learners (Monzalvo and Dehaene-Lambertz, 2013) and of literate and illiterate adults (Castro-Caldas et al., 1998). Given that picture naming has been shown to activate very similar neural networks to those involved in reading aloud (Caravolas et al., 2012; Denckla and Cutting, 1999), we could speculate that the qualitative difference between children and adults in the early time windows is also related to reading acquisition.

The similar underlying brain mechanisms for language processes although differently distributed in time are consistent with behavioural studies showing similar encoding processes in adults and school-age children despite lower accuracy and longer production latencies (Cycowicz et al., 1997; D'amico et al., 2001; Bragard et al., 2010; Brooks and McWhinney, 2000; Jerger et al., 2002, see the Introduction). Interestingly, these functional similarities were observed despite the existence of different electrophysiological patterns in early processing time-windows. Differences in the duration of similar stable global electrophysiological patterns only appeared in the mid portion of the analysed time-window, while the duration of the two very last periods of topographic stability (closer to articulation onset) was virtually identical across all groups. Hence, the observed speeding up of word production in picture naming from school-age children to adulthood seems not to involve linear rescaling of all encoding processes but rather concentration of changes in specific time-windows: qualitative changes are associated with pre-linguistic and quantitative changes with lexical processes. In particular, if we refer to a serial model of word planning, expertise in word production seems to increase the efficacy of lexical processes (lemma and lexeme retrieval according to the model reviewed in the Introduction) more than the dynamics of “later” processes, likely associated with motor planning and monitoring, which may be already automatized in school-age children at least for early acquired words such as those used in the present study. Shorter periods of topographic stability associated with lexical processes also appeared in the older children relative to the 7–8 year-olds suggesting a continuous change of the underlying processing speed with expertise and increased lexicon from the age of seven to young adulthood. As ERP correlates and latencies no longer changed between the two subgroups of young adults we can conclude that modification of the brain processes underlying pre-linguistic processes and speeding up of lexical processes underlying picture naming is completed by the latest at the age of 20.

#### **Conclusions**

By analysing the periods of stable electric fields (topographies) in the ERP signal from picture onset to the individual onset of articulation in children and adults, we have been able to track simultaneously functional and temporal changes in the development of the word encoding processes. Our results have shown that both qualitative and quantitative changes intervene in this development from childhood to adulthood but in different time-windows. It appears that the speeding up of word production in picture naming does not involve linear rescaling of all encoding processes. Future research should fill in the gap between our older group of children and adults to determine how during adolescence the brain processes underlying pre-linguistic processes are modified and when the speeding up of lexical processes in picture naming become adult-like. Finally, it should be possible with ERP analyses of the type shown here to track qualitative and quantitative age-related changes related to the development of other psycholinguistic processes.

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.neuroimage.2015.02.027>.



## Acknowledgments

This study was supported by a grant of the Geneva Neuroscience Center (2012); the first author was supported by Swiss National Science Foundation grant no. PPOOP1-140796. The authors wish to thank Laurent Spinelli for his help with the source estimation in children.

## References

- Alario, F.X., Ferrand, L., 1999. A set of 400 pictures standardized for French: norms for name agreement, image agreement, familiarity, visual complexity, image variability, and age of acquisition. *Behav. Res. Methods Instrum. Comput.* 31, 531–552.
- Allison, T., Hume, A.L., Wood, C.C., Goff, W.R., 1984. Developmental and aging changes in somatosensory, auditory and visual evoked potentials. *Electroencephalogr. Clin. Neurophysiol.* 58, 14–24.
- Aristei, S., Melinger, A., Abdel Rahman, R., 2011. Electrophysiological chronometry of semantic context effects in language production. *J. Cogn. Neurosci.* 23, 1567–1586.
- Baayen, R.H., 2008. *Analyzing Linguistic Data. A Practical Introduction to Statistics Using R*. Cambridge University Press.
- Batty, M., Taylor, M.G., 2002. Visual categorization during childhood: an ERP study. *Psychophysiology* 39, 482–490.
- Bonin, P., Peerman, R., Malardier, N., Méot, A., Chalard, M., 2003. A new set of 299 pictures for psycholinguistic studies: French norms for name agreement, image agreement, conceptual familiarity, visual complexity, image variability, age of acquisition, and naming latencies. *Behav. Res. Methods Instrum. Comput.* 35, 158–167.
- Bragard, A., Schelstraete, M.A., Collette, E., Grégoire, J., 2010. Child word-finding difficulties assessment: developmental data from French-speaking children aged from 7 to 12. *Eur. Rev. Appl. Psychol.* 60, 113–127.
- Brecejli, J., Strudl, M.S., Zidar, I., Tekavcic-Pompe, M., 2002. Pattern ERG and VEP maturation in schoolchildren. *Clin. Neurophysiol.* 113, 1764–1770.
- Brem, S., et al., 2006. Evidence for developmental changes in the visual word processing network beyond adolescence. *NeuroImage* 29, 822–837.
- Brem, S., Bach, S., Kucian, K., Guttorm, T.K., Martin, E., Lyytinen, H., Brandeis, D., Richardson, U., 2010. Brain sensitivity to print emerges when children learn letter speech sound correspondences. *Proc. Natl. Acad. Sci. U. S. A.* 107, 7939–7944.
- Brooks, P.J., McWhinney, B., 2000. Phonological priming in children's picture naming. *J. Child Lang.* 7, 335–336.
- Brown, T.T., Lugar, H.M., Coalson, R.S., Miezin, F.M., Petersen, S.E., Schlaggar, B.L., 2005. Developmental changes in human cerebral functional organization for word generation. *Cereb. Cortex* 15, 275–290.
- Brunet, D., Murray, M.M., Michel, C.M., 2011. Spatio-temporal analysis of multichannel EEG: CARTOOL. *Comput. Intell. Neurosci.* 2011, 813870. <http://dx.doi.org/10.1155/2011/813870>.
- Budd, M.J., Hanley, J.R., Griffiths, Y., 2011. Simulating children's retrieval errors in picture naming: a test of Foygel & Dell's 2000 semantic/phonological model of speech production. *J. Mem. Lang.* 64, 74–87.
- Budd, M.J., Paulmann, S., Barry, C., Clahsen, H., 2013. Brain potentials during language production in children and adults: an ERP study of the English past tense. *Brain Lang.* 127, 345–355.
- Caravolas, M., Lervag, A., Mousikou, P., Efrim, C., Litavsky, M., Onochie-Quintanilla, E., Hulme, C., 2012. Common patterns of prediction of literacy development in different alphabetic orthographies. *Psychol. Sci.* 23, 678–686.
- Castro-Caldas, A., Pettersson, K.M., Reis, A., Stone-Elender, S., Ingvar, M., 1998. The illiterate brain: learning to read and write during childhood influences the functional organization of the adult brain. *Brain* 121, 1053–1063.
- Changeux, J.P., Michel, C.M., 2004. Mechanisms of neural integration at the brain scale level: the neuronal workspace and microstate models. In: Grillner, S., Grabyel, A.M. (Eds.), *Microcircuits: The Interface between Neurons and Global Brain Function*. The MIT Press, Cambridge, MA, pp. 347–370.
- Chauveau, N., Franceries, X., Doyon, B., Rigaud, B., Morucci, J.P., Celsis, P., 2004. Effects of skull thickness, anisotropy, and inhomogeneity on forward EEG/ERP computations using a spherical three-dimensional resistor mesh model. *Hum. Brain Mapp.* 212, 86–97.
- Clark, E.V., 1993. *The Lexicon in Acquisition*. Cambridge University Press, Cambridge.
- Costa, A., Strijkers, K., Martin, C., Thierry, G., 2009. The time course of word retrieval revealed by event-related brain potentials during overt speech. *Proc. Natl. Acad. Sci.* 106, 21442–21446.
- Cycowicz, Y.M., Friedman, D., Rothstein, M., Snodgrass, J.G., 1997. Picture naming by young children: norms for name agreement, familiarity, and visual complexity. *J. Exp. Child Psychol.* 65, 171–237.
- D'Amico, S., Devescovi, A., Bates, E., 2001. Picture-naming and lexical access in Italian children and adults. *J. Cogn. Dev.* 2, 71–105.
- Dell, G.S., 1986. A spreading activation theory of retrieval in sentence production. *Psychol. Rev.* 93, 283–321.
- Denckla, M.B., Cutting, L.E., 1999. History and significance of rapid automatized naming. *Ann. Dyslexia* 49, 29–42.
- Durston, S., Casey, B.J., 2006. What have we learned about cognitive development from neuroimaging? *Neuropsychologia* 44, 2149–2157.
- Emmerson-Hanover, R., Shearer, D.E., Creel, D.J., Dustman, R.E., 1994. Pattern reversal evoked potentials: gender differences and age related changes in amplitude and latency. *Electroencephalogr. Clin. Neurophysiol.* 92, 93–101.
- Friederici, A.D., 2006. The neural basis of language development and its impairment. *Neuron* 52, 941–952.
- Friedrich, M., Friederici, A.D., 2005. Semantic sentence processing reflected in the event-related potentials of one- and two-year-old children. *Neuroreport* 16, 1801–1804.
- Fonov, V., Evans, A., McKinstry, R., Almlí, C., Collins, D., 2009. Unbiased nonlinear average age-appropriate brain templates from birth to adulthood. *Neuroimage* 47, S102.
- Fonov, V., Evans, A., Botteron, K., Almlí, C., McKinstry, R., Collins, D., 2011. Unbiased average age-appropriate atlases for pediatric studies. *Neuroimage* 54, 313–327.
- Grave de Peralta, R., Gonzalez Andino, S., Lantz, G., Michel, C.M., Landis, T., 2001. Noninvasive localization of electromagnetic epileptic activity. I. Method descriptions and simulations. *Brain Topogr.* 14, 131–137.
- Greenham, S.L., Stelmack, R.M., 2001. Event-related potentials and picture-word naming: effects of attention and semantic relation for children and adults. *Dev. Neuropsychol.* 20, 619–638.
- Hoffmann, K., Leistriz, L., Feucht, M., Benninger, F., Reiter, D., Witte, H., 2001. Identification of the stimulated hemiretina in primary school children and adults based on left and right hemifield pattern reversal visual evoked potentials – a comparative study. *Clin. Neurophysiol.* 112, 359–368.
- Holcomb, P.J., Coffey, S.A., Neville, H.J., 1992. Visual and auditory sentence processing: a developmental analysis using event-related brain potentials. *Dev. Neuropsychol.* 8, 203–241.
- Indefrey, P., 2011. The spatial and temporal signatures of word production components: a critical update. *Front. Psychol.* 2, 255. <http://dx.doi.org/10.3389/fpsyg.2011.00255>.
- Indefrey, P., Levelt, W., 2004. The spatial and temporal signatures of word production components. *Cognition* 92, 101–144.
- Jaeger, T.F., 2008. Categorical data analysis: away from ANOVAs transformation or not and towards logit mixed models. *J. Mem. Lang.* 59, 434–446.
- Jerger, S., Martin, R.C., Damian, M.F., 2002. Semantic and phonological influences on picture-naming by children and teenagers. *J. Mem. Lang.* 47, 229–249.
- Koenig, T., Melie-García, L., 2010. A method to determine the presence of averaged event-related fields using randomization tests. *Brain Topogr.* 3, 233–242.
- Koukou, M., Lehmann, D., 1987. An information processing perspective of psychophysiological measurements. *J. Psychophysiol.* 1, 109–112.
- Krishnan, S., Leech, R., Mercure, E., Lloyd-Fox, S., Dick, F., 2014. Convergent and divergent fMRI responses in children and adults to increasing language production demands. *Cereb. Cortex* 2014. <http://dx.doi.org/10.1093/cercor/bhu120>.
- Laganaro, M., 2014. ERP topographic analyses from concept to articulation in word production studies. *Front. Psychol.* 5, 493. <http://dx.doi.org/10.3389/fpsyg.2014.00493>.
- Laganaro, M., Perret, C., 2011. Comparing electrophysiological correlates of word production in immediate and delayed naming through the analysis of word age of acquisition effects. *Brain Topogr.* 24, 19–29.
- Laganaro, M., Valente, A., Perret, C., 2012. Time course of word production in fast and slow speakers: a high density ERP topographic study. *NeuroImage* 59, 3881–3888.
- Laganaro, M., Python, G., Toepel, U., 2013. Dynamics of phonological-phonetic encoding in word production: evidence from diverging ERPs between stroke patients and controls. *Brain Lang.* 126, 123–132.
- Lehmann, D., Skrandies, W., 1984. Spatial analysis of evoked potentials in man—a review. *Prog. Neurobiol.* 23, 227–250.
- Lehmann, D., Strik, W.K., Henggeler, B., Koenig, T., Koukou, M., 1998. Brain electric microstates and momentary conscious mind states as building blocks of spontaneous thinking: I. Visual imagery and abstract thoughts. *Int. J. Psychophysiol.* 29, 1–11.
- Levelt, W., Roelofs, A., Meyer, A.S., 1999. A theory of lexical access in speech production. *Behav. Brain Sci.* 22, 1–75.
- Maess, B., Friederici, A.D., Damian, M., Meyer, A.S., Levelt, W.J.M., 2002. Semantic category interference in overt picture naming: sharpening current density localization by PCA. *J. Cogn. Neurosci.* 14, 455–462.
- Mahajan, Y., McArthur, G., 2012. Maturation of visual evoked potentials across adolescence. *Brain Dev.* 34, 655–666.
- Michel, C.M., Murray, M.M., 2012. Towards the utilization of EEG as a brain imaging tool. *NeuroImage* 61, 371–378.
- Michel, C.M., Thut, G., Morand, S., Khateb, A., Pegna, A.J., Grave de Peralta, R., 2001. Electric source imaging of human brain functions. *Brain Res. Rev.* 36, 108–118.
- Michel, C.M., Koenig, T., Brandeis, D., Gianotti, L.R.R., 2009. *Electric Neuroimaging*. Cambridge University Press, Cambridge.
- Möller, J., Jansma, B.M., Rodriguez-Fornells, A., Münte, T.F., 2007. What the brain does before the tongue slips. *Cereb. Cortex* 17, 1173–1178.
- Monzalvo, K., Dehaene-Lambertz, G., 2013. How reading acquisition changes children's spoken language network. *Brain Lang.* 127, 356–365.
- Murray, M.M., Brunet, D., Michel, C., 2008. Topographic ERP analyses, a step-by-step tutorial review. *Brain Topogr.* 20, 249–269.
- Pascual-Marqui, R.D., Michel, C.M., Lehmann, D., 1995. Segmentation of brain electrical activity into microstates: model estimation and validation. *IEEE Trans. Biomed. Eng.* 42, 658–665.
- Perret, C., Laganaro, M., 2012. Comparison of Electrophysiological Correlates of Writing and Speaking: a Topographic ERP Analysis.
- Picton, T.W., Taylor, M.J., 2007. Electrophysiological evaluation of human brain development. *Dev. Neuropsychol.* 31, 249–278.
- Price, C., Devlin, J.T., Moore, C.J., Morton, J., Laird, A.R., 2005. Meta-analyses of object naming: effect of baseline. *Hum. Brain Mapp.* 25, 70–82.
- Protopapas, A., 2007. CheckVocal: a program to facilitate checking the accuracy and response time of vocal responses from DMDX. *Behav. Res. Methods* 39, 859–862.
- Shaw, N.A., Cant, B.R., 1981. Age-dependent changes in the amplitude of the pattern visual evoked potential. *Electroencephalogr. Clin. Neurophysiol.* 51, 671–673.



- Shaywitz, B.A., Skudlarski, P., Holahan, J.M., Marchione, K.E., Constable, R.T., Fulbright, R.K., Zelterman, D., Lacadie, C., Shaywitz, S.E., 2007. Age-related changes in reading systems of dyslexic children. *Ann. Neurol.* 61, 363–370.
- Spinelli, L., Gonzalez Andino, S., Lantz, G., Seeck, M., Michel, C., 2000. Electromagnetic inverse solutions in atomically constrained spherical head models. *Brain Topogr.* 13, 115–125.
- Taylor, M.J., Batty, M., Itier, R.J., 2004. The faces of development: a review of early face processing over childhood. *J. Cogn. Neurosci.* 16, 1426–1442.
- Zemon, V., Eisner, W., Gordon, J., Grose-Fifer, J., Tenedios, F., 1995. Shoup, H. Contrast-dependent responses in the human visual system: Childhood through adulthood. *Int. J. Neurosci.* 80, 181–201.