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Abstract

An adult continues acquiring new lexical entries in everyday life. Brain networks and processes at play when producing newly learnt words might be similar to well-known words, yet some processes are bound to be slower. Here, we compared the neural dynamics of producing newly acquired words with those of well-known frequent words, both qualitatively and quantitatively, using event-related potentials (ERPs) associated to high-density microstate analyses.

ERPs revealed several temporal windows with differences in waveform amplitudes, which correspond to enhanced duration of similar microstates for newly acquired words.

The time-periods of these ERP modulations converged to suggest that both lexical processes and word form encoding are slowed down for words that have been learned recently, but that the same brain processes are implemented as for well-known words.

Keywords: word production, picture naming, learning, ERPs, topographic analyses

1. Introduction

Although most of the words in the adult speaker's lexicon have been learned many years earlier, an adult continues acquiring new lexical entries in everyday life. One core question concerning the processing of these new lexical entries is whether they are processed in the same way as the words that have been in the mental lexicon for a long time. Even if similar brain networks and processes are probably at play when producing newly learnt words and well-known words, some processes (e.g. lexical-semantic vs. phonological) are bound to be costlier or slower for newly learnt words. In this study, we compare the neural dynamics of producing newly acquired words with those of well-known frequent words.

Much of the work focusing on the status of new lexical entries used spoken word recognition/comprehension experiments, in which participants are taught novel word forms (e.g. "cathedruke" for cathedral). Behavioral data showed that, very rapidly, newly learnt words generate lexical competition with familiar words, illustrating that these novel entries have reached the same lexical status as familiar words (Davis et al., 2009; Dumay and Gaskell, 2007; Gaskell and Dumay, 2003; Kapnoula et al., 2015; Tamminen et al., 2010). Studies also looked more specifically at how lexical entries connect to semantic representations notably by way of semantic priming tasks (Coutanche & Thompson-Schill, 2014; Van der Ven et al., 2015; Tamminen & Gaskell, 2013; Borovsky et al., 2012). Competition and priming effects for new lexical entries are assumed to reflect the emergence of connections between orthographic/phonological and semantic representations of existing words and novel ones. Some studies indicate that this process is observed only after overnight consolidation (Dumay and Gaskell, 2007; Gaskell and Dumay, 2003), thus endorsing a role of sleep in memory formation (Davis et al., 2009; Takashima et al., 2009). Recent work has shown that hippocampal memory systems and then neocortical brain networks as a result of consolidation, are engaged during processing of novel words (Takashima et al., 2017). Yet, results suggesting the involvement of similar neural circuits already from the start of learning have also been reported (Kapnoula et al., 2015). Indeed, other word comprehension studies concluded that newly learnt words were processed in the same way as known words (McCandliss et al., 1997; Mestres-Missé et al., 2007) as event-related potentials (ERPs) waveforms were similar between the two.

Analogous discrepancies on the similarity/differences of the networks underlying novel and known words can be found in language production research, in which participants have to

produce newly learnt words (either real or pseudo-words) associated with pictures of rare objects (Cornelissen et al., 2004; Grönholm et al., 2005; Hultén et al., 2009). Cornelissen et al. (2004) reported similar activation after learning whether training focused on semantic or phonological information. Differences in activation for learnt words relative to familiar words appeared however in the inferior parietal cortex. These were interpreted as reflecting increased phonological processes and phonological working memory for newly learnt words (for similar results see (Breitenstein et al., 2005) although no overt production was required). Grönholm et al. (2005) also suggested that the same main networks were associated with the naming of novel (unfamiliar) objects and familiar objects and argued that the observed quantitative differences in Broca's area, left anterior temporal areas, and in the cerebellum likely reflected enhanced semantic and lexical-phonological demands for newly learnt words.

Hence, while most studies conclude that, at least after consolidation, the same networks are involved in the production of both newly learnt words and words that have been in the lexicon for a long time, different activations in the main language network are also reported before consolidation. Given the relatively sparse evidence on corresponding spatio-temporal dynamics, it is difficult to interpret the nature of differences or commonalities in the neural processing of novel words and existing lexical entries. Discrepancies can reflect either qualitative differences reflecting different sequences of mental events underlying planning of these two kinds of words, or quantitative differences, i.e. different dynamics or time-distributions of similar underlying brain processes.

With regard to picture naming, it has been proposed that a simple association between the visual representation and the corresponding word might be enough to perform the task for well-known words (Brennen et al., 1996; Kremin, 1988). If the weight of semantic processes necessary to trigger lexical retrieval differs between novel and well-known words, then qualitatively different neural networks might be called for during word planning (see Fargier and Laganaro, 2017 for a similar proposal as a function of referential vs. inferential naming). Alternatively, if the same sequence of events is engaged and the processing of new and familiar words differs only quantitatively, one might expect that some word encoding processes are more costly for the former.

The aim of the present study is thus to shed light on this issue by investigating qualitative and/or quantitative differences in the neural signature of mental processes underlying the production of novel words relative to well-established words. The participants were trained to learn novel words corresponding to unfamiliar rare/ancient objects names in two different sessions. On the last session of the experiment, participants were tested with a picture naming

task while EEG was recorded. In this test session, participants had to name the pictures of unfamiliar objects that they were trained on (i.e. newly acquired words) as well as pictures of familiar objects (i.e. well-known words). We compared stimulus-aligned and response-aligned evoked-response potentials (ERPs) obtained in the picture naming task used to elicit the production of newly acquired words and well-known words.

The temporal resolution of electroencephalography (EEG), associated to high-density topographic analyses, offers precious perspectives to explore the issue of qualitative versus quantitative differences in the production of newly learnt words as compared to words that have been in the lexicon for years. We rely in particular on microstates that correspond to stable electrophysiological activities at scalp (Michel et al., 2004). Microstates are independent of neural response's magnitude and are defined by their topographical configuration and their duration in the neural signal. Because of these features, microstates can be used to reveal quantitative differences (i.e. same topographic patterns, corresponding to same mental states, but with varying durations) and/or qualitative differences (i.e. different topographic patterns, different explained variance) in neural events underlying the production of well-known and novel words. Microstates analyses can indeed reveal whether specific topographic patterns are extended or shortened as a function of experimental manipulations (Laganaro, 2014). As estimated by Indefrey (Indefrey, 2011), differences observed earlier than 300 ms after picture onset would likely reflect modulations occurring on semantic and lexical processes whereas effects observed after 300 ms (or close to vocal onset) would rather indicate modulations at post-lexical stages.

We used this approach to compare the dynamics of word planning processes of newly acquired words to those of well-known words.

2. Results

2.1. Behavioral results

The data of one participant was removed due to technical problems and a second one was excluded because less than 50 newly learnt words were produced correctly within the first 1500 ms. The following analyses were conducted on 14 participants. The number of artefact free ERP epochs corresponding to correctly produced words within 1500 ms did not differ significantly across lists (newly learnt: 103, SD=34.5; well known: 87, SD=29.4, t(13)=1.3,

p=.22). Production latencies were about 200 ms longer for newly learnt words (1074 ms, SD=168), than for well-known words (868 ms, sd=92ms, t(13)=5.2, p<.001).

2.2.ERP results

2.2.1. Waveform analysis

Statistical analyses revealed modulations of waveform amplitudes between well-known words and novel words on stimulus- and response-aligned data.

Several time-periods of significant differences were found on stimulus-aligned epochs (see Figure 1a): around 50 ms after picture onset and from 100 to 160 ms post picture onset on right frontal and posterior electrodes, and from 250 to 300 ms and 400 to 520 ms post picture onset at anterior sites. In the early time window (before 160 ms), waveform amplitudes were less pronounced for well-known words compared to novel words, with an apparent delay of the P2 component (see Figure 1c).

The topographic ANOVA (TANOVA) performed on these epochs revealed significant differences on Global Map Dissimilarity values (GMD) on several time-periods: 25-75 ms,110-160 ms and 250-350 ms post picture onset (see Figure 1b).

On response-aligned epochs, consistent differences were found roughly throughout the entire period (see Figure 1b). Amplitudes of well-known words were more negative on frontal sites relatively to novel words. The TANOVA indicated major effects between 490 and 260 ms prior to vocal onset and from 530 to 510 ms prior to vocal onset.

*** Figure 1 about here ***

2.2.2. Microstate analysis

The same sequence of 6 different periods of quasi-stable electrophysiological activity at scalp or microstates was obtained on stimulus-aligned epochs of well-known and novel words, although with different time-distribution (see Figure 1d).

A topography consistency test (TCT, (Koenig et al., 2011)) indicated that the period ranging from 150 to 200 ms displayed topographic inconsistencies. In order to better evaluate differences in duration across conditions, we applied the topographic fitting procedure on time-periods excluding the period with inconsistency: from 0 to 150 ms with topographic map templates M1, M2, M3 and from 200 ms to the end of the ERPs with topographic map templates M4, M5 and M6. The fitting revealed differences on duration of microstates labelled M1, M2, M4 and M6 (see Table1). In particular, consistent differences were found

on duration of microstate M4 (p=0.0044), which displayed a posterior positivity (Figure 1e) with longer duration of M4 for novel words (106 ms) compared to well-known words (74 ms). We also observed significant differences on M6 (p=0.0152), with increased duration for well-known words due to shorter duration of previous maps (see Table1).

*** Table 1 about here ***

Microstates	Stimulus-aligned epochs						Response-aligned epochs			
	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
Microstate duration - Novel words	80	62	16	106	140	54	88	180	168	44
Microstate duration - Well-known words	72	70	44	74	136	92	218	166	58	56
Level of significance p	*0.0106*	*0.0314*	*ns*	*0.0044*	*ns*	*0.0152*	*0.0082*	*ns*	*0.0018*	*ns*

Table 1: Mean duration of the 10 microstates for both kind of words according to the fitting procedures (in ms)

On response-aligned data, the same sequence of 4 different periods of quasi-stable electrophysiological activity at scalp was obtained. Significant differences between conditions were found on duration of microstates M7 (p=0.0082) and M9 (p=0.0018) but not of M8 and M10 (see Table1). M9 displayed a central positivity and lasted about 58 ms for well-known words and 168 ms for novel words. The microstate M9 started about 210 ms prior to vocal onset for novel words and around 310 ms prior to vocal onset for well-known words. M7, which displayed posterior positivity lasted longer for well-known words (218 ms) relatively to novel words (88 ms).

As microstates computed separately on stimulus-aligned and response-aligned data can correspond to the same topographic pattern, we performed correlations of visually similar microstates. This indicated that M5 and M7 were correlated at 98% and M6 and M8 at 95%. The longer durations of M6 and M7 for well-known words are therefore likely to be due to overlap between stimulus-aligned and response-aligned epochs as a function of reaction times in well-known words.

3. Discussion

In this study, we examined whether naming pictures corresponding to novel words is achieved similarly to naming pictures corresponding to words that have been in the mental lexicon for a long time.

Obviously, production latencies for newly acquired words were extensively longer than those of well-known words (+200 ms on average). Coherently, ERPs revealed several temporal windows displaying differences in waveform amplitudes and in periods of stable electrophysiological activity at scalp or microstates. The microstate analysis showed that these modulations were related to differences in the time distribution of several specific, yet similar, mental processes. Indeed, ERPs of both kinds of words were summarized by the same sequence of ten microstates from picture onset to 100 ms prior to vocal onset. This result suggests that the same brain events occur during word planning, which is in line with previous work showing that similar cortical networks are involved in the production of newly learned words and familiar words (Cornelissen et al., 2004; Grönholm et al., 2005; Hultén et al., 2009).

Given differences in the speed of naming, we found a slowing down of specific mental processes: increased duration of two periods of stable electrophysiological activity at scalp (microstates M4 and M9), occurring respectively between 200 and 300 ms post picture onset and from 350 to 150 ms prior to vocal onset, was observed when producing newly acquired words compared to well-known words. This indicates that the associated mental processes took longer for the former. According to previous estimates of word planning processes in picture naming tasks (Indefrey, 2011), differences observed between 200 and 275 ms indicate modulations of lexical processes. This is supported by studies suggesting that the P2 component (a positive wave around 200 ms) is a marker of lexical selection onset (Aristei et al., 2011; Costa et al., 2009; Strijkers et al., 2010) or by studies showing lexical effects in brain oscillatory activity in the same time-window (see Piai et al. 2012). Here, the microstate M4 encompassing the P2 component lasted longer for newly acquired words, which is coherent with lexical frequency effects (Strijkers et al., 2010) as frequency of novel words was close to 0.

Apart from these early effects, later modulations of amplitudes were associated to increased duration of microstate M9. It has been repeatedly shown that phonological processes are engaged around 400 ms after picture onset in picture naming tasks (Laganaro et al., 2012; Laganaro and Perret, 2011; Valente et al., 2014). Following this rationale, and given that the

microstates identified here displayed similar topographic patterns as reported previously (see Laganaro, 2017 for a meta-analysis), it can be concluded that post-lexical processes, likely word form encoding, are also stretched out in naming novel words compared to familiar words. ERP modulations in this later time-window may be due to the following reasons. Firstly, it could reflect a reduced ease to encode the word-form corresponding to the picture if one assumes less trained connections between lexical and phonological representations for recent words. This is also in line with studies indicating that word age-of-acquisition affects lexical-phonological processes (Bonin et al., 2006) and ERPs in time-windows after 300 ms (Perret et al., 2014). Precisely, late acquired words are produced slower than early-acquired words, and this is associated with increased duration of mental processes occurring after 300 ms post picture onset (Perret et al., 2014). A second related explanation is that monitoring processes are more significant for novel words. It is assumed that internal monitoring starts as soon as a portion of the phonological form is encoded (Indefrey and Levelt, 2004). In keeping with the idea of increased competition among newly acquired words, additional monitoring would be necessary to select the correct word form, leading to the increased duration of the microstate associated to phonological encoding (Fargier and Laganaro, 2019).

Interpreting the effects observed early in the course of picture naming (<200 ms) is less straightforward. The time-period ranging from 150 to 190 ms after picture onset is known to involve several processes such as image categorization and memory access (Hassan et al., 2015), but in the present study it corresponds to a period of topographic inconsistency, which means that there are no consistent patterns of active neural sources across subjects in this time-window. We therefore did not analyze further this effect and cannot discuss it. Nevertheless, waveform modulations could reflect differences in visual processing (associated to the P100) rather than a delay of the onset of lexical selection (Strijkers et al., 2010). In particular, it could be linked to familiarity with the picture set, as effects seem to indicate shorter time processing for pictures associated with novel words. Those pictures were seen multiple times across the experiment: during the training sessions and during the test sessions. Pictures associated with well-known words were seen, in contrast, only the last day of the study. Additional analyses contrasting ERPs associated to pictures of novel words at three points across the study revealed similar differences (around 170 ms) between first and subsequent exposures (see supplementary data) with apparent shorter time processing after multiple exposures. This is probably the downside of comparing the production of novel and well-known words. Novel words need to be sufficiently acquired to be produced: the 1-week

training allowed us to have a similar number of correct trials. Moreover, the need for an equal number of trials prevents learning studies to compare the production of novel words before and after training. Future studies should nonetheless make sure that overall all stimuli are presented equally during the experiment. Note that this does not hamper our main conclusions as our data indicate increased processing times (i.e. increased duration of microstates) for novel words, which is obviously not related with potential picture familiarity/repetition issues that would provide a (reversed) processing advantage.

Finally, the here-reported data have only limited implications regarding complementary learning system account as we compared novel words and familiar words only at the end of the week of training. Recent studies showed different temporal features for specific mental processes in word learning. For instance, it was revealed that semantic processes were already similar before consolidation, in contrast to lexical effects which emerged only overnight in word recognition tasks (Bakker et al., 2015a; see Weighall et al., 2017 for similar approach). Bakker-Marshall and colleagues notably used brain oscillatory patterns to reveal undistinguished brain activity in theta (4-8 Hz) and beta (16-21 Hz) frequency bands between familiar words and words learned 24 hours earlier (Bakker et al., 2015b; see also Bakker-Marshall et al., 2018). Hence, it remains to be explored whether similar results would be found for word planning; in other terms whether quantitative differences observed here in specific time periods supersede qualitatively different microstates before consolidation and whether specific mental events (e.g. lexical-semantic vs. post-lexical) would be concerned.
Yet, the present study revealed different dynamics of mental events inherent to word planning of novel and well-known words, which might underlie the neuroimaging evidence for commonalities and differences as a function of learning (Cornelissen et al., 2004; Grönholm et al., 2005; Hultén et al., 2009).

Conclusion

Taken together, waveforms and topographic modulations illustrate the differences in the ease of naming newly acquired and well-known words and converge to suggest that both lexical processes and word form encoding are slowed down for words that have been learned recently, but that the same mental processes are implemented as for well-known words.

4. Material and methods

4.1.Participants

16 French-native speakers (4 men, mean age = 25 ± 5 years) took part in the study. All were right-handed, had normal or corrected-to-normal vision and none reported a significant history of psychiatric or neurological disorders. They gave their informed written consent prior to the study and were paid for their participation.

The data were part of a larger learning study conducted on the 5 days of a week and which included continuous theta burst stimulation (cTBS) or sham stimulation of the right Broca homologue (Nicolo et al., 2016). The true vs. sham stimulation was applied on the second or the fourth day of the week during which participants were trained on novel words and tested via picture naming tasks. The results obtained as a function of learning and stimulation are the topic of another article (Nicolo et al., 2016) where the entire procedure can be found. Participants' performance in naming trained items increased throughout the learning period with maximal performance at the last session (about 60 % of items correctly named, compared to 20% prior to training). There was a main effect of session indicating improved naming after training [$F(1,15) = 195.3$, $p < 0.0001$] but no main effect of stimulation type ($F < 1$) and no interaction between session and stimulation ($F < 1$). We concluded that the inhibition of the right Broca homolog with cTBS did not influence the ability to learn novel words. The present study thus focuses on the last day of the study (session 3) during which participants were tested on these newly learnt items and on well-known frequent words as well.

4.2.Stimuli

100 pictures of unfamiliar objects (line drawings on white squares) and their corresponding words were used (i.e. newly learnt words). Pictures depicted ancient or rare objects. All corresponding words had very low lexical frequency (mean oral frequency: 0.4 occurrences per million word, from Lexique, (New et al., 2004). These stimuli were used in the learning sessions.

An additional set of 60 pictures of familiar objects (line drawings on white squares) and their corresponding words were used (from (Alario and Ferrand, 1999) (i.e. well-known words). All pictures had high name agreement (mean =94.85) with mean oral frequency of 39.6 occurrences per million words.

Procedure

Learning sessions: The learning procedure was conducted two times during the week (on the second and fourth days). Pictures of unfamiliar objects were presented together with their definition on a computer screen. Participants were invited to type the corresponding name of the picture. If the name was unknown or incorrect, participants could hear and/or read the word (see Nicolo et al. 2016 for an illustration of the procedure). Each stimulus remained on screen until the picture name provided by the participant was correct. Four blocks with 50 items each were used on each learning session.

Test sessions: Participants were tested individually in a soundproof dark room. Pictures were presented in constant size on a black screen (60 cm from their chest). The newly learnt objects-names naming task preceded the well-known objects naming task.

All items were presented twice in a different pseudo-random order and in separate blocks, preceded by 2 warming-up filler trials. An experimental trial began with a fixation cross for 500 ms, followed by a blank screen preceding picture onset. Participants were requested to produce overtly the word corresponding to the picture as soon as possible when they knew the word. If they did not know the answer, they were asked to overtly say "no". A blank screen lasting 2000 ms was displayed before the next trial. Pictures were presented twice in a different pseudo-random order and in separate blocks.

The picture naming task associated with the rare/ancient objects trained during the learning procedure was conducted three times during different days of the week (session 1 on first day prior to any training, session 2 and session 3 on third and fifth days after training) whereas the picture naming task associated with the names of familiar objects was performed only on session 3.

Production latencies were recorded by a microphone and digitized for further systematic latency and accuracy check.

For the sake of the present study, we compared only the correct trials during the picture naming task of rare/ancient objects trained during learning with those of the picture naming task of familiar objects. Only correct responses within the first 1500 ms following picture onset were retained for both sets of items.

4.3.EEG Acquisition and Pre-analyses

EEG was recorded continuously using the Active-Two Biosemi EEG system (Biosemi V.O.F. Amsterdam, The Netherlands) with 128 electrodes covering the entire scalp. Signals were sampled at 512 Hz (filters: DC to 104 Hz, 3dB/octave slope).

EEG activity was analyzed using the Cartool software (Brunet et al., 2011). Stimulus-aligned and response-aligned (aligned to 100 ms before the vocal onset) epochs of 500 ms each (250 time-frames) were averaged across conditions. Each trial was visually inspected and epochs contaminated by eye blinking or other artefacts were excluded. ERPs were bandpass-filtered to 0.2-30 Hz and recalculated against the average reference. About 73 epochs was averaged for newly learnt items and 66 for well-known items.

4.4.Behavioral analyses

After rejection of errors, production latencies (i.e. Reaction Time RT hereafter) were quantified with a speech analysis software (Check vocal 2.2.6; (Protopapas, 2007)).

4.5.ERP analyses

4.5.1. Waveform analyses

Waveform analyses were carried out on evoked potential amplitudes by means of a cluster-based non-parametric analysis (Maris and Oostenveld, 2007) using the FieldTrip MATLAB toolbox (Oostenveld et al., 2011). This allowed to compare each time point and channel while correcting for multiple comparisons by taking into account spatial (four neighboring channels) and temporal adjacency (α set at .05).

Significant differences in map topographies between conditions were tested with a topographic analysis of variance called TANOVA consisting of a non-parametric randomization test based on the global map dissimilarity GMD (Brunet et al., 2011). Differences extending over at least 20 ms with a alpha criterion of 0.05 were retained.

4.5.2. Microstate analysis

The spatio-temporal segmentation obtained with the software Ragu (Koenig et al., 2011) allows summarizing ERP data into a limited number of quasi stable topographic map configurations or microstates (Lehmann and Skrandies, 1984), likely corresponding to specific underlying mental processes. This method is independent from the reference electrode (Michel et al., 2004, 2001) and not sensitive to pure amplitude modulations across conditions.

The optimal number of microstates that best explained the group-averaged datasets was determined using the following procedure: Each time randomly splitting the subjects into training and test datasets and testing between 1 and 20 microstates classes. Every microstate identification run used the traditional *k*-means cluster algorithm (5000 random initializations each). The number of microstates with the highest correlation between training and test datasets is retained as the optimal number of maps. Statistical validation was obtained via a

microstate fitting procedure during which each time point is labeled according to the map with which it best correlated spatially. Randomization procedures are applied such that for each participant, ERPs corresponding to the conditions being compared are randomly assigned to arbitrarily defined groups. ERPs in these different groups are averaged and the variables of interest are computed (here map duration). Details of this procedure can also be found in (Koenig et al., 2014).

5. Acknowledgments

We warmly thank Adrian Guggisberg and Pierre Nicolo for their contribution in the project. This research was supported by Swiss National Science Foundation grant no 105319_146113. Raphaël Fargier's research is supported by grants ANR-16-CONV-0002 (ILCB), ANR-11-LABX-0036 (BLRI) and the Excellence Initiative of Aix-Marseille University (A*MIDEX). The funding source was not involved in study design or in the collection, analysis and interpretation of the data.

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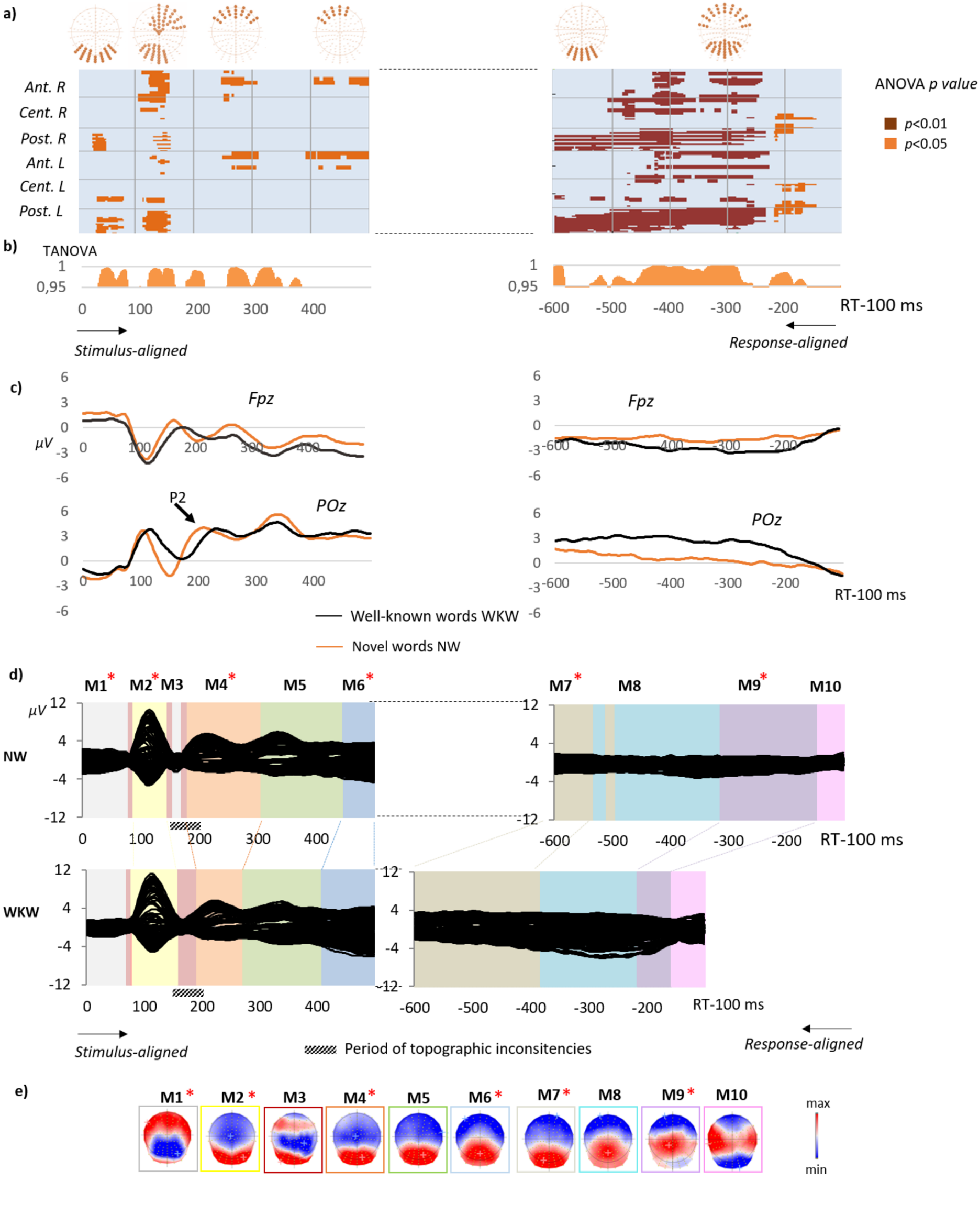
Figure captions:

Figure 1: (a) Significant differences (cluster-based non parametric p values) on ERP waveform amplitudes on each electrode (Y axis) and time point (X axis) between naming pictures corresponding to newly-acquired words and to well-known words. (b) Significant differences on GMD values thresholded at 0.05 (TANOVA). (c) Examples of group averaged ERP waveforms for novel words (solid orange line) and well-known words (solid black line) on anterior (Fpz) and posterior (POz) electrodes. The black arrow indicates the P2 component. (d) Grand-average ERPs (128 electrodes) for each condition from picture onset to 100 ms before the vocal onset and temporal distribution of the topographic patterns revealed by the spatio-temporal segmentation analysis. Stable electrophysiological configurations are color-coded. (e) Map templates for the ten stable topographies observed from picture onset to RT-100ms. Positive (red) and negative (blue) values are displayed as well as maximal and minimal scalp field potentials. * indicate significant differences on duration ($p < 0.05$) observed on any specific topographic pattern between novel words and well-known words.


a)
Ant. R
Cent. R
Post. R
Ant. L
Cent. L
Post. L
ANOVA p value
p<0.01
p<0.05
b)
TANOVA
1
0,95
0
100
200
300
400
Stimulus-aligned
-600
-500
-400
-300
-200
RT-100 ms
Response-aligned
c)
Fpz
μV
6
3
0
-3
-6
P2
POz
Well-known words WKW
Novel words NW
d)
M1*
M2*
M3
M4*
M5
M6*
M7*
M8
M9*
M10
μV
12
4
-4
-12
NW
WKW
Period of topographic inconsitencies
e)
max
min