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Semantic processing of highly repeated concepts presented in single-word trials: Electrophysiological and behavioral correlates

Louis Renoult [a,c], Mathieu B. Brodeur [a,d], J. Bruno Debruille [a,b,c,*]

[a] Douglas Mental Health University Institute, Montréal, Québec, Canada
[b] Department of Psychiatry, McGill University, Montréal, Québec, Canada
[c] Department of Neurology and Neurosurgery, McGill University, Montréal, Québec, Canada
[d] Department of Psychiatry and Behavioural Neurosciences, McMaster University, Hamilton, Ontario, Canada

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ABSTRACT

Repetition has often been associated with a reduction or a suppression of semantic effects. However, several studies have reported that semantic processing can still be effective for repeated target stimuli when the context, prime word or sentence frame, changes from trial to trial. This type of context-target designs allows to study semantic associations between repeated words. However, it is not optimal to study single concepts or categories and therefore structural aspects of semantic memory. Here, we tested whether semantic effects could be observed if single-word trials were used. Concrete and Abstract words were presented multiple times in two concrete-abstract classification experiments. In the first experiment, 6 words of each category were repeatedly presented. In the second experiment, only one word of each category was used. Results of both experiments showed significant effects of concreteness on reaction times and N400-like event-related potentials (ERPs), which were comparable to those reported in non-repeated conditions. In the second experiment, in which repetitions occurring in consecutive and non-consecutive trials were contrasted, N400-like effects were observed only for non-consecutive repetitions. These findings suggest that it could be possible to study the brain activity corresponding to individual concepts in experimental designs using single-word trials, provided that consecutive repetitions are avoided.

1. Introduction

Behavioral studies have generally shown that a prior encounter with a word facilitates its subsequent processing. This phenomenon is referred to as repetition priming. Examples include faster reaction times (RTs) to previously presented words or more accurate identification of a perceptually degraded version of the word (reviewed in Henson, 2003). However, word repetition is not always associated with facilitation. Two different sets of studies have shown that repetition can disrupt the processing of word meaning, resulting in a reduction or a suppression of semantic effects. These interactions between repetition and semantic processing illustrate the importance of novelty assessment systems in minimizing the probability that redundant information will be encoded in long-term memory (Tulving et al., 1996; Habib, 2001) and in biasing attentional processes towards changing information (MacKay, 1990).

A first set of studies has reported that massed repetitions of a word could result in the phenomenon of "semantic satiation" (Severance and Washburn, 1907). Semantic satiation is a temporary loss or attenuation of the meaning of a word that is experienced by subjects when this word is repeatedly produced or perceived. Evidence of satiation is classically indexed by a diminution of the RT difference between semantically related and unrelated pairs of words after massive repetition of the prime or context word. This effect has been observed in tasks requiring explicit access to the meaning of words, such as semantic categorization (Smith, 1984; Smith and Klein, 1990; Pynte, 1991; Balota and Black, 1997; Lewis and Ellis, 2000). In these studies, participants typically repeat a category word numerous times (e.g., fruit) and then perform a relatedness decision on a target word (e.g., apple). It has to be emphasized that semantic satiation tasks use immediate repetition, which is sometimes considered a "special case" as it can be mediated by sensory memory effects (Henson, 2003). As a consequence, immediately repeated stimuli would not require re-accessing semantic memory (Bentin and McCarthy, 1994). Accordingly, a few studies have shown that only one immediate repetition of prime words could suppress semantic priming effects (Neely et al., 1998; Pitzer and Dagenbach, 2001).

* Corresponding author at: Human Neurocognitive Science Lab, Douglas Mental Health University Institute, 6875 Boul. LaSalle, Verdun, Québec H4H 1R3, Canada. Tel.: +1 514 761 6131x3405; fax: +1 514 888 4099.
E-mail address: bruno.debruille@mcgill.ca (J.B. Debruille).

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A second set of studies has reported that even when two presentations of the same word are separated by other stimuli, semantic effects can be reduced or disappear. In these studies, target words instead of prime words were presented twice. The interaction between repetition and semantic processing was shown for semantic priming effects (Carroll and Kirsner, 1982; den Heyer and Benson, 1988; Hanze and Meyer, 1995) or concreteness effects (James, 1975; Kounios and Holcomb, 1994). In other words, repeated target words in these studies were no longer processed according to their semantic context or concreteness. However, other studies reported an additivity of semantic priming effects and repetition (den Heyer et al., 1985; Wilding, 1986; Durgunoglu, 1988) indicating that both priming and repetition speeded up RTs. den Heyer and Benson (1988) attempted to reconcile these findings by hypothesising that the interaction between repetition and semantic processing would only occur when the number of trials intervening between repetitions is relatively limited (i.e., between 0 and 7). These authors divided repetition effects into three different components corresponding to short (sensory), intermediate (lexico-semantic) and long-term (episodic) durations (see also Ratcliff et al., 1985). They then proposed that only the lexico-semantic component would interact with semantic priming. It is important to note that the second set of studies that we have just mentioned used lexical decision tasks, and thus tasks in which access to the meaning of words is not necessary. It is known that semantic effects, such as semantic priming (Maxfield, 1997), category (Devlin et al., 2002) or concreteness (Schwanenflugel, 1991), are greater when meaning retrieval is explicitly encouraged. The use of the lexical decision task in this second set of studies could thus have favoured the presence of interactions between repetition and semantic processing. In accordance with this interpretation, in Kounios and Holcomb study (1994), in which an explicit semantic task was also included (i.e., concrete-abstract classification), the difference in RTs between concrete and abstract words was eliminated by repetition in the lexical decision task but simply reduced in the explicit task.

One important difference between these two sets of studies has to be noted. Only in the second set was semantic processing evaluated for the words that were repeated, which, arguably, can be considered a more direct test of the interaction between semantic processing and repetition. In these studies, target words were repeated and RTs to these words were measured to evaluate effects of semantic congruity or concreteness. In contrast, in the first set of studies using semantic satiation designs, prime words were repeated and semantic processing of target words was evaluated. In any case, the fact that semantic effects tend to disappear with repetition resulted in an implicit consensus that the use of repetition should be avoided in semantic paradigms. This is unfortunate as using repeated stimuli would allow avoiding problems of category specificity and physical variance that are present when using large groups of words (Pulvermuller and Shtyrov, 2006). Moreover, this would allow the study of categories that include only few exemplars.

Electrophysiological studies of semantic processing have greatly complemented the above mentioned behavioral studies. The N400 event-related potential (ERP), a negative deflection which develops between 250 and 500 ms after the onset of a word, has consistently been associated with semantic processing (for a review see Kutas et al., 2006). Intracranial studies have described generators of the N400 in the anterior medial temporal lobe (AMTL) (Smith et al., 1986; Nobre and McCarthy, 1995; Grunwald et al., 1998), in the vicinity of the superior sulcus of the lateral temporal lobe (Halgren et al., 1994; Guillem et al., 1995; Elger et al., 1997) and in the posterior parietal cortex (Halgren et al., 1994; Guillem et al., 1995, 1999). The amplitude of N400 is modulated both by semantic manipulations and repetition. When it is immediate, only one repetition can result in a total suppression of N400, even with relatively important time delays between the two presentations (Chao et al., 1995; Kim et al., 2001). In contrast, for non-immediate repetition, N400 amplitude is simply reduced until a floor is reached, which can occur at the second or third presentation (Besson et al., 1992; Kounios and Holcomb, 1992; Young and Rugg, 1992; Kazmerski and Friedman, 1997; Van Strien et al., 2005). The amplitude of N400 is also modulated by semantic manipulations. It is decreased for primed or congruous words compared to unprimed or incongruous words in sentence (Kutas and Hillyard, 1980, 1984) or prime-target (Bentin et al., 1985) contexts. N400 amplitude is also larger for concrete words than for abstract words (Kounios and Holcomb, 1994; Holcomb et al., 1999; West and Holcomb, 2000). Within concrete words, different distributions of N400 amplitude on the scalp have been associated with words belonging to living and artifactual categories (Kiefer, 2001, 2005; Sim and Kiefer, 2005). These effects are typically found to be greater in tasks in which meaning has to be explicitly retrieved (Holcomb, 1988; Mitchell et al., 1991; West and Holcomb, 2000).

Paralleling the first set of behavioral studies described above, Kounios et al. (2000) showed that multiple repetition of prime words resulted in reduced N400 congruity effects. This was demonstrated in the visual and auditory modalities, with primes varying in letter case or pitch between presentations to prevent sensory adaptation. Another study failed to observe this reduction, and only reported a non significant diminution of the N400 effect of congruity at temporal sites (Frenck-Mestre et al., 1997). In this study, multiple repetitions of the prime words (i.e., 30) simply resulted in more positive ERPs for the target words than in the case of few repetitions (3). This effect had previously been described for repetition of target words (e.g., Besson et al., 1992).

Adding to the second set of behavioral studies, repetition of target words was shown to interact with N400 effects of semantic congruity (Besson et al., 1992; Mitchell et al., 1993), semantic category (Kiefer, 2005; Sim and Kiefer, 2005) and concreteness (Kounios and Holcomb, 1994). More specifically, these N400 effects were shown to be reduced or suppressed when stimuli were repeated. In contrast, several studies have found that when words in sentences are repeated in a context different from that of their initial presentation, effects of semantic congruity can still be observed on N400 (Besson and Kutas, 1993; Mitchell et al., 1993; Woodward et al., 1993). In two studies using prime-target word pairs, we have recently shown preserved effects of semantic congruity and category on RTs and N400 despite the use of very high rates of repetition (Debruille and Renoult, 2009; Renoult and Debruille, 2010). In Renoult and Debruille (2010), these effects were obtained with only two primes and two target words repeated throughout the experiment. The results of this study indicated that, rather than simply retrieving the response associated with each prime-target pair in previous trials (i.e., congruent or incongruent), participants still processed the words deeply after numerous repetitions. An analysis of the effect of semantic congruity across repetition levels showed that this effect did not interact with the level of repetition. Two important features of these studies could explain the preservation of semantic effects. First, repeated target words were presented at random with equal probability (0.5) so that the occurrence of one word or the other could not be predicted, which is somewhat similar to repeating final words in varying sentence contexts. Second, both studies used explicit semantic designs to maintain the semantic processing of repeated words.

These findings thus provided a strong support to the idea that the semantic processes indexed by the N400 and RTs could occur and be measured for highly repeated words. As previously mentioned, this could allow the study of more homogeneous and specific categories of words and notably categories that include only few typical exemplars. However, the resistance of semantic effects to repetition that was observed may be restrained to the experimental designs used, and thus to designs in which the context, sentence frame or prime word, is varied from trial to trial. These types of designs allow studying associations between individual repeated words and thus contextual aspects of semantic processing but are not optimal to study single concepts or categories and therefore structural aspects of semantic memory (Kounios, 1996). Effects of category (Kiefer, 2001) or concreteness (Kounios and Holcomb, 1994) are better studied by controlling for the influence of contextual factors, for instance by using trials that include only one word (Kounios, 1996). However, with highly repeated words, such tasks could theoretically be performed by simply retrieving the response associated to each word (e.g., concrete or abstract) in previous trials and thus by processing stimuli only for their physical characteristics. Accordingly, the processing requirements of an experimental design with single-word trials could be even less demanding than those required in our previous prime-target designs. In contrast, it is possible that the use of an explicit semantic task, such as a concrete/abstract decision, may maintain semantic processing of highly repeated words even in single-word designs. If this were the case, it could allow the investigation of the organization of semantic representations at a finer scale than usual, that is, at the scale of individual concepts. We chose to test this hypothesis for the effect of concreteness, as this effect is one of the best known correlates of the organization of conceptual knowledge. It is well described by behavioral (Paivio, 1991; Schwanenflugel, 1991) and ERP studies (Kounios and Holcomb, 1994; Holcomb et al., 1999; West and Holcomb, 2000; Zhang et al., 2006; Kanske and Kotz, 2007; Tolentino and Tokowicz, 2009; Tsai et al., 2009) and the demonstration of its resistance to repetition would complement findings obtained for the effects of semantic congruity and category.

Two concrete-abstract classification experiments were used to test whether semantic processing would still be effective in single-word trials using only a few highly repeated words. In both experiments, participants had to repeatedly categorize words as belonging to one or the other category. In the first experiment, six concrete and six abstract words were presented each twenty times to a first group of participants, but no word was repeated in consecutive trials. In the second experiment, only one word of each category was presented repeatedly to a second group of participants. In half of the trials, the same word was presented in consecutive trials and, in the other half, at least one presentation of the other word occurred between successive presentations. Importantly, in that second experiment, each subject was presented with a different pair of words to ensure that potential differences between concrete and abstract words would not be restrained to a particular pair of stimuli. This second experiment allowed testing the resistance of semantic effects in conditions in which the retrieval of the responses given in previous trials was maximally facilitated. In Experiment 1, the presence of 12 different words may indeed render such strategy more difficult. Even if these words were presented numerous times, the capacity of working memory is probably too small for 12 items (Luck and Vogel, 1997; Awh et al., 2007). This number and the use of a random mode of presentation could thus discourage participants from responding based on simple visual–motor associations.

We hypothesized that concreteness effects on RTs and N400 would be observed in both experiments but that they would be restricted to conditions in which repetitions occurred in non-consecutive trials, as suggested by the effect of immediate repetitions (Bentin and McCarthy, 1994). Independent component analysis (ICA) was used to compare the generators of the N400-like deflection of both experiments with those found in previous studies.

2. Methods: Experiment 1

2.1. Participants

15 native-French monolingual speakers (11 women) took part in the first experiment. All of them identified themselves as right-handed. They had normal or corrected to normal vision and no history of neurological or psychiatric disorders. They were recruited by newspaper advertisements among people aged between 18 and 30 years (mean: 22 ± 2.9) who had at least a college level of education. They signed an informed consent form accepted by the Douglas Institute Research and Ethics Board.

2.2. Task and procedure

Participants were seated comfortably in a dimly lit room in front of a computer screen placed 1 m from their eyes. Black words, written in Boston 15 font, were presented at the center of the screen in lower-case letters on a white background. In each trial, a word was displayed for 300 ms. Participants were instructed to rapidly and accurately press a button labeled "Concrete" to indicate that the stimulus was a concrete word, or to press another button labeled "Abstract" to indicate that the stimulus was an abstract word. The button used for each type of response was counterbalanced across participants. All participants were instructed to use their right index finger to respond (for both buttons). Fifteen-hundred milliseconds after the onset of each word, a blink instruction ('clignez des yeux') was displayed for one second to signal that it was acceptable to blink and move one's eyes. The next trial began after a time interval that randomly varied between 0.7 and 1.2 s.

Six concrete and six abstract French words were used. There were chosen for being typical members of their category and having similar psycholinguistic characteristics. The concrete words were (French is indicated in brackets): tree ('arbre'), chicken ('poulet'), horse ('cheval'), boat ('bateau'), bottle ('bouteille') and bedroom ('chambre'). The abstract words were: principle ('principe'), talent ('talent'), concept ('concept'), wisdom ('sagesse'), opinion ('opinion') and illusion ('illusion'). As indicated by Table 1, concrete and abstract words were matched in their number of letters, frequency of usage, bigram frequency and number of orthographic neighbors. On the other hand, they differed in imagery and concreteness.

Frequency of usage was evaluated with the Brulex database (Content et al., 1990), bigram frequency with the surface database (New et al., 2004), the number of orthographic neighbors with the Lexique 3.55 database (http://www.lexique.org/moteur/) and imagery with the 7 points rating scales of Desrochers and Thompson (2009). Concreteness was quoted by an independent group of 27 participants (mean age: 25; 15 women) who did not participate in the experiment. The results of this evaluation on a 1–7 scale were very similar to the imagery ratings of Desrochers and Thompson (2009) (see Table 1).

The experiment included 240 trials: 120 concrete and 120 abstract trials. Each of the twelve words was thus presented 20 times in the experiment. Concrete and abstract words were presented with equal probability in a pseudo-random order, avoiding repetition of the same word in consecutive trials.

2.3. Data acquisition

Accuracy and reaction time were recorded for each trial. The EEG was recorded with tin electrodes mounted in an elastic cap (Electrocap International) from 30 active points, all referenced to the right ear lobe. Twenty-eight of these points were placed according to the extended International 10–20 System (Electrode nomenclature committee, 1991). These electrode sites could be grouped in a sagittal subset, which comprised Fz, FCz, Cz, and Pz; a para-sagittal subset, including FP1/2, F3/4, FC3/4, C3/4, CP3/4, P3/4, and O1/2; and a lateral subset, including F7/8, FT7/8, T3/4, TP7/8, and T5/6. The remaining two active electrodes were placed below each eye in order to allow the monitoring of vertical eye movements by comparing their EEG signals to those derived from FP1 and FP2. The monitoring of horizontal eye movements was done by comparing F8 to F7 signals. The impedance was kept below 5 kΩ. The EEG was amplified 20.000 times by Contact Precision amplifiers. High and low-pass filter half-amplitude cut-offs were set at .01 and 100 Hz, respectively, with an additional 60 Hz electronic notch filter. Signals were then digitized on-line at a sampling rate of 256 Hz and stored along with stimulus and response codes for subsequent averaging using the Instep (version 4.3) software package.

EEG epochs contaminated by eye movements, excessive myogram, amplifier saturations or analog to digital clippings were removed offline by setting automatic rejection criteria. Trials for which analog to digital clipping exceeded a 100 ms

Table 1
Characteristics of the concrete and abstract words used in Experiment 1. Mean and standard deviations are reported for each characteristic.

	Concrete words	Abstract words
Number of letters	7 (±1.4)	7 (±0.8)
Frequency of usage (log)	3.8 (±0.5)	3.8 (±0.3)
Mean Bigram frequency (log)	3.7 (±0.3)	3.6 (±0.3)
Number of orthographic neighbors	1.8 (±1.8)	1.4 (±1.8)
Imagery	6.7 (±0.3)	2.7 (±0.5)
Rated concreteness	6.7 (±0.5)	2.4 (±1.4)

duration, and electrodes for which amplitude exceeded ± 100 μV were excluded from averaging. We then further ensured that the signals recorded by frontal electrodes were not contaminated by ocular activity. For vertical eye movements, this was done by comparing the activity recorded by FP1/2 channels to that recorded by the electrodes placed below each eye, subject by subject and condition by condition, looking for polarity inversions. Similarly, for horizontal eye movements, we compared F8 signal to F7 signal and looked for polarity inversions that could signal ocular activity. No subject had to be re-averaged after this inspection.

2.4. Data processing and measures

Mean reaction times for each condition were computed using only the correct responses and excluding the trials where participants took more than 2000 ms to respond. ERPs were computed by averaging the 1000 ms EEG epochs of these trials in each experimental condition, using a –200 to 0 ms baseline before word onset.

The negative peak obtained in the 200–500 ms time window will be referred to as the N400-like, as in previous studies (Debruille and Renoult, 2009; Renoult and Debruille, 2010). In addition to its amplitude, the amplitudes of two other ERPs were measured: the late positive complex (LPC) that was previously reported to be modulated by word concreteness or imageability (Nittono et al., 2002; West and Holcomb, 2000; Kanske and Kotz, 2007) and another negative ERP that was observed in the grand averages and peaked right after the N400-like deflection.

For measuring the N400-like, we computed the mean voltage respective to the baseline in a time window that was chosen with a mid-peak latency technique, also referred to as the fractional latency approach in the guidelines of Picton et al. (2000). This was done because the classic 300–500 ms time window cannot be chosen to measure the N400-like potential observed with high rates of repetition as this deflection was shown to peak earlier than the classic N400 and to be temporally less extended (Debruille and Renoult, 2009; Renoult and Debruille, 2010). Moreover, the mid-peak latency technique has the advantage of focusing on particular deflections, whereas focusing on specific effects may bias statistical analyses. The latency of the negative peak that appeared between 200 and 500 ms at Cz electrode on the grand average of concrete trials was first measured. This negative peak culminated around 330 ms after word onset, similar to that found by Debruille and Renoult (2009) and Renoult and Debruille (2010). We then measured the peak latency of the preceding P200. This latency was added to the latency of the N400-like and the sum was divided by 2. The result was used as the onset of the N400-like time window. Similarly, the peak latency of the N400-like was added to that of the succeeding LPC and the result was divided by 2 to obtain the offset of the N400-like time window. The time window obtained was 290–440 ms.

The grand average of concrete and abstract trials revealed the presence of another negative deflection that peaked right after the N400-like deflection and which was also modulated by concreteness. Because this negativity was only observed at frontal and central sites, it was considered that it could be an ERP component different from the N400-like. Observations of individual averages allowed confirming that this deflection was not restricted to a subset of participants as it could be observed non-ambiguously in 14 out of the 15 subjects. Similarly, contrasting the grand averages of the first half of the trials of the experiment to the second half showed that it was present in both cases and was thus not restricted to a subset of trials. A similar mid-latency technique as for the N400-like potential was used to measure this negativity. This deflection peaked at 460 ms after word onset at Cz on the grand average of concrete trials. We will thus refer to it as N460. The onset of the window of measure of the N460 corresponded to the offset of the N400-like time window (440 ms). The offset of the window was obtained by adding the value for the peak latency of the N460 to that of the succeeding LPC and by dividing the result by 2. The resulting time window was 440–500 ms. Despite the relative narrowness of this time window, it could be verified in individual subject averages that it captured a significant portion of the deflection in each subject.

Finally, the LPC was measured with the same time window as in West and Holcomb (2000), that is, from 550 to 800 ms after word onset. The grand average ERPs indeed showed that the onset of the late effect occurred right at the onset of the LPC (around 550 ms at Cz) and that it lasted until the end of the averaging epoch (800 ms). Note that in West and Holcomb (2000), this deflection was referred to as N700.

2.5. Statistical analyses

For analyzing behavioral data, we ran two repeated-measures ANOVAs with a multivariate approach. One was made for the numbers of errors (accuracy) and the other for mean RTs (excluding incorrect responses). Both had concreteness (concrete vs. abstract) as within-subjects factor.

For each time window of measures of the ERPs, 3 repeated-measures ANOVAs with multivariate approaches were performed with the same within-subject factors as the RT analysis plus the electrode factor: one ANOVA for the sagittal subset, one for the para-sagittal subset and one for the lateral subset of electrodes. For the para-sagittal and the lateral subsets, another within-subject factor, hemiscalp (right vs. left), was included. The Greenhouse and Geisser (1959) procedure was used to compensate for possible violations of the sphericity assumption associated with the electrode factor which had more than two levels. In this case, the original degrees of freedom are reported together with the epsilon (E) and the corrected probability level. For all post hoc comparisons, the Scheffé test (Scheffé, 1953) was used.

2.6. Independent component analysis

In an attempt to compare the ERP generators of the effects of concreteness of the present study with those found by previous studies, ERPs of individual participants for concrete and abstract words were submitted to an independent component analysis. ICA decomposes the unaveraged EEG (Jung et al., 2001) or the event-related potentials (Makeig et al., 1999; Dien et al., 2007) into a sum of sparsely activated independent components with fixed scalp maps and maximally independent time courses (Makeig et al., 1997). For biologically plausible components, these component maps have been shown to nearly fit the projection of a single equivalent current dipole, allowing hypotheses as to the localization of this dipole (Onton et al., 2006).

The ICA was conducted with EEGLAB 6.01b (Delorme and Makeig, 2004), a freely available open source toolbox (http://www.sccn.ucsd.edu/eeglab), running under Matlab 7.7 (The Mathworks). Individual subject ERPs of 1 second (−200 to 800 ms after word onset) from our 30 active electrodes were concatenated separately for concrete and abstract trials, yielding two different matrices of 30 × 3855 points (15 participants × 257 time points) that were submitted to the same ICA. We applied infomax ICA (Bell and Sejnowski, 1995) with the EEGLAB function *runica* (Delorme and Makeig, 2004). The PCA option of *runica* was used as a preprocessing step to reduce data dimensionality and prevent individual differences to influence the decomposition (Dien et al., 2007). 14 factors were retained as a prior PCA revealed that 7 factors accounted for 95% of variance in each condition.

We then used the *envtopo()* function of EEGLAB (Delorme and Makeig, 2004; Onton et al., 2006) to identify the independent components (ICs) that together accounted for at least 80% of the variance of the effect of concreteness (i.e., concrete – abstract) in each of the window of measures of ERPs, that is, that of the N400-like (290–440 ms after word onset), N460 (440–500 ms), and LPC (550–800 ms). The activity of each of these ICs in each time window was then submitted to a repeated-measures ANOVA with concreteness (concrete vs. abstract trials) as within-subject factor. Finally, source localization was computed for these ICs with DIPFIT2, an EEGLAB plug-in that performs component localization by fitting an equivalent current dipole model using a non-linear optimization technique (Scherg, 1990). ICs for which scalp maps indicated a left-right symmetric activity were fit using 2 dipoles constrained to be located symmetrically across the (corpus callosum) midline. The head model used for the analyses was the spherical model (BESA) that is co-registered with the average Montreal Neurological Institute (MNI) brain. Spherical dipole coordinates were converted to Talairach coordinates by DIPFIT using a non-linear transform of MNI to Talairach implemented in the Matlab function "mni2tal.m" (http://imaging.mrc-cbu.cam.ac.uk/imaging/MniTalairach). The brain structures where the dipoles were localized were identified using the Talairach atlas coordinates (Talairach and Tournoux, 1988). The location solution was restricted to the gray matter, within a search range of 3 mm.

3. Results: Experiment 1

3.1. Behavioral data

The analyses of mean reaction times showed that participants were significantly faster ($F_{1,14} = 8.5$, $p = .011$) at classifying concrete (711 ms ± 67) than abstract words (797 ms ± 95).

The analyses of errors revealed that participants, although very accurate, made more errors in classifying abstract (3% of the trials) than concrete words (1.3% of the trials). This difference was significant ($F_{1,14} = 6.27$, $p = .025$).

3.2. Electrophysiological data: Mean voltage analyses

3.2.1. N400-like time window

Statistical analyses of the mean voltage amplitudes of the N400-like ERP revealed a main effect of concreteness for all subsets of electrodes ($F_{1,14} = 8.2$, $p = .013$ for the sagittal; $F_{1,14} = 8.94$, $p = .009$ for the para-sagittal, and $F_{1,14} = 4.42$, $p = .054$ for the lateral subset) indicating that the N400-like deflection was greater for concrete than for abstract words (mean difference: −1.01-μV for the sagittal; −0.86-μV for the para-sagittal and −0.62-μV for the lateral subset; see Fig. 1). Concreteness interacted with the electrode factor at the lateral subset ($F_{4,56} = 6.77$, $E = 0.51$, $p = .004$). For this subset, a triple interaction between these two factors and the hemiscalp factor was also found ($F_{4,56} = 4.52$, $E = 0.51$, $p = .018$). Post hoc Scheffé tests showed that, at the lateral subset, the effect of concreteness was greater at anterior sites and greater over the right than over the left hemiscalp. This is illustrated by Fig. 2A, which

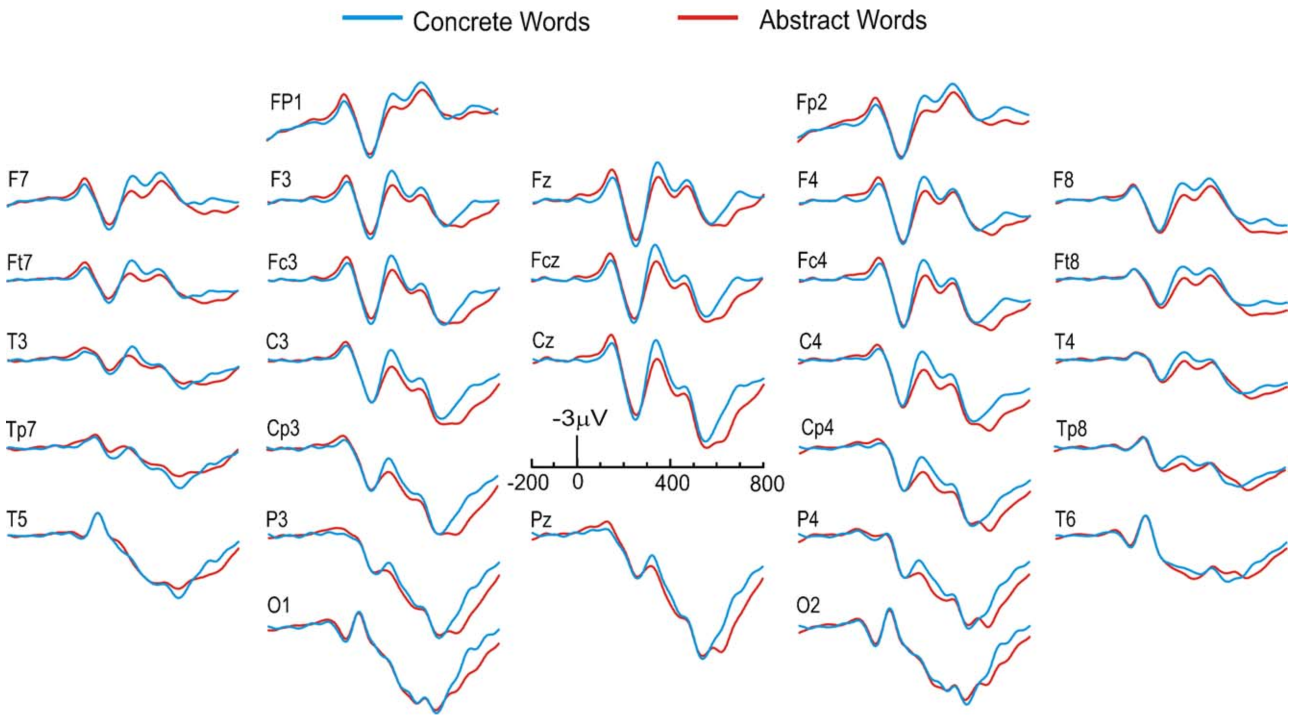

Fig. 1. Grand average ERPs ($n = 15$) for concrete (blue lines) and abstract words (red lines) in Experiment 1. Negativity is up. Each concreteness condition included 6 different words that were repeated 20 times. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

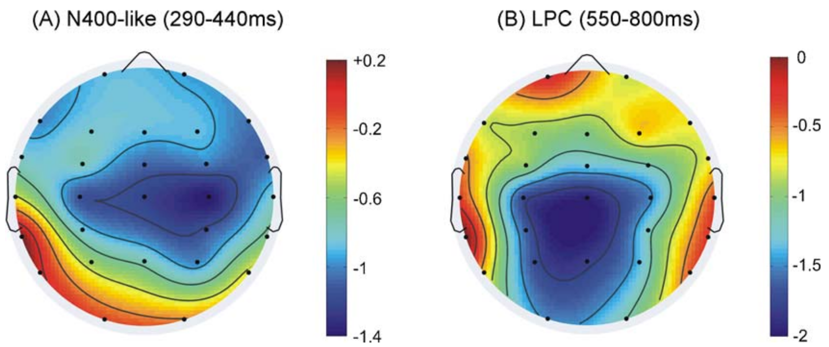

Fig. 2. Spline interpolated isovoltage maps of the effect of concreteness in Experiment 1. These maps were obtained by subtracting the mean voltages of the grand mean ERPs evoked by abstract words from those evoked by concrete words in the time windows of (A) the N400-like deflection (290–440 ms after word onset); (B) the LPC (550–800 ms).

shows the scalp voltage map that was obtained by subtracting mean voltages evoked by abstract words to those evoked by concrete words in the N400-like time window. At the lateral subset, the effect of concreteness was significant ($F \geq 8$; $p \leq .01$) at F8, F7, FT8, FT7, T4 and TP8.

3.2.2. N460 time window

Statistical analyses of the mean voltage amplitudes of the N460 deflection showed no main effect of concreteness. There was an interaction between this factor and the electrode factor at the lateral subset of electrodes ($F_{4,56} = 5.82$, $E = 0.46$, $p = .009$), indicating that N460 was more negative for concrete than for abstract words at frontal sites (see Fig. 1). However, post hoc Scheffé tests revealed that the effect of concreteness was never significant, except at F8 and F7 where it was just at significance level ($F_{1,14} = 4.59$, $p = .049$).

3.2.3. LPC time window

Statistical analyses of the mean voltage amplitudes of the LPC showed a main effect of concreteness at the sagittal ($F_{1,14} = 9.97$, $p = .006$) and the para-sagittal ($F_{1,14} = 9.84$, $p = .007$) subsets of electrodes. At these subsets, ERPs were more negative for concrete than abstract words (mean difference: -1.46 μV for the sagittal and -1.13 μV for the para-sagittal subset). This difference was more pronounced at centro-parietal sites, as indicated by the voltage map (see Fig. 2B). However, no interactions involving the electrode or hemiscalp factors were found.

3.3. Electrophysiological data: Independent component analysis

3.3.1. N400-like time window

Three independent components accounted for 85% of the variance (PVAF) of the effect of concreteness in the N400-like time window (see Fig. 3A). Note that because ICs are not spatially orthogonal, the variance accounted for by all components together does not equal the sum of the variance accounted by each component alone (Groppe et al., 2008).

IC4 had a right centro-parietal scalp distribution and was the greatest contributor to the effect of concreteness in the N400-like time window (PVAF: 66%). This IC made its maximum contribution 339 ms after stimulus onset. Its activity significantly differentiated concrete and abstract words ($F_{1,14} = 5.65$, $p = .033$). Dipole source

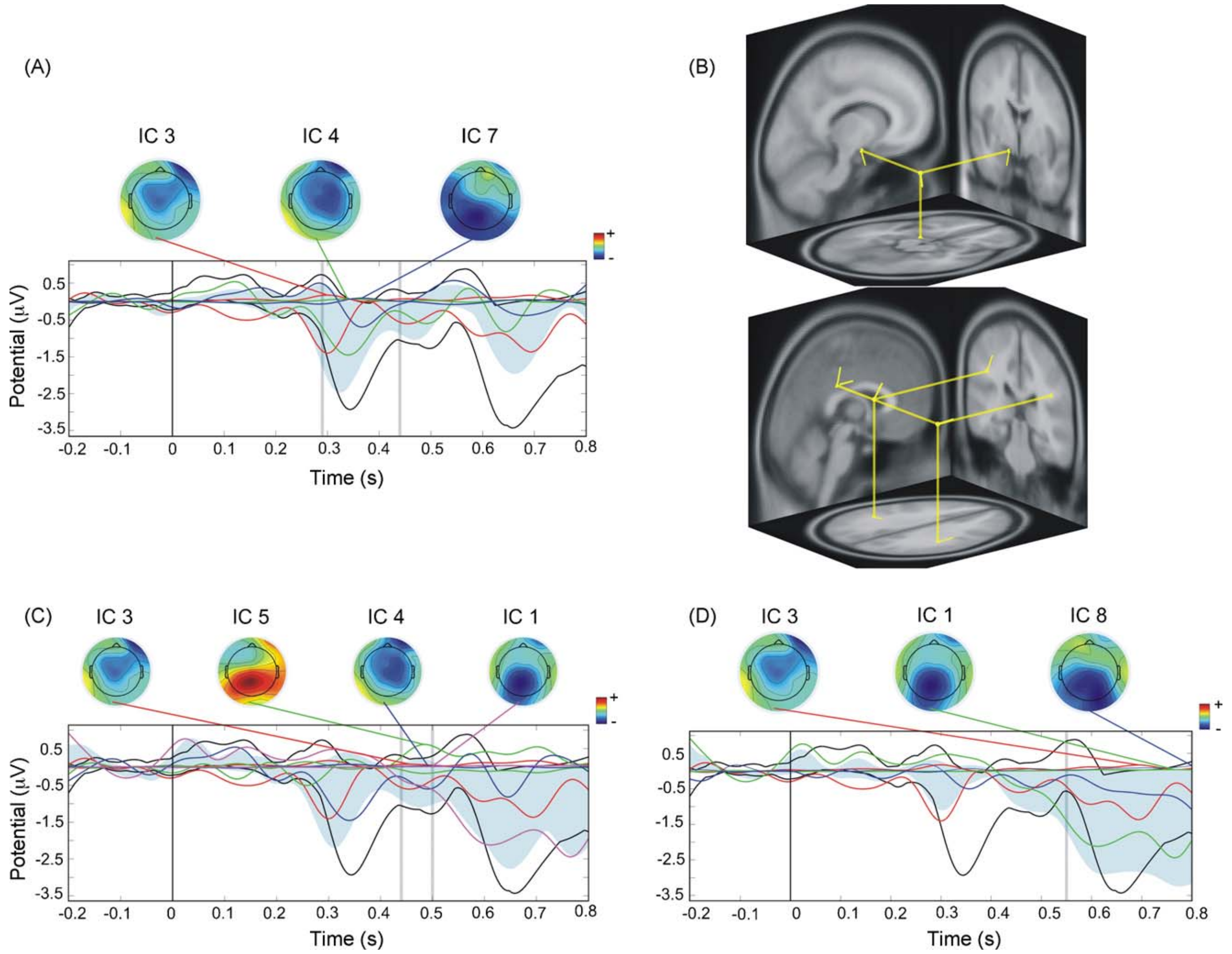

Fig. 3. Independent component contributions to the effects of concreteness in various time windows in Experiment 1. (A) N400-like time window. The vertical black line at time 0 indicates word onset. The thick black lines show the envelope, that is the most positive and negative values of the ERPs over all channels and at each time point. The blue traces show the envelopes of the contribution of the independent components (ICs) represented. Each IC scalp map is connected to its data envelope by a color line that points to the moment of peak contribution to the ERP (see Delorme and Makeig, 2004). (B) Equivalent current dipoles for IC4 (top) and IC3 (bottom). These two ICs were the greatest contributors to the effect of concreteness in the N400-like time window and accounted for 66% and 31% of the variance of the effect, respectively. (C) ICs contributions in the N460 time window. (D) LPC time window. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

modeling for this IC revealed that it was best modeled with a source in the left parahippocampal gyrus (see Fig. 3B), in the vicinity of Brodmann areas (BA) 34 and 28 (x: −12, y: −5, z: −13). The residual variance of the dipole model (RVDM) was 8%.

IC3 and IC7, made smaller contributions to the effect (respective PVAF of 31% and 15%) and did not significantly differentiate the two conditions. IC3 had a fronto-central scalp distribution and made its peak contribution to the effect 300 ms after word onset. This IC was best modeled by a bilateral generator in the inferior parietal lobe (see Fig. 3B), in the vicinity of BA40 (x: −41, y: −28, z: 29), with a RVDM of 8%. IC 7 had a left occipito-temporal scalp distribution and its peak contribution occurred 366 ms after word onset. It was best modeled by a source in the right posterior cingulate cortex (BA 23) (x: 6, y: −19, z: 29), with a RVDM of 9%.

3.3.2. N460 time window

Four ICs accounted for 80% of the concrete vs. abstract difference in the 460 time window (Fig. 3C). However, as found for mean voltage analyses, none of these ICs significantly differentiated concrete and abstract words.

The greatest contributor to the effect of concreteness in the N400-like time window, IC4, was also the greatest contributor in the N460 time window (PVAF: 48%). Its maximum contribution occurred 491 ms after stimulus onset. IC3, as also described for the N400-like time window, made a greater contribution to the concrete vs. abstract difference in the N460 time window (PVAF: 43%), its peak contribution occurring 456 ms after stimulus onset. IC1 had a bilateral occipito-temporal scalp distribution and made its greatest contribution 499 ms after word onset (PVAF: 30%). It was best modeled by a bilateral generator in the superior temporal gyrus (x: −41, y: −45, z: 24), with a RVDM of 4%. Finally, IC5 had a centro-parietal scalp distribution and a PVAF of −36%. Its maximum contribution occurred 484 ms after word onset. As shown by Fig. 3C, in contrast to the other ICs, this IC made a positive contribution to the concrete vs. abstract difference during the N460 time window while the mean subtraction ERP was negative. Its PVAF was thus negative, as subtracting the component would actually increase signal variance. This IC was best modeled by a bilateral generator in the middle frontal gyrus (BA 6) (x: −22, y: −12, z: 51), with a RVDM of 5%.

3.3.3. LPC time window

Three ICs accounted for 81% of the effect of concreteness in the LPC time window (Fig. 3D).

IC1, as described for the N460 time window, was by far the greatest contributor to the effect (PVAF = 67%). This IC made its maximum contribution 765 ms after word onset and it significantly differentiated the conditions ($F_{1,14}$ = 7.36, p = .017). IC3, as described for the two other windows of analysis, accounted for 36% of the effect in the LPC time window and made its maximum contribution 695 ms after word onset. Finally, IC8 projected maximally to occipito-parietal sites and accounted for 29% of the effect. Its maximum contribution occurred 800 ms after word onset. This IC was best modeled by a bilateral generator in the parahippocampal gyrus, in the vicinity of BA36 (x: 24, y: −28, z: −16), with a RVDM of 4%.

4. Discussion: Experiment 1

This first experiment was designed to test whether effects of concreteness could still be observed using repeated words presented in single-word trials. Six concrete and six abstract words were presented each twenty times while participants had to repeatedly categorize them as belonging to one or the other category. We reasoned that despite the theoretical possibility that participants may simply retrieve the response associated to each word in previous trials, the use of an explicit semantic design could maintain semantic processing.

Results showed significant effects of concreteness both for RTs and ERPs that mirrored the results of studies using designs with no repetition. As usually observed in these studies, participants were faster and more accurate at classifying concrete than abstract words (Paivio, 1991; Schwanenflugel, 1991). The amplitude of a N400-like ERP, similar to that observed by Debruille and Renoult (2009) and Renoult and Debruille (2010), was found to be greater for concrete than for abstract words. A late deflection that peaked approximately 700 ms after stimulus onset was also more negative for concrete words, as the N700 ERP described by West and Holcomb (2000). The independent component analysis (ICA) showed that the components that made the greatest contribution to the effect of concreteness in the N400-like time window had similar neural generators as that described for the N400 in non-repeated conditions. Taken together, these results suggest that semantic processes can remain active in explicit semantic designs, even for words that have been processed and categorized numerous times in single-word trials.

As found by previous N400 studies, the present effect of concreteness on the N400-like deflection was significant over midline and para-sagittal sites. Similar to some of these studies[1], this effect was also greater over anterior than posterior lateral sites (Kounios and Holcomb, 1994; Holcomb et al., 1999; Swaab et al., 2002), and slightly right lateralized (Kounios and Holcomb, 1994; see also Holcomb et al., 1999 for a similar trend). Other findings include a left lateralization of the effect (Zhang et al., 2006; Tolentino and Tokowicz, 2009) or no lateralization (West and Holcomb, 2000; Nittono et al., 2002; Swaab et al., 2002; Kanske and Kotz, 2007; Tsai et al., 2009). Variations in the lateralization of concreteness effects will be further considered in the general discussion.

The independent components that made the greatest contribution to the effect of concreteness in the N400-like time window were best fit by generators in the left parahippocampal gyrus, the inferior parietal lobe bilaterally and the right posterior cingulate cortex. A recent meta-analysis of Binder et al. (in press) showed that the inferior parietal lobe and the posterior cingulate cortex were two of the most commonly activated regions in fMRI studies contrasting concrete and abstract words. More generally, these two regions and the parahippocampal gyrus are among the main areas associated with semantic processing in these studies (Binder et al., in press; see also Martin, 2001).

The main generator found for the effect of concreteness in the N400-like time window was the one located in the left parahippocampal gyrus (BA28). Intracranial studies as well as high-density ERP recordings (Johnson and Hamm, 2000) have frequently described N400 generators in the anterior medial temporal lobe (Smith et al., 1986; Nobre and McCarthy, 1995; Grunwald et al., 1998), close to the collatereral sulcus which separates the parahippocampal gyrus from the fusiform gyrus. This region, which includes BA 28 as found in the present study, would have a critical role in accessing semantic information (Van Petten and Luka, 2006). BA 28 was also recently associated with semantic congruity effects in an fMRI study (Meyer et al., in press), using a task that was previously associated with N400 effects (Meyer et al., 2007). Finally, it was also the main generator of the N400 effect in repeated and non-repeated conditions in Debruille and Renoult (2009).

As mentioned, two other contributors to the N400 effect of concreteness were localized in the inferior parietal lobe bilaterally (BA40) and in the right posterior cingulate cortex. Inferior parietal generators have been described by several N400 studies (Nenov et al., 1991; Halgren et al., 1994; Guillem et al., 1995, 1999; Helenius et al., 1998; Renoult and Debruille, 2010) and lesions of these areas including the temporo-parietal junction are known to result in large N400 amplitude reductions (Hagoort et al., 1996; Swaab et al., 1997; Friederici et al., 1998). Inferior parietal regions have been associated with active maintenance of verbal information (reviewed in Smith et al., 1998). A generator in the posterior cingulate cortex was found to make a small contribution to the N400 effect of concreteness (15%). Although this brain region has consistently been found in fMRI studies of semantic processing and concreteness (Binder et al., in press), only few studies have described similar N400 generators (Halgren et al., 1994; Frishkoff et al., 2004). Several authors have proposed that the cingulate cortex would act as an interface between semantic and episodic memory systems (Binder et al., in press; Guillem et al., 1999).

The present ERP results were also characterized by a late effect, in the time window of the LPC, that peaked approximately 700 ms after stimulus onset as in West and Holcomb (2000) or in Nittono et al. (2002). The LPC was more negative for concrete than abstract words at sagittal and para-sagittal electrodes. This effect was found to have a centro-parietal distribution as in Nittono et al. (2002). Other authors (West and Holcomb, 2000; Kanske and Kotz, 2007) have reported a similar effect but with a frontal distribution. The ICA revealed that this contradiction could be due to possible interactions between a fronto-central component and centro-parietal components. In the present study, this fronto-central component was active before and during the LPC time window (550–800), but made its greatest contribution to the concrete vs. abstract difference (43% of the variance) between 440 and 500 ms after stimulus onset. This latter effect corresponded to a small but distinct negative deflection over frontal sites in the ERPs, peaking around 460 (N460). The fact that the N400-like deflection peaked earlier than it is usually observed for the N400 (see also Debruille and Renoult, 2009; Renoult and Debruille, 2010) perhaps allowed observing the influence of this component as a separate deflection in the ERPs. Observations of ERP figures of previous studies sometimes reveal the presence of a second bump during the N400 deflection, especially at right frontal sites (e.g., Kounios and Holcomb, 1994: experiment 2; West and Holcomb, 2000; Tolentino and Tokowicz, 2009). It is thus possible that depending on its timing of activation, a similar fronto-central component could have influenced the distribution of both N400 and LPC effects in other studies.

[1] In the following discussion, we include studies that manipulated concreteness as well as imageability (Nittono et al., 2002; Swaab et al., 2002) since these variables were shown to be highly correlated (r = .83 in Paivio et al., 1968).

Although each word was repeated 20 times in the present experiment, the use of 12 different words may have prevented participants to simply retrieve the associated response of previous trials from working memory. Several studies have shown that working memory capacity may be limited to about 4 items (Luck and Vogel, 1997; Awh et al., 2007). A second experiment was thus designed in which only one concrete and one abstract word were presented repeatedly throughout the experiment. This design allowed testing whether semantic processing would still be effective for repeated words presented in single-word trials in conditions in which retrieval of behavioral responses from previous trials was maximally facilitated. Each participant was presented with different words to ensure that significant effects of concreteness would not be due to a particular set of stimuli. Furthermore, we used a random mode of presentation and a large number of trials (i.e., 120 by condition) to compare the effects of repetition in consecutive and non-consecutive trials. We hypothesized that, as found for Experiment 1, the use of an explicit semantic design may maintain concreteness effects in these conditions, at least for repetition occurring in non-consecutive trials.

5. Methods: Experiment 2

5.1. Participants

12 native-French monolingual speakers (6 women) took part in the second experiment. All of them identified themselves as right-handed. They had normal or corrected to normal vision and no history of neurological or psychiatric disorders. They were recruited by newspaper advertisements among people aged between 18 and 30 years (mean: 25 ± 3.7) who had at least a college level of education. They signed an informed consent form accepted by the Douglas Institute Research and Ethics Board.

5.2. Task and procedure

In this experiment, a new set of 24 words was used. All parameters of word presentation were the same as in Experiment 1. The concrete words were (French is indicated in brackets): pillow (‘oreiller’), mouth (‘bouche’), chair (‘chaise’), rabbit (‘lapin’), doctor (‘docteur’), leopard (‘léopard’), dress (‘robe’), dog (‘chien’), table (‘table’), car (‘voiture’), garden (‘jardin’) and letter (‘lettre’). The abstract words were skill (‘habileté’), luck (‘chance’), value (‘valeur’), ideal (‘idéal’), quality (‘qualité’), will (‘volonté’), idea (‘idée’), rest (‘repos’), narrative (‘récit’), aspect (‘aspect’), agreement (‘accord’) and measure (‘mesure’).

As in Experiment 1, these words were chosen for being typical members of their category and having similar psycholinguistic characteristics. They were matched for their number of letters, frequency of usage, bigram frequency and number of orthographic neighbors, but they differed in imagery and concreteness (see Table 2). Concreteness was quoted by the same group of 27 participants as in Experiment 1 (mean age: 25; 15 women). These subjects did not participate in any of the experiments.

In Experiment 2, each participant was shown only one concrete and one abstract word throughout the experiment. Each subject saw a different pair of words. As in Experiment 1, there were 240 trials (120 concrete and 120 abstract trials). Each word was thus presented 120 times in the experiment. Concrete and abstract words were presented with equal probability in a pseudo-random order so that, in half of the trials (i.e., 60), the same word was repeated in consecutive trials and, in the other half, at least one presentation of the other word occurred between successive presentations. Note that consecutive repetitions are different from immediate repetitions as, in our case, successive presentations did not occur in the same trial and were separated by the blink instruction.

5.3. Data acquisition

All parameters of data acquisition were the same as in experiment 1, except that the EEG was sampled at 300 Hz instead of 256 Hz.

Table 2
Characteristics of the concrete and abstract words used in Experiment 2. Mean and standard deviations are reported for each characteristic.

	Concrete words	Abstract words
Number of letters	6 (±1.1)	6 (± 1.1)
Frequency of usage (log)	3.8 (±0.7)	4.1 (±0.4)
Mean Bigram frequency (log)	3.7 (±0.3)	3.4 (±0.5)
Number of orthographic neighbors	3.3 (±3.5)	2.9 (±3.1)
Imagery	6.1 (±0.9)	2.9 (±0.6)
Rated concreteness	6.6 (±0.3)	2.6 (±0.7)

5.4. Data processing and measures

Data processing was the same as in Experiment 1, except for the windows of measures of ERPs. Both the N400-like deflection and the LPC were found to peak earlier in Experiment 2. For the N400-like ERP, the latency of the negative peak that appeared between 200 and 500 ms at Cz electrode on the grand average of concrete trials was 315 ms after word onset. The window of measure of the N400-like deflection was determined with a mid-peak latency technique as in Experiment 1 and in our previous studies (Debruille and Renoult, 2009; Renoult and Debruille, 2010). This resulted in a window of 265–375 ms after word onset. The grand average ERPs did not reveal the presence of an intermediate negative deflection similar to that found in Experiment 1, which succeeded the N400-like deflection. The LPC deflection thus peaked earlier, that is about 430 ms after word onset at Cz. As in Experiment 1, the late effect was measured in a 250 ms time window that started at the peak of the LPC, that is from 430 to 680 ms after word onset.

5.5. Statistical analyses

The same analyses as in Experiment 1 were applied in Experiment 2, except that another within-subject factor, namely repetition type (consecutive vs. non-consecutive repetitions), was added.

5.6. Independent component analysis

The methodological details were the same as in Experiment 1, except for the size of the matrices that were submitted to ICA (due to the use of different sampling rates and number of participants) and the number of selected ICs. Individual subject ERPs of 1 second (−200 to 800 ms after word onset) from our 30 active electrodes were concatenated separately for concrete and abstract trials, yielding two different matrices of 30 × 3612 points (12 participants × 301 time points) that were submitted to the same ICA. We applied infomax ICA (Bell and Sejnowski, 1995) with the EEGLAB function *runica* (Delorme and Makeig, 2004). The PCA option of *runica* was used as a preprocessing step to reduce data dimensionality and prevent individual differences to influence the decomposition (Dien et al., 2007). 18 factors were retained as a prior PCA revealed that 9 factors accounted for 95% of variance of the effect of concreteness both in consecutive and non-consecutive repetitions.

We then used the *envtopo()* function of EEGLAB (Delorme and Makeig, 2004; Onton et al., 2006) to identify the independent components (ICs) that together accounted for at least 80% of the variance of the effect of concreteness (i.e., concrete-abstract) in each of the window of measures of ERPs, that is, that of the N400-like (265–375 ms after word onset), and the LPC (430–680 ms). The activity of each of these ICs in each time window was then submitted to a repeated-measures ANOVA with concreteness (concrete vs. abstract trials) and repetition type (consecutive vs. non-consecutive repetitions) as within-subject factors. Finally, source localization was computed for these ICs with DIPFIT2 as in Experiment 1.

6. Results: Experiment 2

6.1. Behavioral data

The analyses of errors revealed that participants were very accurate. The mean percentage of errors was 1.7% of trials. The number of errors did not vary with concreteness or repetition type.

The analyses of mean reaction times showed that participants were significantly faster ($F_{1,11} = 13.03$, $p = .005$) at classifying concrete (685 ms ± 71) than abstract words (716 ms ± 80). There was also a main effect of repetition type ($F_{1,11} = 6.33$, $p = .031$), illustrating that RTs were (unexpectedly) faster for non-consecutive (692 ms ± 71) than consecutive repetitions (710 ms ± 77). However, there was no significant interaction between concreteness and repetition type.

6.2. Electrophysiological data: Mean voltage analyses

6.2.1. N400-like time window

Statistical analyses of the mean voltage amplitudes of the N400-like ERP revealed a main effect of concreteness for all subsets of electrodes ($F_{1,11} = 6.72$, $p = .022$ for the sagittal; $F_{1,11} = 6.86$, $p = .021$ for the para-sagittal and $F_{1,11} = 8.62$ $p = .012$ for the lateral subset). There were also interactions between concreteness and repetition type for all subsets ($F_{1,11} = 5.77$, $p = .032$ for the sagittal; $F_{1,11} = 5.62$, $p = .034$ for the para-sagittal and $F_{1,11} = 5.86$ $p = .031$ for the lateral subset).

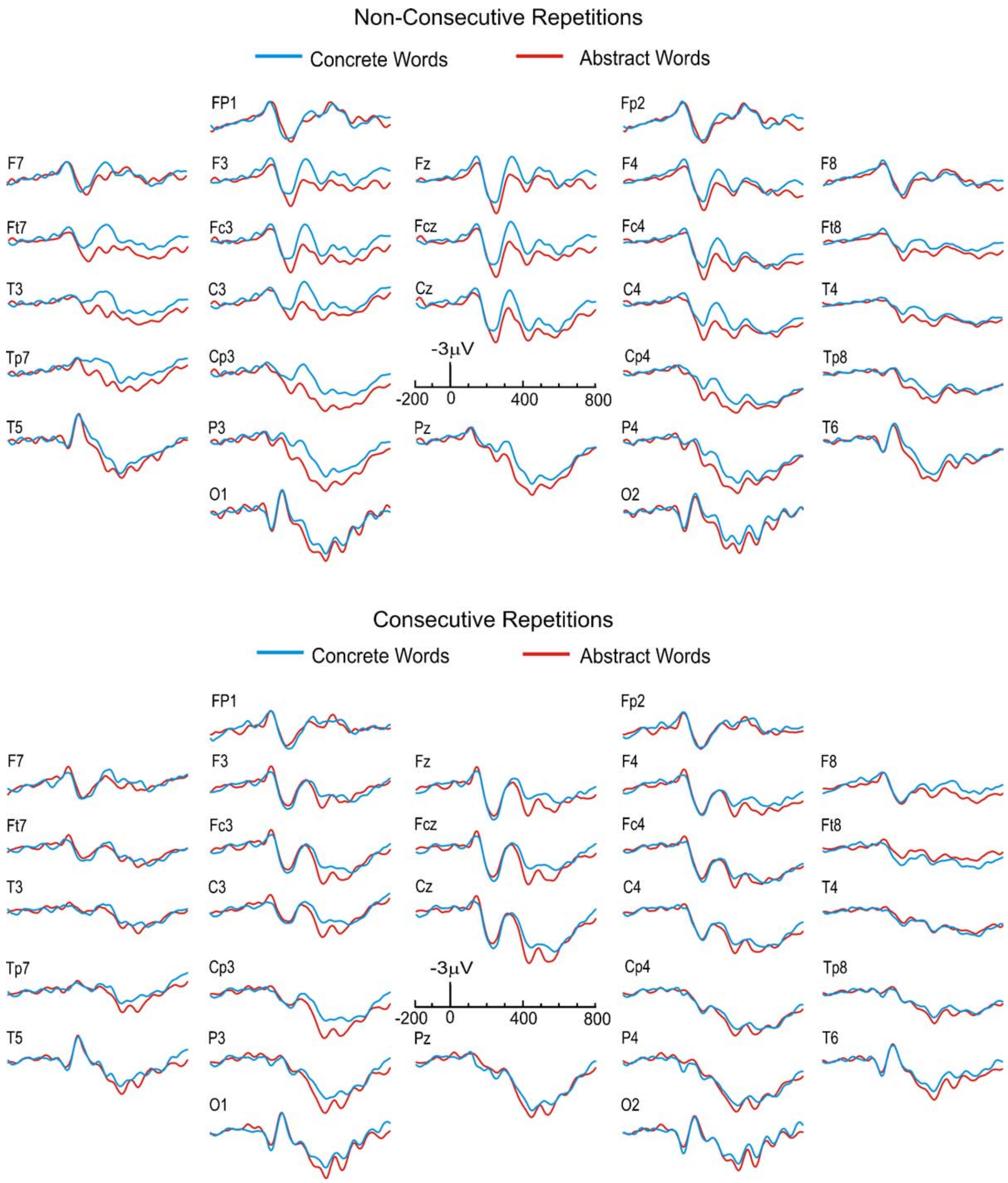

Fig. 4. Grand average ERPs (n = 12) for concrete (blue lines) and abstract words (red lines) in Experiment 2. Each concreteness category included only one word that was repeated 120 times, 60 times consecutively and 60 times non-consecutively. For the trials with non-consecutive repetitions (top), there was at least one presentation of the other word between successive presentations. For the trials with consecutive repetitions (bottom), only the blink instruction separated successive presentations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Follow-up analyses showed that the N400-like deflection was greater for concrete than for abstract words only for non-consecutive repetitions (mean difference: −1.88 μV, $F_{1,11}$ = 13.95, p = .003 for the sagittal; −1.59 μV, $F_{1,11}$ = 15.68, p = .002 for the para-sagittal and −1.44 μV, $F_{1,11}$ = 20.12 p = .001 for the lateral subset) (see Fig. 4). At the lateral subset, there was also an interaction between concreteness and laterality ($F_{1,11}$ = 8.39, p = .012). As indicated by the scalp voltage map computed from all trials with non-consecutive repetitions (Fig. 5A), concrete words were more negative than abstract words at all electrode sites but the effect was maximal over midline and parietal sites and, for the lateral subset, greater over the left than over the right hemiscalp. Post hoc Scheffé tests revealed that the effect was significant for both hemiscalps (mean difference: −1.87 μV, $F_{1,11}$ = 23.73, $p < .001$ for the left and −1.01 μV, $F_{1,11}$ = 9.99, p = .008 for the right hemiscalp).

6.2.2. LPC time window

Statistical analyses of the mean voltage amplitudes in the LPC time window revealed a main effect of concreteness for the sagittal ($F_{1,11}$ = 7.61, p = .016) and the para-sagittal subsets of electrodes ($F_{1,11}$ = 5.78, p = .032). For these subsets, the LPC was more negative for concrete than for abstract words (mean difference: −1.28 μV for the sagittal and −0.92 μV for the para-sagittal subset). At the lateral subset, the effect of concreteness was just at

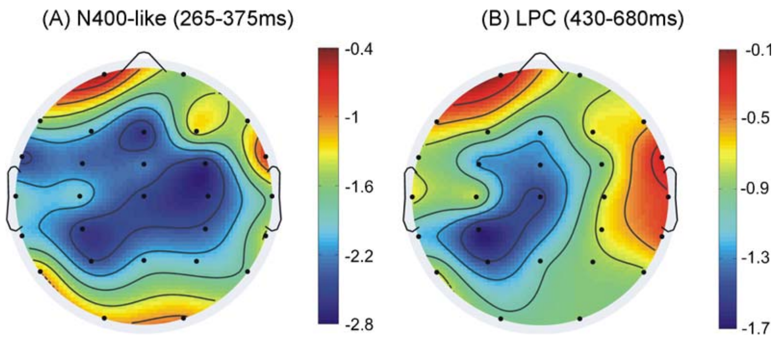

Fig. 5. Spline interpolated isovoltage maps of the effect of concreteness in Experiment 2. These maps were obtained by subtracting the mean voltages of the grand mean ERPs evoked by abstract words from those evoked by concrete words. (A) Time windows of the N400-like deflection (265–375 ms after word onset). This map was computed from all trials with non-consecutive repetitions, the only condition in which the effect of concreteness was significant. (B) LPC time window (430–680 ms). This map was computed from all trials of the Experiment, since no interaction involving repetition type was found.

significance level ($F_{1,11}$ = 4.63, p = .051). There was a main effect of repetition type for the sagittal ($F_{1,11}$ = 12.91, p = .003) and the para-sagittal ($F_{1,11}$ = 6.95, p = .021) subsets, indicating that the LPC was more positive for repetition occurring in consecutive than in non-consecutive trials (mean difference: 1.32 μV for the sagittal and 0.66 μV for the para-sagittal subset). However, no interaction was found between concreteness and repetition type. As indicated by the scalp voltage map computed from all trials of the Experiment (Fig. 5B), the effect of concreteness was maximal over centro-parietal sites and greater over left than right parietal sites. However, no significant interactions involving the electrode or hemiscalp factors were found.

6.3. *Electrophysiological data: Independent component analysis*

6.3.1. *N400-like time window*

Four ICs accounted for 81% of the variance (PVAF) of the effect of concreteness in the N400-like time window (see Fig. 6A).

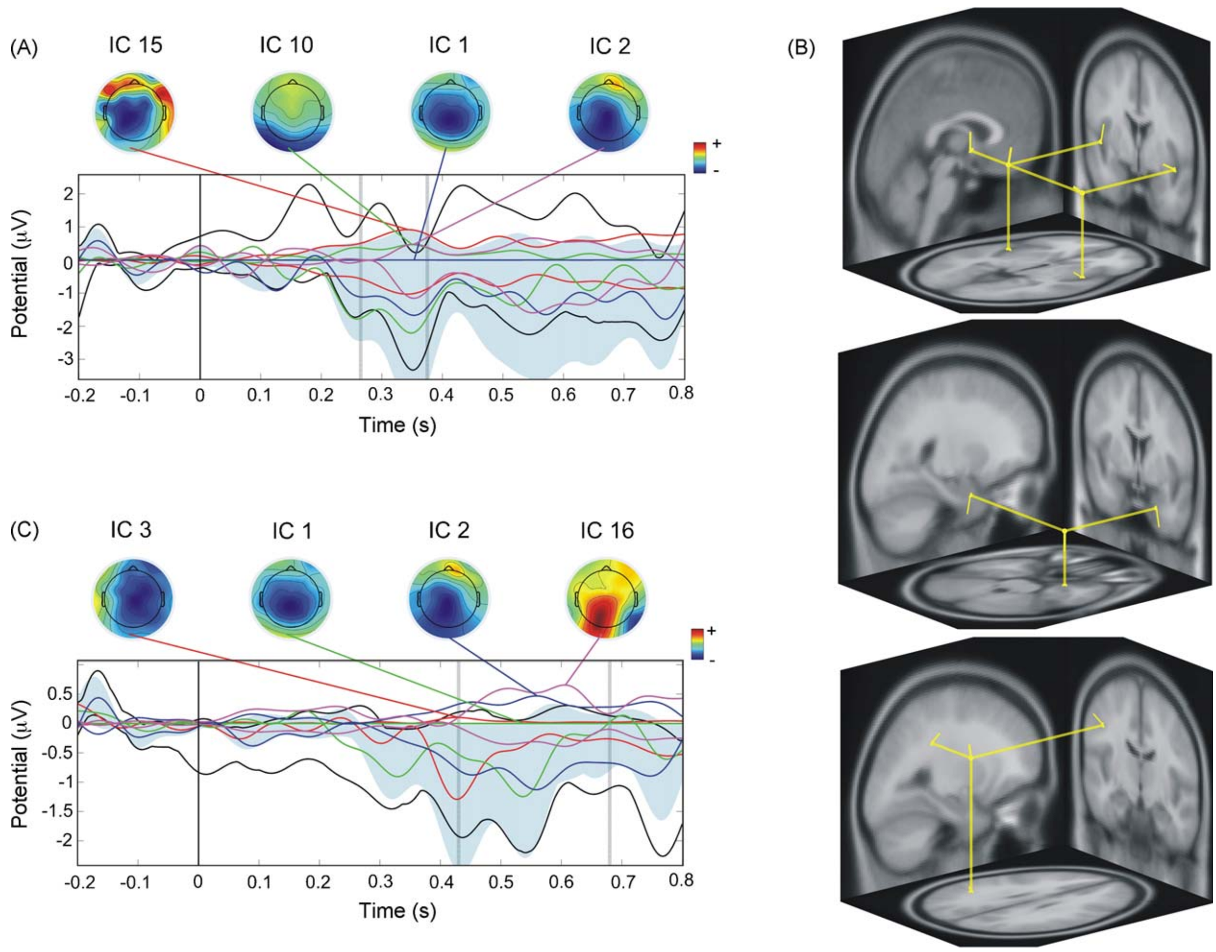

Fig. 6. Independent component contributions to the effect of concreteness in Experiment 1. (A) N400-like time window. ICs contribution is shown for trials with non-consecutive repetitions. (B) Equivalent current dipoles for IC1 (top), IC15 (middle) and IC2 (bottom). These ICs were the greatest contributors to the effect of concreteness in the N400-like time window and accounted for 65%, 42% and 37% of the variance of the effect, respectively. Note that because ICs are not spatially orthogonal, the variance accounted for by all components together does not equal the sum of the variance accounted by each component alone (C) ICs contributions in the LPC time window averaged across repetition types. For more details, see Fig. 3.

IC1 had a centro-posterior scalp distribution and was the greatest contributor to the effect (PVAF: 65%). This IC made its peak contribution 353 ms after word onset. Statistical analyses of its mean activity showed a main effect of concreteness ($F_{1,11}$ = 9.03, p = .01) but no interaction with repetition type. Dipole source modeling for this IC revealed that it was best modeled with a bilateral source in the depth of the superior temporal gyrus (x: −44, y = 0, z = −4), in the vicinity of BA22 and the insular cortex (see Fig. 6B). The residual variance of the dipole model (RVDM) was 4%.

IC15 had a centro-parietal scalp distribution and a PVAF of 42%. This IC made its peak contribution 343 ms after word onset. Statistical analyses of its mean activity showed a main effect of concreteness ($F_{1,11}$ = 10.83, p = .006) and an interaction between concreteness and repetition type ($F_{1,11}$ = 8.05, p = .014). Follow-up analyses showed that this IC differentiated concrete and abstract words only for non-consecutive repetitions ($F_{1,11}$ = 12.91, p = .003). It was best modeled by a source in the right parahippocampal gyrus, in the vicinity of BA28 and BA34 (x: 22, y = 0, z = −24), with a RVDM of 9% (Fig. 6B).

IC2 had a posterior midline scalp distribution and a PVAF of 37%. This IC contributed maximally to the concrete vs. abstract difference 355 ms after word onset but its activity did not significantly differentiate the two conditions. It was best modeled as a generator in the left inferior parietal cortex, in the vicinity of BA40 (x: −43, y = −34, z = 32), with a RVDM of 3% (Fig. 6B).

Finally, IC10 had an occipito-temporal scalp distribution and a PVAF of 30%. This IC made its maximum contribution 350 ms after word onset. Statistical analyses of its mean activity showed a main effect of concreteness ($F_{1,11}$ = 7.51, p = .017) and an interaction between concreteness and repetition type ($F_{1,11}$ = 7.09, p = .02). Follow-up analyses showed that this IC differentiated concrete and abstract words only for non-consecutive repetitions ($F_{1,11}$ = 12.18, p = .004). Dipole source modeling for this IC revealed that it was best fit with a bilateral source in the fusiform gyrus (BA19), close to the lingual gyrus (x: −25, y = −60, z = −7), with a RVDM of 2%.

6.3.2. LPC time window

Four ICs accounted for 82% of the effect of concreteness in the LPC time window (see Fig. 6C).

IC1, as described for the N400-like time window, accounted for 55% of the effect. Its maximum contribution occurred 537 ms after word onset. Statistical analyses of its mean activity showed a main effect of concreteness ($F_{1,11}$ = 5.78, p = .032) but no interaction with repetition type.

IC2, as also mentioned for the N400-like window, accounted for 54% of the difference between concrete and abstract words in the LPC time window. This IC contributed maximally to the difference 560 ms after word onset but its activity did not significantly differentiate the two conditions.

IC3 had a right fronto-central scalp distribution and accounted for 37% of the effect. Its maximum contribution occurred 430 ms after word onset. Statistical analyses of its mean activity showed no main effect of concreteness but an interaction between concreteness and repetition type ($F_{1,11}$ = 4.94, p = .041). Follow-up analyses showed that this IC differentiated concrete and abstract words only for non-consecutive repetitions ($F_{1,11}$ = 4.92, p = .044). It was best fit by a generator in the left superior frontal gyrus, in the vicinity of BA9 (x: −12, y = 59, z = 36), with a RVDM of 6%

IC16 had an occipito parietal scalp distribution and a PVAF of −30%. This IC made a positive contribution to the effect of concreteness while the mean subtraction ERP was negative (peak contribution 607 ms after word onset). Statistical analyses of its mean activity showed a main effect of concreteness ($F_{1,11}$ = 6.31, p = .026) but no interaction with repetition type. This IC was best modeled by a bilateral generator in the superior temporal gyrus, in the vicinity of BA42 (x: −69, y = −10, z = 10), with a RVDM of 7%.

7. Discussion Experiment 2

This second experiment was designed to test the resistance of concreteness effects to repetition in conditions in which the retrieval of the response given in previous trials was maximally facilitated. Only one concrete and one abstract word were repeatedly presented throughout the experiment to a second group of participants. Results showed that participants still deeply processed the words and took longer to categorize abstract than concrete words. As in Experiment 1, the effect of concreteness on the N400-like ERP was significant for all subsets of electrodes but only when at least one presentation of the other word occurred between successive presentations (i.e., in non-consecutive repetitions). As in our first experiment, concreteness also modulated the LPC at sagittal and para-sagittal subsets of electrodes. This effect did not interact with repetition type. The independent component analysis showed that the neural generators of the effect of concreteness were very similar to those of Experiment 1 and to those of studies using designs with no repetition.

The effect of concreteness on the N400-like ERP was maximal at midline and parietal sites. It was also greater over left lateral sites as found by Zhang et al. (2006) and Tolentino and Tokowicz (2009) (see below and general discussion). Crucially, these N400-like effects were only significant when repetitions occurred in non-consecutive trials. As previously mentioned, repetition in consecutive trials is different from immediate repetition, that typically occurs in the same trial. Here consecutive repetitions were separated by a blink instruction. However, as in designs using immediate repetitions (e.g., Bentin and McCarthy, 1994), repetition in consecutive trials resulted in a suppression of semantic effects. Importantly, this suppression may be specific to experimental designs using single-word trials. Indeed, in Renoult and Debruille study (2010), in which two prime and two target words were repeatedly presented in a semantic categorization task, it could be verified that the effects of semantic congruity were identical for repetitions occurring in consecutive and non-consecutive trials. In such prime-target designs, it thus seems that the onset of the prime may reset categorization processes.

As in Experiment 1, the present results were also characterized by a late effect in the time window of the LPC. This effect, which was again maximal at parietal sites, consisted in a more negative LPC for concrete than abstract words. The LPC was also found to be more positive for consecutive than consecutive repetitions, but repetition type did not interact with the effect of concreteness (see below for further discussion).

The independent components (ICs) that made the greatest contributions to the effect of concreteness in the N400-like window were best fit by generators in the superior temporal gyrus bilaterally (BA22), the right parahippocampal gyrus (BA28) and the left inferior parietal cortex (BA40). These two last generators were also the greatest contributors in Experiment 1, except that the parahippocampal source was found in the left hemisphere. Interestingly, mean voltage analyses of N400 effects showed a mirrored pattern with the effect of concreteness being maximal over the right hemisphere in Experiment 1 and over the left in Experiment 2. A generator in the superior temporal gyrus (STG) was also found in our first experiment, but it made its maximum contribution in the time window of the LPC. In both experiments, this generator and the inferior parietal source were the main contributors of the effect of concreteness in the LPC time window. Recently, Groppe (2007) showed that the N400 and the LPC in language tasks shared similar ICs, notably midline central components as found in the present experiment. A large number of studies, using various localization techniques, have described N400 generators in the vicinity of the auditory cortex, that is in the STG (Helenius et al., 1998, 2002; Halgren et al., 2002; D'Arcy et al., 2004; Matsumoto et al., 2005; Renoult and Debruille, 2010) or in the superior temporal sulcus (Halgren et al., 1994; Guillem et al., 1995; Elger et al., 1997; Simos et al., 1997; Halgren et al., 2002). Other studies have shown that the LPC or P600 in language tasks also had generators in the STG (Ishiwatari et al., 2002; Friederici et al., 2003; Service et al., 2007). Although little studied in this context, the LPC is often found to be modulated by the same variables as the N400, such as concreteness (Kanske and Kotz, 2007), semantic category (Kiefer, 2005) or semantic congruity (Mitchell et al., 1993).

One difference between N400 and LPC modulations in the present experiment was that LPC, as found for RTs, was not modulated by repetition type. The effect of concreteness on LPC was thus similar in consecutive and non-consecutive repetitions. Statistical analyses of ICs activity showed that the main common generator of N400 and LPC, localized in the STG, was indeed not modulated by repetition type. Other N400 generators, however, were found to be modulated by concreteness only for non-consecutive repetitions. These results are thus compatible with the existence of common generators for N400 and LPC, with similar functional correlates, as well as specific generators with distinct functional correlates.

Taken together, the results of this experiment both replicate and extend the results of Experiment 1. First, as a limited number of stimuli was used in the first experiment, the replication of these results with another set of 24 words demonstrated that these results were not restricted to a particular choice of stimuli. Second, as each subject was presented with only one concrete and one abstract word throughout the experiment, these results indicate that semantic processing can still be effective in conditions in which the retrieval of behavioral responses given in previous trials would have been straightforward and theoretically sufficient.

8. General discussion

The present study aimed to test if semantic processing would remain effective for highly repeated words presented in single-word trials. Two experiments in which participants had to repeatedly categorize words as being concrete or abstract were presented. It was hypothesized that the use of an explicit semantic design would maintain semantic processing for these highly repeated words. Alternatively, participants could have retrieved the response given in previous trials from working memory and simply performed visual–motor associations. This was certainly possible in Experiment 2, in which only one concrete and one abstract word were presented repeatedly. Results of both experiments showed significant effects of concreteness on reaction times and N400-like potentials, except in conditions in which repetitions occurred in consecutive trials. Concreteness also modulated the LPC independently of repetition type. Behavioral as well as electrophysiological results of both experiments thus indicate that the structure of semantic representations may be investigated at the scale of individual concept in paradigms in which consecutive repetitions are avoided.

In both experiments, word stimuli were matched for their number of letters, frequency of usage, mean bigram frequency and orthographic neighborhood. In Experiment 1, all participants were presented with the same abstract and concrete words while in Experiment 2, all participants saw a different pair of words. This allowed verifying that the effects observed were not due to the use of a specific set of words. One variable that was not controlled for in the present study and has been the subject of increasing interest (e.g., Adorni and Proverbio, 2009) is the age of acquisition (AoA) of concrete and abstract words. As observed by Schwanenflugel (1991), until at least early adolescence, most acquired nouns are concrete nouns. Although we did not find French norms that included all the stimuli of the present study, the concrete words used, as typical members of their category, clearly had an earlier AoA than our set of abstract words. However, this should only constitute a potential confound for RT analyses. Words with late AoA or abstract words are associated with longer RTs than early acquired or concrete words (Gilhooly and Gilhooly, 1979). In contrast, the few ERP studies on the influence of AoA suggest that it results in opposing modulations of the N400 compared to concreteness manipulations (Cuetos et al., 2009; Adorni and Proverbio, 2009; see also Tainturier et al., 2005 for a similar but later effect). Words with late AoA are associated to larger N400 amplitudes compared to those with early AoA, whereas abstract words evoke N400 of smaller amplitudes than concrete words. Therefore, concreteness effects on N400 amplitude should be attenuated rather than increased by associated variations in AoA.

The distribution of N400-like effects in both experiments were maximal at centro-parietal sites. However, at lateral sites, they differed in that the effects were maximal over the right hemiscalp in Experiment 1 and over the left in Experiment 2. This difference was mirrored by the results of dipole source analysis which revealed a left parahippocampal generator in the first experiment and a right parahippocampal source in the second. This variation in lateralization is representative of the ERP literature in which right lateralization (Kounios and Holcomb, 1994; Holcomb et al., 1999), left lateralization (Zhang et al., 2006; Tolentino and Tokowicz, 2009) or no lateralization (West and Holcomb, 2000; Nittono et al., 2002; Swaab et al., 2002; Kanske and Kotz, 2007; Tsai et al., 2009) have been described. These various findings are also reminiscent of the findings of fMRI studies. A subset of these studies have reported that a network of brain regions in the left hemisphere was responsible for the processing of abstract words while concrete words were bilaterally represented (Binder et al., 2005; Sabsevitz et al., 2005). These observations were taken as evidence for the dual coding theory (reviewed in Paivio, 1991). According to this theory, all words would activate verbal representations, for which the left hemisphere is generally more specialized, but only concrete words would activate image-based representations, located in both hemispheres. However, other fMRI studies have reported a somewhat inverted laterality of concreteness effects, with greater activity in the right hemisphere for abstract words (Kiehl et al., 1999), or a bilateral representation of these words (Grossman et al., 2002).

More generally, the heterogeneity in the distribution of concreteness effects described in the literature is unlikely to be simply due to variations in tasks parameters. The heterogeneity of the categories themselves is probably at stake. For concrete words, a large literature has now demonstrated that knowledge about living and non-living stimuli has distinct neural representations (reviewed in Martin, 2001). Dissociations have also been reported inside these categories, with for example different neural representations of plants and animals (Capitani et al., 2009). Comparatively, abstract concepts have been much less studied (Crutch and Warrington, 2005), even if dissociations have also been described (Setti and Caramelli, 2005). Taken together, it is thus likely that important variations in the neural correlates identified for concrete and abstract items can be due to the use of different sub-categories in different studies. The present findings of the persistence of concreteness effects with high rates of repetition, along with similar observations for other semantic effects (Debruille and Renoult, 2009; Renoult and Debruille, 2010), should allow studying and comparing more specific categories. For instance, in Renoult and Debruille (2010), only two typical exemplars were used as target words throughout the whole experiment. Crucially, the fact that the present results were obtained for single-word trials and not for prime-target word pairs, as in our previous studies, demonstrates that this new type of semantic paradigms should not be restricted to the study of contextual associations between categories. These findings constitute evidence that the structure of semantic memory could be investigated for single repeated words and thus potentially at the scale of individual concepts. Interestingly, a repetition priming study by Heit et al. (1988) reported that the response of at least some N400 generators could differentiate individual repeated words. While recording single neurons in humans intracranially, they showed that cells in the medial temporal lobe, including the hippocampus and parahippocampal gyrus, fired preferentially for the presentation of one particular word from a set of 10 different words. This selectivity was maximally expressed in the time window of the N400. The response of these cells was initially reduced by repetition but it was still increased for the preferred stimulus compared to the others after 9 repetitions. This study did not include any measure of conceptual processing, preventing to reach definitive conclusion about the semantic nature of this activity. However, considered with the present findings, where a similar N400 generator in the parahippocampal gyrus was found to be modulated by concreteness of highly repeated words, these results indicate that at least some N400 generators could be modulated by the semantic processing of individual repeated words.

In conclusion, despite the theoretical possibility that participants could have simply retrieved the response associated to each word in previous trials, our results demonstrated that semantic processing was still effective for highly repeated concepts presented in single-word trials in two concrete/abstract decision experiments. The use of similar experimental designs may allow investigating the structural aspects of semantic memory at the level of individual concepts, provided that consecutive repetitions are avoided.

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