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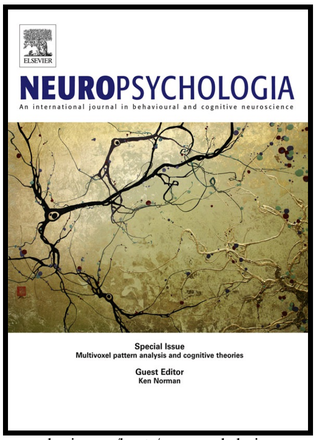

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PII: S0028-3932(18)30301-4
DOI: https://doi.org/10.1016/j.neuropsychologia.2018.07.001
Reference: NSY6837

To appear in: *Neuropsychologia*

Received date: 17 December 2017
Revised date: 22 June 2018
Accepted date: 2 July 2018

Cite this article as: Laura Kaczer, Luz Bavassi, Agustín Petroni, Rodrigo S. Fernández, Julieta Laurino, Sofía Degiorgi, Eithan Hochman, Cecilia Forcato and María E. Pedreira, Contrasting dynamics of memory consolidation for novel word forms and meanings revealed by behavioral and neurophysiological markers, *Neuropsychologia,* https://doi.org/10.1016/j.neuropsychologia.2018.07.001

Contrasting dynamics of memory consolidation for novel word forms and meanings revealed by behavioral and neurophysiological markers

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Abstract

Learning novel words is a challenging process for our memory systems; we must be able to recall new word forms and meanings in order to communicate. However, the dynamics of the word memory formation is still unclear. Here, we addressed the temporal profile of two key cognitive markers of memory consolidation in the domain of word learning: *i*) the susceptibility of recently learned novel words to memory interference; *ii*) their lexical integration using a semantic judgment task while recording the ERPs responses. Young adults acquired a set of novel picture-label-meaning associations. In a first experiment, we performed a temporal gradient of retroactive interference (5min, 30 min, 4h and 24h) and evaluated the memory retention 48h after learning. In a second experiment, we studied the dynamics of the integration of these novel words, by measuring theirN400 modulation when preceded by semantically related words, at 30 min or 48 h after learning. Our results showed that the word-form memory was affected by the interference treatment when it was presented 5 min after learning, but not at later times. On the other hand, only 48h after learning it was possible to observe a neurophysiological index of semantic-priming (reduced N400 response). These results point to the existence of two contrasting processes that help to build the memory for word forms and meanings. A rapid mechanism would enable word learning while mitigating forgetting, while a slow consolidation would allow the novel meanings to be integrated into previous semantic networks.

Keywords: Word learning; memory consolidation; interference; N400; semantic memory

1. Introduction

Humans are phenomenally good at learning words. By early adulthood, first language speakers will know at least 20,000 base words plus their morphologically complex forms, and some estimates suggest a far higher figure (Gaskell & Ellis, 2009). Besides, we constantly enrich our mental lexicons as our environment presents us with neologisms, loanwords, or specialist terminology. Remembering these words is just as important as learning them; we must be able to recognize and recall recently learned words in order to communicate (Wojcik, 2013). An intriguing question is how these new words come to achieve their status as familiar and meaningful units and what cognitive changes occur throughout this process.Considering that a fully specified lexical entry involves episodic and semantic traits, it is possible to conceive that word memory formation has distinctive properties. This work will focus on the temporal constraints of memory formation after word learning, dissecting the word form and the word meaning integration in the mental lexicon.While most word learning research has taught participants new labels for familiar concepts, emulating second language learning (e.g., Breitenstein et al., 2007; Mestres-Missé et al., 2007), our study simulates word learning in the first language, where a new word is usually associated with a new concept (e.g. Cornelissen et al., 2004; Takashima et al., 2014).

How long does it take for a new word to become a part of a mental lexicon?A predominant view is that novel words can be swiftly acquired (Salasoo, Shiffrin, & Feustel, 1985; Whittlesea & Cantwell, 1987)—a process dubbed “fast mapping” by some authors (Carey, 2010; Markson & Bloom, 1997; Spiegel & Halberda, 2011). This view was originally proposed based on the rapid vocabulary growth found in children, but later support was also found in adults (Coutanche & Thompson-Schill, 2014; Halberda, 2006; Trueswell, Medina, Hafri, & Gleitman, 2013). Electrophysiological markersof word processing (Borovsky, Kutas, & Elman, 2010; Mestres-Missé et al., 2007) as well as indexes of cortical activation (Shytrov et al., 2010) have been shown to emerge quickly after learning. However, the idea of the acquisition being seemingly fast is balanced with the proposal that the integration of newly-acquired words requires a sleep-dependent time period after learning, generally referred as consolidation (e.g Gaskell &Dumay, 2003; Tamminen & Gaskell, 2008). According to this view, it is only once consolidated into neocortical representations that newly learned words should be recognized quickly and efficiently, and be able to compete with existing words, i.e., they become ‘lexicalized’(Davis, Di Betta, Macdonald, & Gaskell, 2009; Tamminen, Davis, Merkx, & Rastle, 2012). These two different accounts of the word learning dynamics are usually combined under the framework of the complementary learning systems (CLS). This model proposes that learned words are first rapidly encoded (by the hippocampus), and then gradually integrated into long-term memory networks in the neocortex(McClelland, McNaughton, & O’Reilly, 1995).Thus, a slow process of offline memory consolidation would be required for new words to be integrated with existing lexical items (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010).

In spite of the above distinction, several studies have reported properties of word integration without a long-term consolidation period.Kapnoula, Gupta, Packard, and McMurray (2015) found evidence for lexical integration o0f newly learned word-forms immediately after training (using eye-movements to directly assess activation of the inhibited target word). Fernandes, Kolinsky, and Ventura (2009) found evidence for lexical integration of word-forms in the context of artificial language learning immediately after training. Besides, Kaczer et al., (2015) found morphological priming for recently learned compound words. In the same vein, De Diego Balaguer et al. (2007) found evidence for ERP changes in a word and rule learning experiment after only a four-minute exposure to an artificial language. Regarding the integration of words with associated meanings, a study of Borovsky, Kutas and Elman (2010) showed semantic priming for novel words (using an N400 paradigm) immediately after training. In addition, Mestres-Missé et al. (2007) showed that new words produced ERP signatures similar to real L1 words after only three exposures when the meaning of the new word could be inferred from the context.

From this mixed pattern of results, the temporal dynamics of the word memory formation is still unclear. The above studies either include a testing immediately after learning or use a long-term testing (24h or more after training). This approach disregards the idea that memory consolidation is not a binary, all-none process but a gradual one where different cognitive changes could occur at different intermediate times from the learning session. As suggested by Dudai et al (2015) and McGaugh (2000), in studying consolidation, we should expect to uncover mechanisms at multiple spatiotemporal scales.This is especially challenging in the area of word learning, where multiple types of memories are being formed, involving orthographic, phonological, and semantic representations, among others. Thus, we suggest to use a controlled temporal profile of the post-training period to tackle the word integration process. To this aim we analyzed two different markers of memory consolidation: the susceptibility of recent words to memory interference and the semantic integration by means of the N400 modulation.

1.1. Present study

The present study evaluated the temporal dynamics of novel word consolidation, dissecting the word form and meaning. We propose that the word integration process can be best understood from the combined use of different cognitive markers of memory consolidation. In two separate experiments we *i)* measured the vulnerability of recently learned words and meanings to external interference and *ii)* analyze their semantic integration by means of the N400 potential.

The vulnerability of memory to amnesic agents, including retroactively interfering stimuli, is one of the hallmarks of the memory stabilization process (Wixted, 2004; Fernández, Bavassi, Kaczer, Forcato, & Pedreira, 2016) and provides an experimental tool to study the temporal dynamics of memory formation.This phenomenon is not only found in laboratory settings, but it is also proposed as the main responsible of forgetting in daily life (Wixted, 2004).Thus, the resistance to interference is important to prevent memory 'overwriting' from incoming novel stimuli, which is common in the word learning scenario. From a neurobiological perspective, the interference task is expected to reactivate the same neural pathways active during initial learning (Shimamura, 2014) implying a competition for shared resources between the original and new memory.

As a marker of semantic integration we used the N400 component, a negative-going event-related potential (ERP) peaking around 400 ms after stimulus onset (Kutas and Federmeier, 2011) and believed to reflect largely automatic processes of lexical–semantic retrieval. Previous ERP studies have found that the N400 is a sensitive index of word learning (McLaughlin, Osterhout and Kim, 2004; Perfetti et al., 2005; Mestres-Missé et al., 2007; Bakker et al., 2015). In addition, the N400 is especially suitable as a measure of semantic integration, as its amplitude is reduced (i.e., more positive) when the stimulus can be predicted based on the preceding context, for example a sentence or a semantically related prime word (Kutas and Federmeier, 2011).

Participants received training on a set of novel picture-name-description mappings. In the first experiment weexamined the susceptibility of novel words memory to interference induced at four different times (5 min, 30 min, 4 h and 24 h relative to the initial exposure to the novel words).Manipulating the time of interference allowed us to obtain a profile of retrograde amnesia that could hint towards the neurobiological basis of novel word consolidation. In addition, we asked the dynamics of semantic integration of novel words indexed by measuring N400 modulation when novel words were preceded by semantically related words at 30 min or 48 h after learning. The emergence of priming effects on N400 amplitude would suggest a degree of integration of novel words into the existing semantic network (Bakker et al., 2015), and we studied whether this response to novel words change as a result of consolidation.

2. Material and Methods

2.1 Participants

A total of 153undergraduate and graduate students from Buenos Aires University, all native Spanish speakersparticipated in two different experiments. From these, 20 subjects were excluded from the analysis based on a low learning performance (equally distributed in all groups), or technical failures during the EEG acquisition. Each participant was randomly assigned to one experimental group (**Figure2**). The demographic information of the included participants is indicated in **Table 1.** Before their participation in the experiment, subjects provided written informed consent that had been approved by the Ethical Committee of the Argentinean Society of Clinical Research Review Board.

2.2. Materials and Procedure

On Day 1, participants studied nine novel words with a corresponding definition, in written format, and an associated picture (see **Figure 1**). The new words were six letter long, trisyllabic (Consonant-Vowel), pronounceable, and morphologically legal in Spanish, e.g. 'musapa'. The pictures corresponded to non-objects adapted from Kroll & Potter (1984). The novel pictures and definitions were selected from three categories: animals, furniture and tools (three words in each case). Each description consisted of a short phrase, such as "an eagle of the desert". Experiments took place in a quiet room and were conducted using a personal computer, between 9AM and 3PM.

2.2.1. **Learning Task**

The word learning protocol is depicted in **Figure 2A**. The task was adapted from the paper of Clay, Bowers, Davis, & Hanley (2007). Participants carried out a study phase followed by two identical test phases, one immediately following study (short-term memory test) and the other two days after (long-term memory test). Participants were given a practice demo to familiarize themselves with the task, and were instructed that they should learn a series of novel words, each associated to a novel picture and a definition.

The **study phase** consisted of four stages, separated by rest breaks. The order of presentation was randomized in all cases. During Familiarization participants were presented with all of the correct pairings of the descriptions, pictures, and new words, and were required to pay attention and try to learn each item. Each item was presented visually for 4 sec. This step was repeated twice, with a different presentation order in each case. In the Word completion task, participants were shown either a definition or a picture in the middle of the screen together with the first syllable of the corresponding new word (in the upper part of the screen in uppercase letters). They were instructed to fill in the correct word by choosing from four response syllable options, presented at the bottom of the screen. The subjects were given 2 seconds to press the keys that corresponded to the correct answers (i.e., the appropriate 2nd and 3rd syllables) on a keyboard. If the subjects answered correctly, the complete word appeared in white for one second; if the subject answered incorrectly or did not respond in time, the word appeared in red. Each new word was practiced two times in the word-picture condition and two in the word-definition conditions. This step was repeated twice, with a different presentation order in each case. During Recognition task, they were shown either a definition or a picture in the middle of the screen and one of the new words in the upper part of the screen. Participants were required to decide whether the new word matched the description or picture. Items matched on half of the trials, and participants were instructed to press the right arrow key for "yes" responses and left arrow key for "no" responses. Once participants had responded they were given feedback that included the new word paired with both the correct definition and the correct picture. New words were paired with one of the following: a matching definition, a matching picture, a mismatching definition, or a mismatching picture. Each new word was practiced one time in each of these conditions. Finally, in the Cued-Naming task, participants were shown one of the pictures, with the first syllable of the corresponding word (provided as a retrieval cue) and were asked to name the aloud the word's name, and afterwards to give the definition. Feedback was provided in each case, presenting the complete word and definition.

The **test phase** was performed 5 min after training, and then again after 48 h and consisted of two tasks in fixed order (Word-form recall and Meaning recall). Participants were initially shown each studied picture in the middle of the screen and were instructed to name the corresponding word name as quickly and as accurately as possible. They were given 4s to name each picture. Secondly, studied words were shown one at a time (in random order), and the participants had to give the corresponding definition. Participants were told that they did not have to know the exact wording of the definitions. No feedback was provided during the test phase.

The duration of the complete task (study + short-term test) was 30 min, and the long-term test lasted 5 min. Paradigms were programmed using Matlab Psychophysics toolbox (Psychtoolbox-3; www.psychtoolbox.org).

2.2.2. **Experiment 1**: **Memory Interference Task**

The interference treatment was introduced after the end of the short-term test phase. It consisted of learning a new set of nine novel words, pictures and definitions (List 2), with similar characteristics to the previous ones, i.e., six-letter words, short definitions, corresponding to the same semantic categories used in the List 1. The learning procedure was identical to the previous one. Different groups of participants received the interference at distinct times after the end of the first phase: 5 min, 30 min, 4 h or 24 h (Int-5min, Int30min, Int4h, Int24h; N=15, 16, 14 and 12 participants per group, respectively, this is the final number of participants after removing subjects that did not reach our inclusion criterion) (**Figure 2B**). In the interval between both learning tasks, participants are asked to leave the experimental room and not to think about the recently learned material. During the long-term test phase, participants were shown the items corresponding to the first learning list. The interfered groups were contrasted with a control group (Control, N=14) that did not receive the interference. In addition, to compare both learning sets, a control group that only received Learning List 2 (Control-L2, N=12) was included.

2.2.3. **Data analysis**

Participant's performances were registered during the study phase, the short and long-term memory test. Responses in the long-term test were normalized respect to the performance in the short-term test. A 100% value would indicate that all items that were correctly recalled in the first session are also recalled in the long-term test (no decay). Different groups were compared by means of a main effects ANOVA followed by paired comparisons respect to a Control group (Dunnet test).

Inclusion criterion: In order to be included in the analyses, participants must obtain at least a 33% accuracy in the short-term test.

In order to analyze the dynamics of the interference effect on the Word-form memory, all time points (5 min, 30 min, 4 h, 24 h) were fitted to a sigmoid function [$f(x)=a/(b+e^{-(x+c)})$] using a nonlinear least squares regression in MatLab. On the other hand, to evaluate the dynamics of the interference effect on the meaning memory, all time points were fitted to a linear function [$f(x)=a*x+b$] using a least squares linear regression in MatLab.

2.3. **Experiment 2: Semantic Judgment Task (ERP task)**

After having established the time course of susceptibility to interference, we were interested in determining whether these novel words become lexically integrated and what was the temporal profile of this integration. Thus, two different groups of participants, not receiving any interference, performed a prime–target semantic judgment task while their EEG signal was registered (**Figure 2C**). The task was performed after the novel word learning, at two separate times: Prim-30min and Prim-48h (N=20, and 19 per group, respectively, final number). Considering that ERPs require a high number of trials to increase the signal-to-noise ratio, it was necessary to increase the number of words to be learned. Thus, in this experiment participants are instructed to learn 15 novel words, with the same procedure as the one described above (see **Figure 1** for the list of stimuli).

The task procedure was adapted from Bakker et al., (2015). Recently learned words were used as targets with related or unrelated real words as primes. In the Bakker et al. (2015) study it was demonstrated that the N400, an electrophysiological marker of semantic processing (Kutas & Federmeier, 2011) was modulated by the prime-target semantic relation, thus revealing a sensitivity of this task to tackle semantic integration. In addition, a set of existing words which are expected to already be part of the semantic lexicon, were included as a control condition to confirm if our task was sensitive enough to show priming effects and to check for possible differences in baseline priming for the novel word prime condition.

The category (e.g. 'insect') of the novel word definition was used as the basis for selecting four semantic associated terms (e.g. 'bee', 'fly', 'wasp', and 'ant'). These target words were chosen from an online questionnaire performed to a group of subjects (not taking part in the experiment), that were asked to rate the level of relatedness between the items. We selected the options with highest ratings, and that met our selection criteria (between 4 and 9 letters, consisting of a single lemma, well-known, not occurring in the definition of the corresponding target, not a synonym of the target). Four semantically unrelated primes were created for each target by pseudo-randomly reusing the related primes. In addition, 15 existing words were selected as primes for the task. These familiar words were matched with the new words in terms of length (6 letters) and number of syllables (three). The corresponding primes were chosen from the same online questionnaire, and were balanced for (logarithmic) frequencies in EsPal between .04 and 2 (average=1, SD=.5) (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013). Thus, the priming task included 15 novel words and 15 existing words, with each of the four semantically related primes and four unrelated primes (i.e., no prime–target pairs were repeated).The average repetition lag is 37.5 trials (SEM:+/-3.6) and 34.3 trials (SEM:+/-2.7) for novel and pre-existing words, respectively. Importantly, considering that subjects are exposed several times to the novel words, and this may lead to an attentional bias during the priming task, we also exposed the participants to the 15 familiar word targets after the learning session.

A trial started with a 500 ms fixation screen. The prime was presented for 250 ms, followed by a blank screen for 250 ms, and the target remained for 2000 ms, where a ‘yes’ or ‘no’ response should be made, otherwise the trial was considered “out of time”. For each prime–target pair, the participants' task was to decide whether the two words were semantically related or not by pressing one of two buttons. The response box was custom made, and included an Arduino microprocessor platform that allowed high precision in response timing (Schubert, D’Ausilio, & Canto, 2013). Half of the participants answered with the right hand and the other with the left hand. Semantic judgment task has been shown to better preserve semantic effects in the ERPs respect to the lexical decision task when stimuli are repeated (Renoult, Wang, Mortimer, & Debruille, 2012), which was necessary here given the limited set of novel words.

RTs and accuracy scores from the semantic judgment task were analyzed by using a repeated-measures ANOVA with Lexicality (novel, existing), Relatedness (related, unrelated) as within-subjects factors, and Time (30 min or 48h) as a between-subjects factor. Reaction Time (RT) was measured from target onset. Incorrect responses and RTs more than two standard deviations from the mean were removed from analysis (16%).

2.3.1. **EEG recording**

Electroencephalographic activity was recorded (Akonic Bio-PC) while participants performed the priming task from 30 cap-mounted tin electrodes (international 10/20 system, Electro-Cap International Inc.), referenced online to the left mastoid. Later, the EEG signal was re-referenced off-line using the mean of the two mastoids. Electrode impedances were kept under 10 kΩ. EEG was sampled at 256 Hz, and bandpass filtered at 0.1–40 Hz. ERPs were time-locked to the onset of the target word. Epoch length was 800 ms, plus a 200 ms pre-stimulus interval as baseline. EEG signal processing and ERP analysis were carried out with EEGLAB software (Delorme & Makeig, 2004). Ocular artefacts were removed from data by means of ICA-based artefact correction, applying the ADJUST algorithm (Mognon, Jovicich, Bruzzone, & Buiatti, 2011). Automatic rejection was used to exclude all epochs containing artifacts. Thus, trials with amplitudes below −200 μV, above +200 μV, or trials that made a 100 μV or larger voltage step within 200 ms were removed from the analysis (15% of trials).

The mean number of trials (+/- S.E.M) per condition per subject that contribute to the ERP grand average (after exclusion of trials with artifacts and incorrect behavioural responses) is: 37.26(1.56); 30.79(1.82); 38.42(2.34); 33.31(2.18) for the Prim-30min Group and 36.21(2.07); 28.42(1.63); 37.47(2.43); 34.05(2.34) for the Prim-48h Group, for the Related familiar, Related novel, Unrelated familiar and Unrelated novel groups, respectively.

2.3.2**. ERPs Data analysis**

To examine semantic priming effects grand average ERPs were formed for correct responses relative to target onset, separately for each experimental condition. ERPs were quantified by measuring the mean amplitude over specific time windows of interest (with respect to the mean pre-stimulus baseline). A latency period from 300–450 ms was chosen, consistently with previous identifications of N400 priming effects in the literature (Kutas and Federmeier, 2011). Here we used for the analysis the recordings from the three main midline electrodes (Fz, Cz, Pz) where meaning effects are robustly observed in word learning studies (e.g., Batterink and Neville, 2011; Mestres-Missé et al., 2007). This allows us to study the characteristics of the N400 in a broad, general approach. In addition, a time window from 450 to 600 ms was chosen to analyze the Late Positive Component. These values were submitted to an omnibus repeated-measures ANOVA with within-subjects factors Lexicality (Novel, Existing), Relatedness (Related prime, Unrelated prime), Anteriority (anterior, central, posterior), and a between-subjects factor Time (30min, 48h). Greenhouse–Geisser adjusted statistics are reported where assumptions of sphericity were violated.

3. **Results**

3.1. **Experiment 1: Performances during acquisition and short-term memory test**

To analyze the general performance during the study phase and short-term memory test, we performed a grouped analysis of all participants. Results are showed in **Table 2**. Participants were able to accurately recognize most of the words and meanings. In the cued-naming task, when confronted with the associated picture and the first syllable of the word, participants are able to recall most of the words 'names, and almost all the definitions. Accuracy values drop when the difficulty of the task was increased, not including a cue. In the short-term test, participants made significantly more errors when recalling the name of the novel words than when retrieving the definitions. Thus, word-form learning was more challenging than learning novel meanings.

Importantly, no initial differences were found between the main experimental groups in the short-term test (**Table 3**), which is a prerequisite for analyzing the effect of interference on a later memory retention.

In addition, a comparison between the performances of Control-List1 and Control-List2 during the short-term test did not yield any significant differences [$t_{1,23}$=1.27, p=.21] thus indicating similar difficulties of both learning materials.

3.2. **Effect of the interference task on the long-term test**

Results corresponding to the long-term memory test are shown in **Figure 3**. Individual performances were normalized to the results obtained in the short-term naming test. Regarding the word naming task (**Figure 3A)**, a main effect was obtained between the experimental groups [$F(4,69)=2.80$, $p<.05$], thus revealing an effect of the interference treatment. Followed-up pairwise comparisons respect to the Control group (Dunnett test) showed a significant difference for the Int-5min ($p<.05$) but not for the other groups [Int-30min: p=.22; Int-4h: p=.38; Int-24h: p=.51].

An analysis of the dynamics of the interference effect on the word memory revealed that after nearly30 min the performance curve reaches a steady state [**Figure 3A** inset, r^2=0.84]. This would indicate that word memory rapidly loses its susceptibility to interference.

In the meaning recall task (**Figure 3B**), no overall significant differences were found between groups [$F(4,69)$ =1.49, p=.21]. Besides, the slope of the regression line is not significantly different from zero [Figure 2B inset; r^2=0.77]. In this task, results indicate a nearly 100% of memory maintenance two days after learning in all groups, revealing no effect of the interference treatment. Thus, not only the performance is better for the word's meanings (**Table 2**), but also the forgetting is less pronounced.

To discard the possibility that the interference effect could be hindered by the testing order (i.e., by the fact that definitions are tested *after* the word forms), we included an additional 5min interference group (N=11), but in this case reversing the order of the tasks in the long term test. In this case, memory for meanings was evaluated *before* memory for words. Results reveal that the memory for definitions was not affected by the interference treatment (mean accuracy 114 ± 2%, not different from the

Control group), thus ruling out a possible order effect in the testing procedure that could overshadow the interference effect.

All in all, results showed that only the word-form memory was affected by the interference treatment, while the memory for meanings was immune to the treatment. The interference was found to be time limited, being evident in the 5 min group, and not in the 30 min, 4 h or 24 h groups.

3.3. Experiment 2: ERP Priming task

3.3.1. Behavioral results

Performance in the word learning task (Cued-naming task) reveals a 65.0 ± 3% accuracy in the Word form recall and 90 ± 2.4% accuracy in the Meaning recall. In the short-term test, accuracy was 53.0 ± 2.3 % (word forms) and 62.0 ± 2.5 % (definitions).

Accuracy scores from the semantic judgment task (**Figure 4A**) revealed that overall performance was better for existing words than for novel words [$F(1,49)=143.69$; $p<.001$]. In addition, a significant effect of Relatedness [$F(1,49)=26.92$; $p<.001$] reveal higher accuracy in the unrelated condition. A significant interaction Lexicality x Relatedness [$F(1,49)=11.26$; $p<.005$], followed up by a paired comparison, indicate that for novel words there is a higher accuracy in the unrelated condition (Bonferroni test, $p<.001$) respect to the related one. These results indicate that the semantic component of newly learned words would be captured by subjects 30 min after training but it is more error-prone than that of already familiar words.

The analysis of mean RTs (**Figure 4A**) corresponding to correct answers, revealed a main effect of Lexicality [$F(1,19)=34.37$; $p<.0001$] showing faster responses to existing words compared to novel ones, for the related and unrelated condition. No significant differences were found between the 30min and 48h groups and no interaction was shown between the main factors [all $Fs<1$].

3.3.2. ERP results

Grand average ERP waveforms representing priming effects (related and unrelated conditions) for existing and novel words are shown in **Figure 5** and a representative electrode (Cz) is shown in **Figure 6** together with an analysis of priming effects. Visual inspection of the waveforms' Grand averages showed a negativity peaking around 350-400 ms that would be compatible with a N400 potential, as well as a later positivity around 500 ms, compatible with a LPC (late positive component). We analyzed each time window separately.

In the N400 time window (300-450ms), the omnibus ANOVA yielded a main effect of Relatedness [F(1,37)=26.26; p<.001); epsilon = 1.00], confirming the expected reduction in N400 amplitude to targets following a related versus an unrelated prime. This priming effect was larger for existing words than for novel words [Relatedness×Lexicality: F(1,37)=13.96; p<.001; epsilon=1.00]. In addition, an effect of Anteriority was found [[F(2,74)=21,81; p<.0005; epsilon=0.78]. Importantly, two triple interactions involving the Time factor were found: Time×Lexicality×Anteriority [F(2,74)=5.05; p<.005; epsilon=0.84] and Time×Relatedness×Anteriority [F(2,74)=5.56; p<.005; epsilon =0.74] reflecting a distinct priming pattern in the Prim-30min and the Prim-48h groups. To follow up these interactions, we conducted separate ANOVAs for each time point.

In the 30min group, results show a main effect of Relatedness [F(1,19)=16.95; p<.0001; epsilon=1.00]; Anteriority [F(2,36)=4.43; p<.05; epsilon=0.74] and a significant interaction between Relatedness×Lexicality [F(1,19)=11.64; p<.005; epsilon = 0.86] revealing that priming effects differ between existing and novel words. While a significant N400 modulation is shown for existing words (Bonferroni test, p<.0001), this is not the case for novel words (p=0.4). In addition, a significant effect of Anteriority×Relatedness [F(2,38)=7.76; p<.005; epsilon= 1.00] reveals a more pronounced N400 modulation in the central and frontal electrodes.

In the 48h group, we observed main effects of Relatedness [F(1,18)=11.85; p<.005; epsilon=1.00] and Anteriority [F(2,36)=19.20; p<.0001; epsilon=0.72], but no significant interactions were found between the main factors (all Fs>1).

To simplify the visualization of results, pairwise comparisons were performed on the mean values of the N400 window to detect lexicality effects (i.e., novel vs. familiar words) and semantic effects (i.e., related vs. unrelated words) in the 30min and 48h groups (**Figure 6**, bottom panel). In the 30min group, results revealed a significant semantic N400 modulation for familiar words (p<.01), but not for novel words. In addition, a significant Lexicality effect was found: related novel words differ from existing words (p<.05). In the 48h group, a significant semantic effect was found for existing (p<.0001) and novel (p<.05) words, while no significant lexicality effects were detected.

In the LPC time window (450-600 ms), the omnibus ANOVA showed a main effect of Lexicality [$F(1,37)=65.29$; $p<.05$)], where familiar words show a greater positivity than novel words. In addition, a main effect of Relatedness [$F(1,37)=38.35$; $p<.05$)] shows a greater positivity for the unrelated conditions. No significant interactions where found between the main factors, and no differences were found between 30min and 48h.

In summary, existing words elicited a reduced N400 when preceded by semantically related word primes, while novel words only exhibit this effect 48h after learning, thus becoming more word-like after a longer consolidation period. On the other hand, the LPC component would not be affected by consolidation.

4. **Discussion**

Words are amazingly complex memories. The main purpose of this study was to analyze how the integration of novel words unfolds after initial exposure. In addition, we wanted to find out whether there are differences between two tightly related word memories: the word-form and the word-meaning. For this purpose we initially analyzed their susceptibility to memory interference and its time course. Secondly, we sought to establish whether these recently learned novel words become integrated into existing semantic networks by analyzing the neurophysiological correlates of lexical integration in a semantic judgment task. Overall, the results of the present study demonstrate a fast, but not immediate resistance to external interference of recently acquired word forms that is balanced with a slow semantic integration. We found that a second task could impair the word memory retention only when it was presented 5 min after training, but this effect was lost half an hour later. Thus, we revealed that this early offline period may encompass important changes in the word formation process. On the other hand, our results showed that a longer consolidation period is needed to integrate the novel words into existing semantic networks and reveal a N400 modulation. This pattern of results shed light into the complex dynamics of word memory formation, and suggest the existence of parallel process that help to build the memory for word forms and meanings. A rapid mechanism would enable word learning while mitigating forgetting, while a slow process would allow the novel meanings to be integrated into previous semantic networks.

4.1. **Dynamics of memory consolidation for novel words**

It is interesting to discuss our results in the light of different memory consolidation proposals. Davis and Gaskell (2009), suggested that adult word learning occurs in two stages with different dynamics: novel items would be rapidly encoded by the hippocampus and then slowly integrated into long-term memory networks. However, there are some views that suggest a faster scenario for memory consolidation. Memories which fit tightly into an existing knowledge framework or 'schema' might use a faster consolidation route in which the medial prefrontal cortex takes on the binding role instead of the hippocampus (Tse et al., 2007; Wang & Morris, 2010). In addition, recent findings suggest that incidental association of novel pictures with novel word forms named 'fast mapping' may promote the formation of a word memory without relying on the medial temporal lobe or hippocampus (Sharon et al., 2011; Borovsky et al. 2010; but see Smith et al., 2014; Warren and Duff, 2014).

Our results revealed a temporally graded interference effect (Figure 3A), showing that around 10 min after acquisition novel words become resistant to interference. It is possible that the linguistic nature of our stimuli may provide a fast pattern of memory formation, suggesting a domain-specific property. If we take into account that novel words are usually learn in close succession, it would be adaptive to rely on a 'consolidation express' mechanism that allow fast resistance to interference

In addition, results of our study demonstrate that the memory for meanings was not affected by the interference treatment. Some authors have viewed semantic memory as fundamentally different from purely episodic one (Tulving & Endel, 1974; Vargha-Khadem et al., 1997). In line with this idea, it is possible that the memory for novel meanings, which occurs against the background of established prior knowledge, can be assimilated into a 'schema' and thereby could use an alternative consolidation route with a faster temporal profile than the word-form memory, making it inaccessible to amnesic treatments. Finally, it is also possible that a 'ceiling' performance hindered an interference effect. Future neuroimaging experiments will allow us to address the actual implication of the hippocampal system and cortical areas in the novel word memory formation.

4.2 **Novel word integration**

As the consolidation process unfolds, different memory properties emerge along the way. This reflects the dynamic nature of memory. Recent work has demonstrated that off-line processing is not limited to just the stabilization of a memory; instead, offline processing can have a rich diversity of effects, from enhancing performance, to integrate new memories with previous ones (Robertson, 2012; Dudai et al, 2015). In the case of word learning, we ask what is the functional consequence of a word becoming 'integrated' into a memory network? One of the key diagnostic features is its ability to engage with long-term stores of lexical knowledge (Davis & Gaskell, 2009; Leach & Samuel, 2007). Previous studies investigated the dynamics of new word learning by tracing the effects of these new representations on the processing of phonologically similar existing words (Gaskell & Dumay, 2003). It was shown that participants rapidly become familiar with fictitious words, whereas lexical competition is only observed after a delay (Dumay & Gaskell, 2007). Notably, this effect was proposed to emerge on the days following training (Davis et al., 2009) and to depend on sleep-related mechanisms (Tamminen et al., 2010). In fact, a critical cornerstone for the role of memory consolidation in word learning is evidence that sleep plays a role in the integration of new and existing linguistic knowledge (Bakker et al., 2015; Davis et al., 2009; Gaskell & Dumay, 2003).However, if we take into account that offline memory changes could occur soon after acquisition (Dudai, 2004), this leaves open the possibility that changes in word processing can occur at earlier stages.

In this sense, our results corresponding to the semantic judgment experiment show that only after 48h it was possible to reveal that novel words show a similar N400 electrophysiological profile to existing words. Thus, as suggested by Bakker et al. (2015), it might be that novel meanings immediately start to contribute to semantic processing, but that the underlying neural processes may shift from strategic to more automatic with consolidation. This reinforces the need to combine both behavioral an ERP measures to address a complete profile of novel word integration. However, taking into account the explicit nature of our semantic judgment task, it would be necessary to perform a standard implicit semantic priming procedure, such as a lexical decision task, to obtain a clearer picture of semantic integration. Our results are consistent with the distinction between lexical configuration and engagement (Leach & Samuel, 2007) that emphasizes the dissociation between the factual knowledge of a word (such as its word form), and its interaction with other lexical entries (such as a semantic integration).

It is interesting to compare our results with the ones obtained in studies using similar experimental designs that involve explicit learning tasks of novel words with an associated meaning. In Tamminen and Gaskell (2013), and Clay et al. (2007) novel words did not revealed to be semantically integrated directly following study, but did so after a week, suggesting the implication of offline consolidation. In addition, a recent study by van der Ven, Takashima, Segers, & Verhoeven (2015), reported similar findings after a 24-hour delay. Finally, a study by Bakker et al., (2015) analyzed the electrophysiological correlates of semantic processing for recently learned words. The ERPs showed that the N400 response to novel words show a variation after a 24-h consolidation period, becoming more word-like, while semantic priming effects in the LPC window were found immediately after training. Thus, data from this study provided experimental evidence for a role of long-term offline consolidation, but also suggest the possibility that some lexical memory may be integrated shortly after learning. These previous results are mostly consistent with the ones obtained in the present study, as we showed that novel meanings revealed a semantic N400 modulation after 48h, but not 30 min after training. In addition, our results show that the LPC is higher for existing than novel words and not affected by consolidation, similar to Bakker et al. (2015). This finding is consistent with the core interpretation from previous studies of the LPC as an index of the relational reprocessing in terms of the difficulty of semantic integration (Van Petten& Luka, 2012). Notwithstanding this extended dynamics of semantic integration, novel word forms did reveal a fast resistance to interference, thus suggesting a dissociation in lexical and semantic consolidation.

Acknowledgments

We thank an anonymous reviewer for helpful comments. Martin Carbó-Tano for help with the picture drawings. Angel Vidal for technical assistance. This research was funded by the Agencia Nacional de Promoción Científica y Tecnológica (grants PICT2013-0718 to LK and PICT2013-0412 to MEP).

Figure legends

Figure 1: List of novel words, pictures and definitions. Nine items were used in Experiment 1, marked with a dotted line, and fifteen were used in Experiment 2.

Figure 2:(**A**). Overview of the learning tasks including an example of one of the novel words with the corresponding definition and figure.The white background indicates the training of the association between the word's name with the picture, and the grey background denotes the association between the word's name and the definition. The blue circles indicate the correct options that the participant should select during the task (**B**). Schematic diagram showing the experimental groups, with the distinct temporal positions of the interfering task—study of List 2 (L2)—during the retention interval of List 1(L1). (**C**). Semantic judgment task (ERP study). Recently learned words are used as targets with related or unrelated real words as primes. A set of existing prime-target pairs was also included. Participants have to decide whether the prime and target are related while their EEG activity is recorded.

Figure 3: Performance on the Long-term memory test (48h after training) of the control and interference groups. Mean correct responses (±SEM) are normalized respect to the performance in the short-term memory test. *Inset*: responses of the interference groups (5min, 30min, 4h and 24h, time in logarithmic scale)are fitted to a sigmoid or linear function (**A**). Word-formTest. Participants have to name the novel word when presented the associated picture. *Inset*: Mean normalized responses of the interference groups were fitted to a sigmoid function (**B**). Word-Meaning Test. Participants have to name the definition when presented the associated word’s name. *Inset*: Mean normalized responses of the interference groups were fitted to a linear function.

Figure 4: Semantic judgment task, performed 30 min or 48 after novel word learning. (**A**). Mean Reaction time (±SEM), measured from target offset, to prime–target pairs of which the prime was either a novel or existing word. Light bars indicate related pairs and dark bars indicate unrelated pairs. (**B**). Percentage of correct prime-target relatedness judgments.*: $p<.05$ (paired comparisons)

Figure 5: Grand average ERPs in the 30 min and 48h group superimposed for the Related (green: Existing, red: Novel), and the Unrelated conditions (black line: Existing, blue line: Novel). Negativity is plotted up.The topographic electrode map shows the position of the selected channels (F3, Fz,F4, C3,Cz, C4, P3,Pz, P4). The N400 and LPC components are indicated with an arrow in Cz.

Figure 6: *Upper panel*. Grand average ERPs from a representative electrode site (Cz) in the 30 min and 48h group, in a reduced time window (until 500ms), superimposed for the Related (green: Existing, red: Novel), and the Unrelated conditions (black line: Existing, blue line: Novel). Boxes highlight the latency interval of interest for N400 priming effects. *Lower panel*: Mean amplitudes (μV) within N400 time window (+/- SE). Pairwise comparisons: *: p<.05 (semantic priming effects). #: p<.05 (lexicality effects).

Table 1: Mean age (±SEM) and gender ratio (male respect to female) in each experimental group

Exp	Group	Mean Age (+/- ES)	M:F Ratio	N
Exp 1	Control-List 1	21.5 (0.7)	0.46	13
	Control-List 2	21.9 (0.2)	0.50	12
	Interf-5min	21.2 (0.5)	0.40	15
	Interf-30min	21.8 (0.9)	0.45	16
	Interf-4h	22.6 (0.4)	0.42	14
Exp 2	Interf-24h	22.8 (0.5)	0.30	12
	Prim-30	21.1 (0.5)	0.40	20
	Prim-48	20.3 (0.4)	0.37	19

Table 2: Mean Percentage of correct responses (±SEM) during the training tasks and short- term memory test.

Training tasks	Word-form	Word-meaning
Word completion	70.29% (±2.11)	78.28% (±2.03)
Recognition	85.64% (±1.58)	87.73% (±1.48)
Cued-naming	74.82% (±1.58)	92.74% (±1.98)
Testing (short-term)	Word-form	Word-meaning
Naming	60.71% (±1.98)	76.97% (±1.78)

Table 3: Mean Percentage of correct responses (±SEM) during in the short- term memory test.

Short-term test	Word-form	Word-meaning
Control-List 1	58.1 (5.0)	80.5 (4.6)
Interf-5min	61.6 (6.6)	72.7 (5.4)
Interf-30min	58.7 (4.4)	73.0 (4.6)

Interf-4h	56.5 (5.5)	73.7 (4.4)
Interf-24h	63.2 (5.2)	82.0 (6.4)

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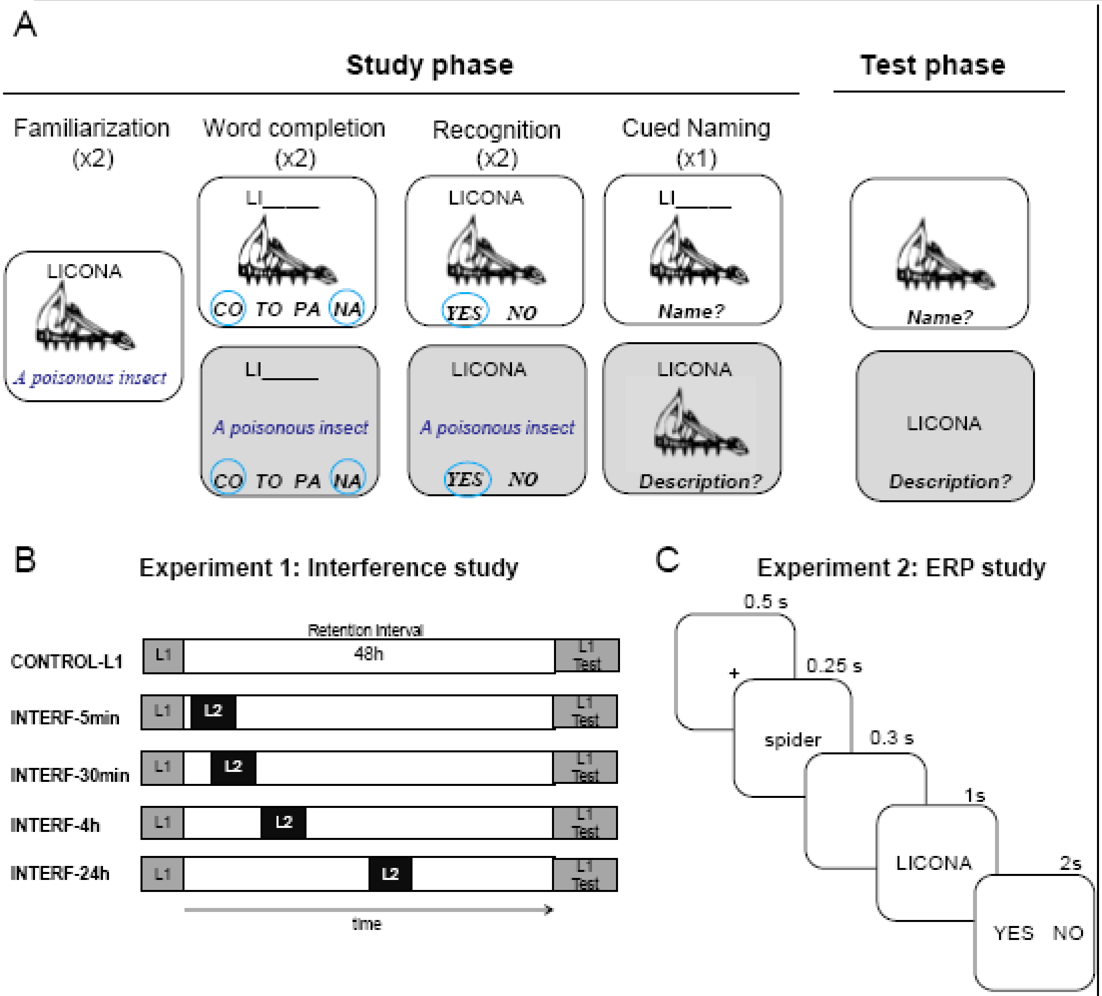
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Study phase
Test phase
Familiarization (x2)
Word completion (x2)
Recognition (x2)
Cued Naming (x1)
LICONA
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LI____
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Name?
Description?
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Experiment 1: Interference study
Retention Interval
48h
CONTROL-L1
INTERF-5min
INTERF-30min
INTERF-4h
INTERF-24h
L1
L2
L1 Test
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Experiment 2: ERP study
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spider
0.3 s
1 s
LICONA
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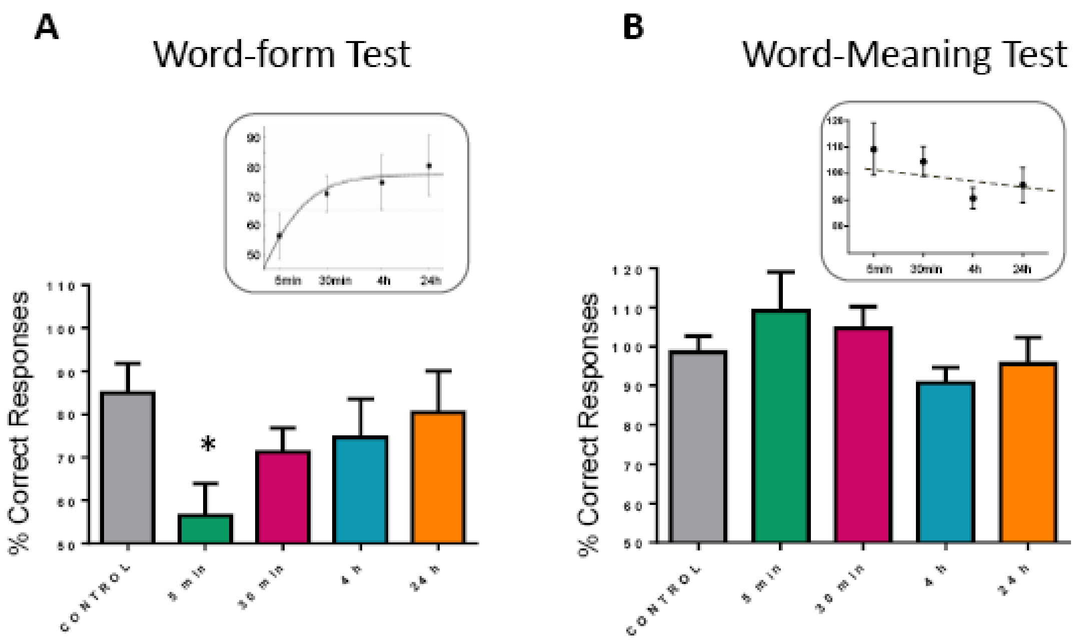
YES NO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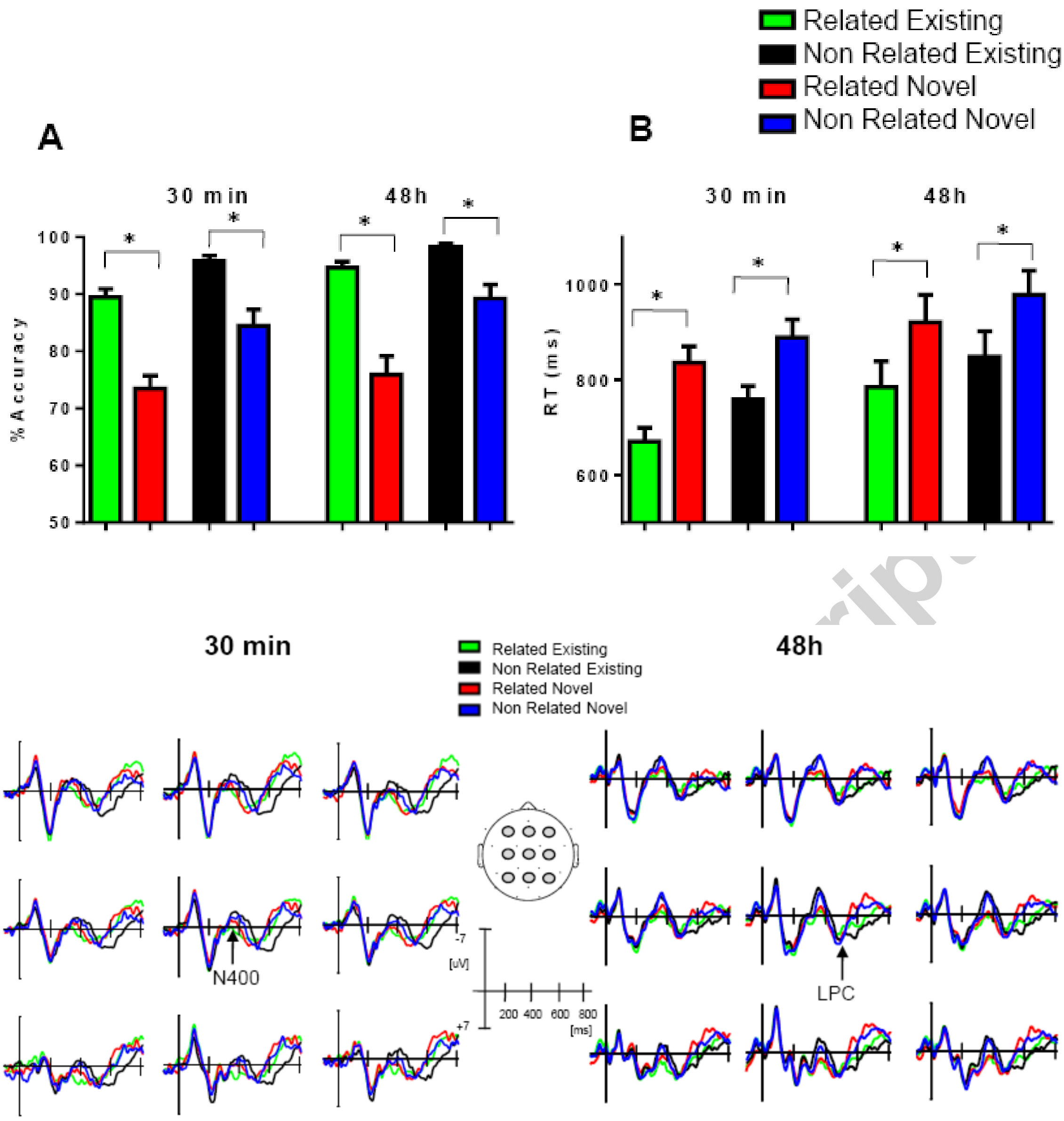
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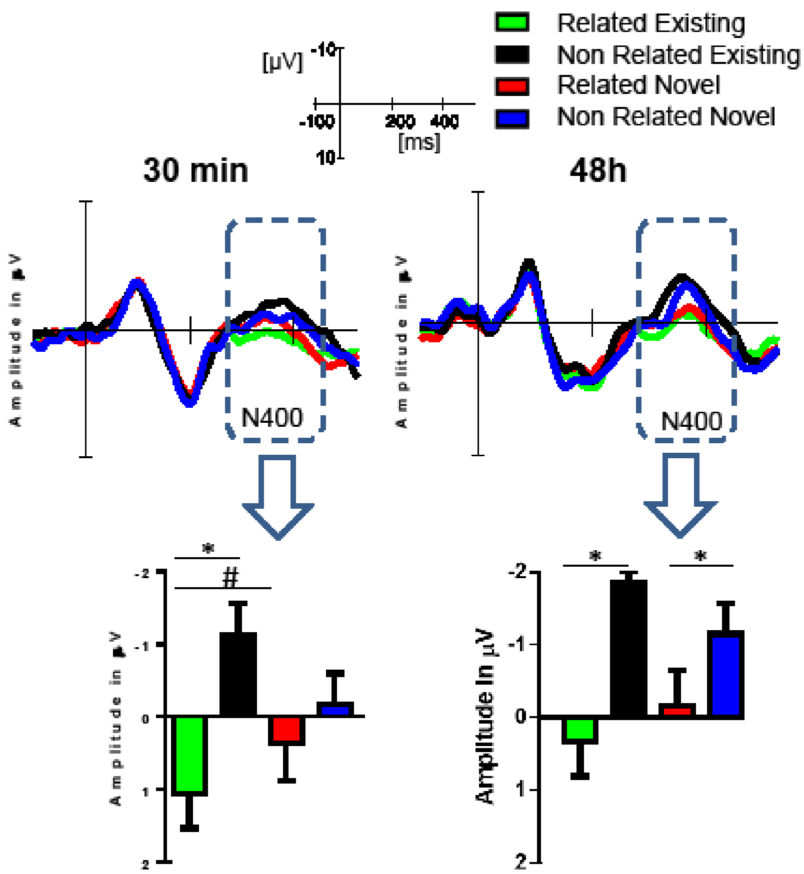

Highlights

- Young adults acquired a set of novel picture-label-meaning associations
- Memory for novel words was susceptible to interference only 5 min after training
- Memory for novel meanings was not affected by retroactive interference
- Semantic N400 modulation for novel words was found only 48h after learning