Learning new words: memory reactivation as a mechanism for strengthening and updating a novel word´s meaning

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ABSTRACT

In the present study we explored the post-learning changes in a novel word's definition using a cue-induced memory reactivation. Native speakers of Spanish (N=373) learned low-frequency words with their corresponding definitions. The following day, reactivated groups were exposed to a reminder and provided a subjective assessment of reactivation for each word, while control groups did not receive a reactivation. Study A demonstrated that memory reactivation enhances both explicit recall and semantic integration of new meanings. Study B investigated the effect of memory reactivation in the modification of the new meanings, through three different experiments. Results show an improvement of the updated definitions according to each word´s reactivation strength. In addition, congruence with previous knowledge was suggested to be a boundary condition, while consolidation time had a positive modulatory effect. Our findings call attention to reactivation as a factor allowing for malleability as well as persistence of long-term memories for words.

Keywords

Word learning, consolidation, reconsolidation, retrieval, semantic, plasticity

INTRODUCTION

Learning new words is one of the hallmarks of human cognition. Although it is mostly associated with children, adults frequently encounter words they have not heard or read before and new words are constantly being created in response to technologic and cultural change (Chaffin, Morris, & Seely, 2001). Remembering these words is just as important as learning them, as we must be able to recognize and recall words and their meanings in order to communicate (Wojcik, 2013). Thus, an interesting question is how these new words become long-term memories, interacting with other lexical entries. The complementary learning systems account of word learning (Davis & Gaskell, 2009) proposes that two neural systems are involved: the hippocampal system, for the rapid acquisition of a new word, and the neocortical system, with a slower-learning dynamics, required for new words to be integrated with existing lexical items (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010). Although this model is compelling in many aspects, there is a lingering question that remains less explored: what mechanisms allow novel words to persist and to be modified through time? In the present study we explore the post-learning changes in word's memory using the framework of the reactivation-reconsolidation hypothesis (Lee, 2008; Nadel, Hupbach, Gomez, & Newman-Smith, 2012)

Historically, memories were seen as stable traces or engrams initially affected by consolidation, leading to stabilization, and later to weakening, leading to forgetting (Lechner, Squire, & Byrne, 1999; McGaugh, 2000). However, contemporary research has provided ample evidence showing that memories continue to be dynamically adapted after initial encoding and, thus, can be modified by external factors throughout their existence (Dudai & Eisenberg, 2004; Sara, 2000). For instance, retrieval practice can reinforce memory traces (Karpicke & Roediger, 2008) and promote meaningful learning (Karpicke & Blunt, 2011). It has been shown that retrieval triggered by certain reminders are able to reactivate an existing memory trace (Sinclair & Barense, 2019), and constitute a key mechanism that renders memories malleable. Memory reactivation is the first stage of memory retrieval but can result from the exposure to salient cues without any behavioral output. In addition, memory reactivation is a central component of computational theories of memory (McClelland, 2013), which hold that it supports the stabilization of memory over distributed brain networks. Besides, it was shown that the quality of memory reactivation, as indexed by an individual's subjective sense of recollection, modulates the extent to which reactivation alters subsequent memories (St. Jacques & Schacter, 2013; van Kesteren, Krabbendam, & Meeter, 2018). It was found that memories were improved when targets were highly reactivated compared with memories that were reactivated at lower levels. Such cue-induced reactivation has seldom been considered as a process involved in language acquisition, particularly in memory for novel meanings. Therefore, we propose to address two properties that might be modulated by memory reactivation: memory enhancement and memory updating.

In word learning there is a useful distinction between lexical configuration and lexical engagement (Leach & Samuel, 2007) that emphasizes the dissociation between the factual knowledge of a word (such as its word form, and meaning), and its interaction with other lexical entries (such as semantic integration). One of the key diagnostic features of lexical integration is the ability of recently acquired words to engage with long-term stores of lexical knowledge (Davis & Gaskell, 2009). Several studies focused on the effects of these new lexical representations on the processing of phonologically similar existing words (Gaskell & Dumay, 2003; Walker et al., 2019). A separate line of research in the visual modality has investigated the integration of novel word meanings with existing semantic knowledge, using semantic priming as a measure of lexical consolidation (Bakker, Takashima, van Hell, Janzen, & McQueen, 2015; Kurdziel, Mantua, & Spencer, 2017; Liu & van Hell, 2020; Tamminen & Gaskell, 2013). The assumption of semantic priming (Meyer & Schvaneveldt, 1971) is that the prime word activates semantically related concepts, which accelerates the lexical retrieval process of a semantically related target word. It is considered that a semantic priming can only occur if a word has been lexically integrated (Tamminen & Gaskell, 2013). In a previous study of our group (Kaczer et al., 2018) we used a semantic judgment task to examine neural activity associated with lexical consolidation of newly learned words. We found that the N400, an electrophysiological marker of lexical-semantic access (Borovsky, Kutas, & Elman, 2010), was modulated only after a 48 h consolidation period has elapsed. From this precedent, we consider that the semantic relatedness task is a reliable measure to address lexical integration.

One of the proposed mechanisms for memory updating relies on the process of memory reactivation, or the activation of a latent memory trace when we are reminded of a past experience (St. Jacques, Montgomery, & Schacter, 2015). There is evidence that new information available when a memory is reactivated can modify that memory as a consequence of the reconsolidation process (Forcato, Rodríguez, Pedreira, & Maldonado, 2010; Hupbach, Hardt, Gomez, & Nadel, 2008; Lee, 2009). The result of this update could be manifested in different forms, depending on the target memory system. In procedural memories, for example, when a finger-tapping sequence memory was reactivated and followed by a new sequence, the accuracy of the initial memory diminished (Walker, Brakefield, Hobson, & Stickgold, 2003). Declarative memories are also open to integration of new information that follows reactivation, affecting the amount of information retrieved from the original memory (Forcato et al., 2010) or enhancing intrusions of the new material into it (Hupbach, Gomez, Hardt, & Nadel, 2007).

In all of these cases, the initial memory is not “erased”, but rather incorporates new information, consistent with the view of memory updating. However, the process of retrieval-based memory updating has not been addressed in lexical memories, although it is clear that throughout our lifespan we are able to update our knowledge of words, adding new information and refining established word representations (Fang, Perfetti, & Stafura, 2017). Thus, we propose that reactivation could be one of the mechanisms that allow this remarkable plasticity.

In the present work, adult participants received training (Day 1) on a set of low frequency Spanish words, with their corresponding definitions. On Day 2, reactivated groups were exposed to a reminder, consisting of the list of words they learnt the previous day, but without giving a response. Participants were then asked to quantify their subjective degree of reactivation. Finally, on Day 3 participants were tested on their knowledge about novel words. In Study A we examined whether memory reactivation could enhance the explicit recall of a word’s meaning and its lexical memory integration. In a second series of experiments (Study B) we investigated the influence of memory reactivation in updating the meaning of the recently acquired word, analyzing the influence of congruence with a prior knowledge (Schlichting & Preston, 2015), and the dynamics of the effect. Our work calls attention to reactivation as a factor in establishment of long-term memories for words. That is, reactivation creates a transient state during which the content of the memory is easily accessible and can be strengthened and modified.

<u>STUDY A</u>. The role of reactivation in memory strength

The experimental design of each group and the corresponding tasks are depicted in **Figure 1**.

<u>MATERIAL AND METHODS (STUDY A)</u>

Participants. The participants were all native Spanish speakers, undergraduate and graduate students with ages ranging from 18 to 35. They were recruited via mail and laboratory's social media pages (Twitter and Facebook). To participate, they first had to tick a box in an online consent form approved by the Ethical Committee of the Argentinean Society of Clinical Research Review Board. Participants who completed the experiment were included in a monthly book draw, whose winner was informed in the social media pages and by mail.

Two different online experiments were performed, including a total of 200 participants. The final number of participants in each group and the demographic information is displayed in **Table 1**. A total of 129 participants were recruited for Experiment A1, being randomly assigned to one experimental group (Control or Reactivated). From these, five participants were excluded due to not following the instructions, one participant due to a technical problem, and 16 participants (11 in the Control group and five in the Reactivated group) presented a low learning performance (less or equal to 50% in the third block of practice). For Experiment A2, a total of 71 participants were recruited and were randomly assigned to one experimental group (Control or Reactivated). One participant was excluded due to not following the instructions, 11 participants due to low learning performance (four in the Control group and seven in the Reactivated group) and one participant in the Control group due to a 100% performance (that suggests cheating) in the first block of practice.

Stimuli.

Novel words. 20 Spanish words with their corresponding definitions were selected from the EsPal - Spanish Lexical Database (Duchon, Perea, Sebastián-Gallés, Martí, & Carreiras, 2013). As our aim was that participants would learn words that were totally unfamiliar to them, we chose words that had a similar and low frequency (Range = 0.01 - 0.06; word frequency per million words in EsPal corpus). These words were six to eight letters long, pronounceable and they were all nouns. The definitions were simplified in order to consist of a short sentence with no more than five words (Range = 3-5 words; 14-28 characters). Before conducting the experiments, we performed a questionnaire in a group of participants not taking part in this study (n = 18) to confirm that none of the 20 words was known by them. See the **Appendix** for the full list of novel words together with their corresponding definitions.

Familiar words. The semantic relatedness task included 20 familiar words for comparison with the 20 novel words. These words were all nouns, with frequency higher than 0.5 in EsPal as to consider them frequent words (Range = 0.83 – 82, frequency per million) and were five to eight letters long.

Primes. For the semantic relatedness task, we selected three related words to act as primes for each of the 20 novel and 20 familiar words (one for each of the three blocks of the task). The 120 words were all nouns, with frequency higher than 0.5 in EsPal (Range = 0.61 – 807, frequency per million) and were five to eight letters long. In order to assign three unrelated primes to the 20 novel and 20 familiar words, we used the 120 previously selected primes and pseudo-randomly reassigned them to each of the target words.

Procedure. The experiment spanned three sessions, performed on consecutive days (see **Figure 1A**). It was designed and conducted using the Gorilla Experiment Builder (Anwyl-Irvine, Massonnié, Flitton, Kirkham, & Evershed, 2020; http://www.gorilla.sc) and is available to run in Gorilla Open Materials at https://gorilla.sc/openmaterials/141968. Participants in Experiment A1 completed the tasks with a computer, a mobile or a tablet while participants in

Experiment A2 were only allowed to use computers for a more precise control of response times.

Learning task. The word learning task is depicted in **Figure 1B**. During the presentation phase, each new word was visually presented for three seconds before its corresponding definition appeared, both remaining on screen for three more seconds. A screen between trials, where participants had to press a 'Next' button, was added to avoid mobile screens from blocking, and to check if participants were involved in the task. Participants were instructed to pay attention and try to learn the words' definitions. The order of presentation was randomized. The practice phase included the presentation of each word and participants were asked to type the definition (or otherwise type 'I don't know'), with no time limit. After giving an answer, participants received feedback with the correct definition in each case. There were three practice blocks (training blocks, TR1, TR2, TR3) and the order of the 20 words was randomized in each case.

Reactivation phase. The Reactivated group received an intermediate session on Day 2, between the learning and testing sessions, while this phase was absent in the Control group. In this session, the reminder consisted of presenting each of the 20 words without their definitions. In each trial, participants were instructed to try to recall the corresponding definition, but without writing it down. Immediately following this, they were asked to rate their subjective feeling of reactivation, i.e., how much they think they were able to recall the word´s definition, being able to answer 'Nothing', 'Little' or 'Very much' as a subjective measure of the reactivation strength, based on van Kesteren et al. (2018).

Testing phase. In Experiment A1, a cued-recall test (TS) was performed 48 h after word learning to evaluate the declarative memory of the words´ definitions. Each word appeared on screen and participants were instructed to type the definition, with no time limit and this time without feedback. This test consisted of a single block and the order of the words was randomized.

Experiment A2 evaluated the integration of the new lexical items by the degree to which they can be semantically primed by related words. A semantic relatedness task (adapted from Kaczer et al., 2018 and Poort & Rodd, 2019) was performed 48 h after the word learning as depicted in **Figure 1**A and **1B**. The choice of this task instead of lexical decision was based on the fact that a high repetition rate was necessary given the limited set of novel words, and it was demonstrated that the semantic relatedness judgment could preserve priming effects better than lexical decision when stimuli are repeated (Renoult et al., 2012).

Participants were instructed to decide as quickly and accurately as possible whether a pair of sequentially presented words (i.e., prime-target) were related or not. Recently learned words (e.g. “CITOLA”, a musical instrument) were used as targets with related words (e.g. “melody”) or unrelated words (e.g. “bottle”) as primes. In addition, a set of familiar words were included as a baseline condition. A practice block with feedback of 12 prime-target pairs was followed by three blocks of 80 experimental pairs each. The order of the pairs within blocks was randomized for each participant, as was the order of the blocks. The experimental pairs included 20 novel words and 20 familiar words, each one associated with three semantically related primes and three unrelated primes (thus, no prime– target pairs were repeated). A trial started with a 1000 ms fixation screen. The prime was presented for 250 ms, followed by a blank screen for 50 ms, and the target remained for 2500 ms, where a “yes” or “no” response should be made. If participants didn't respond after 2000 ms passed, a warning was presented on screen indicating that response was being slow. The responses were made with a button press from the keyboard, using the “j” key for the “yes” responses and the “k” key for the “no” responses.

Data analyses. Experiment A1 employed a mixed design. Reactivation was a between-participants factor, as participants were assigned either to the Control or the Reactivated group; Phase was a within-participants factor as participants in both groups performed the three learning task phases and the testing phase; and Degree of reactivation was a within-participants factor as participants in the Reactivated group had to choose between the three levels of reactivation strength (“Nothing”, “Little” or “Very much”) for each word. Experiment A2 also employed a mixed design. Reactivation was a between-participants factor; Degree of reactivation was a within-participants factor; and Relation and Familiarity in the semantic relatedness task were within-participants factors as participants in both groups saw all words belonging to each word type (related and unrelated; familiar and novel). All models included significant random intercepts for participants and items.

All data was analyzed within R (R Core Team, 2019). Accuracy data was analyzed with the *glmer* function from the lme4 package (Bates, Maechler, & Bolker, 2015) to perform a generalized linear mixed model (GLMM) using a binomial family and the logit link. In the learning task and in the declarative test, a response was considered as correct if the written answer reflected the kernel of the word´s meaning, allowing the use of synonyms and the omission of adjectives accompanying the noun. For example, if the response for the word “CITOLA” (whose definition is “ancient musical instrument”) was “*instrument*”, this was considered as a correct response. In the semantic judgement task, reaction times were analyzed with the lmer function from the *lmerTest* package (Kuznetsova, Brockhoff, & Christensen, 2017) to perform a linear mixed model (LMM). Only accurate trials were considered for the response times analysis (discarding 12.7 % of the data). Also, trials with reaction times less than 300 ms were discarded (< 0.01 % of the data). The RTs were log10-transformed (logRT = log10(RT)) as visual inspection of a residuals versus fitted values plot and a histogram of residuals revealed deviations from homoscedasticity and normality (the log10-transform revealed a better distribution of the residuals across the range of fitted values than an inverse-transform). After transforming the RTs, any logRTs that were more than two standard deviations above or below each participant's mean per condition were removed (4 % of the remaining data). The significance of a factor was determined with a Likelihood-Ratio Test comparing the model that includes the factor with a model dropping that factor. Pairwise post-hoc analysis was performed using the *emmeans* package in R and applied the Tukey correction to the p-values for comparisons.

<u>RESULTS (STUDY A)</u>

Experiment A1. The aim of this experiment was to evaluate the effect of memory reactivation on long-term memory for the recently acquired definitions. It is shown (**Figure 2**) that during the learning task participants are able to recall most of the novel meanings when confronted with the associated words, reaching an accuracy higher than 75% at the end of the learning session (TR3) in both groups. Regarding the type of errors, most correspond to blank responses (64%), followed by exchange errors where participants wrote down other definition from the list (31%), while other types of errors, such as confusion are less common (5%). Accuracy data for the cued-recall test were analyzed using mixed-effects models with two fixed factors: Phase (within-participants levels: TR1, TR2. TR3, TS) and Reactivation (between-participants levels: Control, Reactivated). Statistical analysis revealed a significant interaction between Phase and Reactivation [χ^2 (3) = 33.80, p <0.001]. Pairwise simple contrasts revealed that, as expected, accuracy values increase significantly throughout the training trials (p <0.001) and that there are no initial significant differences in the learning task performance between the Control and the Reactivated group ($p = 0.76$), which is a prerequisite for analyzing the effect of reactivation on a later memory retention (see the data of the initial learning for both groups in Supplementary Table 1). Importantly, pairwise simple contrasts revealed significant differences between the Control and the Reactivated group in the testing session ($p < 0.001$, $\Delta = -12.3\%$), indicating that the Control group presented a significant decay in the accuracy from training to testing session ($p < 0.001$, $\Delta = -11.1\%$), while the Reactivated group presented no significant differences in accuracy from training to testing ($p = 0.901$, $\Delta = 0.8\%$). Finally, we performed a within-participants analysis in the Reactivated group for which we only included the words that were correctly answered by each participant in the last block of practice of the learning task (TR3), in order to ensure that all words start from the same level of learning. Then, we compared the performances in the cued-recall test, according to the response offered by the participants on Session 2, where they were asked to rank how much they were able to recall each word´s definition. We analyzed accuracy data for the cued-recall test within the Reactivated group with using mixed-effects models with Degree of reactivation (within-participants levels: “Nothing”, “Little”, “Very much”) as fixed factor. This analysis revealed a significant effect of the Degree of reactivation [$\chi^2 (2) = 186.25$, $p < 0.001$], showing that a higher reactivation reported by participants resulted in a higher performance in the testing phase (**Figure S1**).

Experiment A2. Our aim was to establish the effect of memory reactivation on the semantic integration of the recently learned words, by analyzing how they were modulated by related meanings. Before analyzing the effect of reactivation on the semantic judgment task, we confirmed that no initial significant differences were present in the learning task performance between the Control and the Reactivated groups, both reaching an accuracy higher than 75%

at the end of the learning session (TR3). Results of the semantic task are shown in **Figure 3**. Accuracy and response times data for the semantic relatedness task were analyzed using mixed-effects models with three fixed factors: Familiarity (within-participants levels: familiar, novel), Relation (within-participants levels: related, unrelated) and Reactivation (between-participants levels: Control, Reactivated). The analysis of accuracy scores (**Figure 3A**) presented non-significant interactions between any of the factors. A significant main effect of Familiarity was revealed [χ^2 (1) = 36.05, p <0.001, Δ = -12.0%], showing that overall performance was better for existing words than for novel words. In addition, a significant effect of Relation revealed higher accuracy in the unrelated condition [χ^2 (1) = 171.72, p <0.001, Δ = 5.8%].

On the other hand, the analysis of response times (**Figure 3B**) revealed a significant interaction between Familiarity and semantic Relation [χ^2 (1) = 31.66, p <0.001]. Pairwise simple contrasts indicated that familiar words presented faster response times than novel words but unrelated words presented a higher difference between the familiar and novel words (p <0.001, Δ = 225 ms) than the related words (p <0.001, Δ = 166 ms) . Besides, we found a significant interaction between Familiarity and Reactivation [χ^2 (1) = 19.78, p <0.001], showing that the Reactivated group presented a smaller difference in response times between the familiar and novel words (p <0.001, Δ = 175 ms) compared with the Control group (p <0.001, Δ = 215 ms).

Regarding the within-participants analysis of the Reactivated group (**Figure S2**), the analysis only included the words that were correctly answered by each participant in TR3. Accuracy and response times data for the semantic relatedness task were analyzed using mixed-effects models with three fixed factors: Familiarity (within-participants levels: familiar, novel), Relation (within-participants levels: related, unrelated) and Degree of reactivation (within-participants levels: “Nothing”, “Little”, “Very much”). Statistical analysis revealed a significant interaction between Relation and Degree of reactivation [χ^2 (2) = 16.70, p <0.001] for accuracy data. Pairwise simple contrasts indicated that a strong reported reactivation ("Very much" level) corresponded to a more accurate response compared with a weak reactivation ("Nothing" level) for both the related ($p < 0.001$, $\Delta = 33.5\%$) and, with a smaller effect, unrelated words ($p = 0.005$, $\Delta = 7.2\%$). Finally, the analysis of degree of reactivation for response times data revealed a significant main effect of Degree of reactivation [$\chi^2 (2) = 14.43$, $p < 0.001$], also indicating that higher values of reported reactivation correspond to faster responses in the semantic judgement task.

DISCUSSION (STUDY A)

Results of Experiment A1 demonstrated that the inclusion of memory reactivation in between learning and testing produces a boosting effect on memory performance. In particular, while the Control group (that did not receive the reactivation) showed a typical decay in memory accuracy from training to testing, the Reactivated group (exposed to the recently learned words 24 h after training) maintained the same level of accuracy 48 h after learning (Figure 2). Therefore, we interpret this finding in the context of a vast literature that demonstrated the positive effects of retrieval on memory performance (Chan, Meissner, & Davis, 2018; Karpicke & Roediger, 2008). In this sense, it has been repeatedly shown that retrieval, i.e., the act of making stored information available for use, plays a central role in later recall (Barcroft, 2007; Bavassi et al., 2019). For instance, it is known that taking a test improves later retention of the information compared with restudying the same material (Roediger & Karpicke, 2006). It was proposed that this 'testing effect' could enrich existing memory traces or facilitate the access to the stored information (Roediger & Butler, 2011). From a neurobiological framework, this effect could be interpreted by the memory reconsolidation hypothesis, that state that specific reminders could enhance memory persistence and precision (e.g., Lee, 2008).

Importantly, our results showed that the effect of memory reactivation depends on the strength of the perceived sense of recall (**Figure S1**), reported immediately after the reminder presentation. Thus, not all cues generate the same boosting effects as reminders: a higher degree of reactivation leads to a better memory performance on the cued-recall test performed the next day. Importantly, to make sure that this result is not due to differences during encoding, we only included in our analysis the words which definition was correctly answered during the last block of the training session (TR3). Moreover, taking into account that the screen display time of the reminder was not fixed (but self-paced), we checked whether differences in the degree of reactivation could be explained by differences in the time spent reading the reminder (data not shown). On the contrary, we found that the higher reported levels of reactivation present shorter display times than lower values. All in all, these results show there is a graded enhancement effect of the reminder according to its level of reactivation, possibly implying differences in the efficiency exerted by the reminders in the process of lexical access. In addition, these results shed light into the importance of metamemory ratings during recall, and constitute a powerful tool to address item variability (van Kesteren, Rignanese, Gianferrara, Krabbendam, & Meeter, 2020).

In Experiment A2 we analyzed the consequences of memory reactivation in the lexical integration of novel meanings, using a semantic judgement task. The rationale for this task is that after learning, novel words may become generalized beyond the specific context in which they were learned, thus becoming stable semantic representations (Davis & Gaskell, 2009) and able to interact with other related lexical entries. Thus, we were interested in determining whether the presentation of a reminder could benefit this process. Results showed that participants in the Reactivated group presented faster response times for novel words respect to the Control (**Figure 3B**), while their accuracy was not compromised (**Figure 3A**). Thus, these results reinforce the previous finding about a boosting effect of memory reactivation, in this case indicating there would be a faster lexical processing when a reminder is included between learning and testing. In addition, we performed a within-participants analysis of the Reactivated group's responses during testing, according to their reported level of reactivation (**Figure S2**). Notably, we found that higher subjective values of reactivation lead to higher accuracy and faster response times in the semantic task. Thus, including the within-participants comparison allowed us to find an effect on accuracy that was occluded in the between-groups comparison (Control *versus* Reactivated), as in the latter all words are considered either reactivated or not, whereas in the former it is possible to disentangle highly from no lower reactivated items.

On the whole, results of Study A reinforce previous findings regarding the positive role of memory retrieval for subsequent memory, extending them to the formation of novel linguistic knowledge, and also provide new evidence for the specific effect of reactivation on semantic integration. However, we know that memories are not static, so in the following set of experiments we studied the implication of memory reactivation in the modification of a novel word's meaning.

STUDY B. Role of reactivation in memory updating

The experimental design and the tasks are depicted in **Figure 1**.

MATERIAL AND METHODS (STUDY B)

Participants. Three different online experiments were performed, recruiting a total of 173 subjects. The final number of participants in each group and their demographic information is shown in **Table 2**. Participants were excluded using the same criteria as for Study A. A total of 107 participants took part in Experiment B1, being randomly assigned to one experimental group (Control or Reactivated). From these, 15 were excluded due to not following the instructions or not fulfilling the age requirements to participate, 16 participants due to low performance (eight in the Control group and five in the Reactivated group) and one participant in the Control group due to a 100% performance in the first block of practice. A total of 34 participants were recruited for Experiment B2. Five participants were excluded due to not following the instructions and seven due to presenting low learning performance. Finally, 32 participants were recruited for Experiment B3, of which four were excluded due to not fulfilling the age requirements and three due to presenting low learning performance.

Stimuli

Novel words. The same 20 Spanish words with their corresponding definitions as Study A were used.

New info. The new information for the words' definitions was constructed using additional data from the original definition of each word. For some words, new information was adapted or invented in a way that it was congruent with the original definition. The new information was no longer than 8 words (Range = 3-8 words; 29-42 characters). See Supplementary Materials for the full list of novel words together with their corresponding new congruent and incongruent information.

Procedure

Learning task. The same Learning task as Study A was used for this study.

Reactivation and updating phase. The Reactivated group from Study B received an intermediate session between the learning and testing sessions where the reactivation and the updating phases took place. The session started with the same reactivation protocol as Study

A, where a reminder consisting of the 20 words without their definitions was presented and, in each case, participants were instructed to try to remember the corresponding definition but without writing it down. Immediately following this, they were asked to rate how much they remembered the word´s definition. The updating phase for each word's definition was performed after its reactivation as shown in **Figure 1A** and **1B**. It consisted of the presentation of the new information together with its corresponding word (e.g. 'CITOLA' next to 'with four strings, similar to a violin'), with no time limit. This new information was then practiced once, as the word appeared again on screen and participants were asked to type the new information that they had just seen, also with no time limit. A single practice trial was included in order to avoid ceiling effects, based on Forcato et al. (2010). The Control group also received this intermediate session but it only included the updating phase, thus starting the session with the presentation of the new information for each word.

-Experiment B1: the reactivation-updating session took place 24 h after the learning session. To accomplish this, a delay was set in the Gorilla Experiment Builder and after completing the experiment we controlled that all participants had performed this session within a delay close to 24 h. Moreover, the new information included for the updating was congruent with the word's definition previously learned.

-Experiment B2: the reactivation-updating phase was performed 30 min after the learning session. A delay was set in the Gorilla Experiment Builder and we controlled that all participants had performed this session after a minimum of 30 min and a maximum of 1 h from the learning session. Again, the new information included for the updating was congruent with the word's definition previously learned.

-Experiment B3: the reactivation-updating was performed 24 h after the learning session. The delay was set the same way as in Experiment B1. In this case, the new information included for the updating was not congruent with the word's definition previously learned. In order to assign the incongruent new information to the 20 novel words, we used the previously selected congruent new information and pseudo-randomly reassigned it to each of the words.

Testing phase. Participants for all three experiments performed a cued-recall test 48 h after the word learning to evaluate the initial definition and the updated definition (i.e., the initial definition plus the new information) of each word. Each word appeared on screen and participants were instructed to type all the information that they remembered, including the one shown in the first and in the second session of the experiment. There was no time limit and they did not receive any feedback. This test consisted of a single block and the order of the words was randomized. Responses that only included the initial definition and responses that included the updated definition were rated independently. For instance, if a participant's response to "CITOLA" was only "*Ancient musical instrument*", the initial definition was considered to be responded correctly but the updated definition was considered to be responded incorrectly because the answer did not include the new information ("With four strings, similar to a violin"). Similarly, if a participant's response to "CITOLA" was only "*With four strings, similar to a violin*", the initial definition was considered as incorrect, and also the updated definition was considered as incorrect because in order to evidence an incorporation of the new information -rather than a replacement- the initial definition has to be present too.

Data analyses. A similar design as Experiment A1 (Study A) was employed: Reactivation was a between-participants factor; Phase was a within-participants factor; and Degree of reactivation was a within-participants factor. Study B also employed Type of definition as a within-participants factor, as participants were evaluated on the initial definition and on the updated definition; and Experiment as a between-participants factor as participants took part either Experiment B1, Experiment B2 or Experiment B3. All models included random intercepts for participants and items.

RESULTS (STUDY B)

Experiment B1. The aim of this experiment was to evaluate the effect of memory reactivation on the incorporation of new information to novel words. We confirmed that no initial significant differences were present in the learning task performance between the Control and the Reactivated groups, both reaching an accuracy higher than 75% at the end of the learning session (TR3). First, accuracy data for the cued-recall test on Day 3 were analyzed using mixed-effects models with two fixed factors: Type of definition (within-participants levels: "initial definition", "updated definition") and Reactivation (between-participants levels: Control, Reactivated). Statistical analysis revealed that the performance between groups does not show a significant interaction between Type of definition and Reactivation [χ^2 (1) = 2.43, p = 0.12] nor a significant effect of Reactivation [χ^2 (1) = 2.60, p = 0.11]. Second, accuracy data for the cued-recall test within the Reactivated group was analyzed using mixed-effects models with Degree of reactivation (within-participants levels: "Nothing", "Little", "Very much") as fixed factor. For this analysis, two separate models were performed for the initial definition responses and for the updated definition responses. The analysis of the degree of reactivation (**Figure 4**, Exp. B1) including the words that were correctly answered by each participant in TR3 showed a significant effect of Degree of reactivation for the initial definition [χ^2 (2) = 27.07, p <0.001], indicating that a higher accuracy is obtained with higher levels of reactivation strength, in coincidence with the findings obtained in Experiment A1. Remarkably, the Degree of reactivation factor also revealed a significant effect in the acquisition of new information [χ^2 (2) = 17.61, p <0.001]: more reactivation of the initial definitions entailed a higher accuracy for the updated definition. It is of note that the new information has lower values of memory accuracy (43.8%, combining all trials), respect to the initial definitions (77.4%), as it was only practiced once, while the original definitions were practiced three times. The data of the total accuracy in the cued-recall test and accuracy by degree of reactivation for the initial and updated definitions is shown in Supplementary Table 2.

Thus, this experiment demonstrated that new information could be better incorporated to an initial definition when the original memory is highly reactivated.

Experiment B2. In this experiment we were interested in determining the time course of the reactivation effect that we obtained in the previous experiment. Thus, the procedure was mostly identical to Experiment B1, but in this case reactivation was performed 30 min after the end of Session 1, addressing whether a long-term consolidation was necessary for obtaining the boosting effect of reactivation. In this case we only performed a within-participants analysis, based on the lack of differences obtained in Experiment B1 between groups.

The learning task performance reached an accuracy of 81% at the end of the learning session (TR3). As it is shown in **Figure 4** (Exp. B2), the pattern of results is similar to the ones obtained in the previous experiment. In the cued-recall test, there is a significant effect of Degree of reactivation for both the initial definition [χ^2 (2) = 27.07, p <0.001] and the updated definition [χ^2 (2) = 8.57, p = 0.01], where higher levels of reported reactivation lead to higher accuracy values. Thus, these results suggest that a 24 h interval is not necessary to obtain the facilitation effect of reactivation on updating.

Finally, we compared Experiments B1 and B2 in order to examine differences in the performance on the initial and updated definitions. We confirmed that no initial significant differences were present in the learning task performance between experiments [$\chi2$ (2) = 3.50, p = 0.17]. In addition, we explored if there were any differences in the distribution of responses of degree of reactivation. Statistical analysis shows that there is no significant difference in the proportion of degree of reactivation responses between experiments from Study B [$\chi2$ (2) = 3.66, p = 0.16]. The data of the initial learning and reactivation strength between experiments is shown in **Supplementary Table 1**. We further compared accuracy data for both experiments using mixed-effects models with two fixed factors: Type of definition (within-participants levels: “initial definition” “updated definition”) and Experiment (between groups levels: “Experiment B1”, “Experiment B2”). The comparison of Experiment B1 and 4 (**Figure 5**) revealed that there is a significant interaction between the factors Time and Type of definition [χ 2 (1) = 7.91, p = 0.004], while pairwise simple contrasts do not show significant differences. These results show that the effect of performing the reactivation session 30 min after learning (Experiment B2) is opposite depending on the type of information: there’s an enhancement in the accuracy for the initial definitions and a reduced accuracy for the updated definitions respect to the 24 h interval.

Experiment B3. In this experiment we aimed to manipulate the congruence between the initial definitions and the new information, taking into account previous findings that demonstrated the importance of schemas in the integration of new information (Gilboa & Marlatte, 2017). Therefore, the procedure was the same as Experiment B1, but in this the new information was unrelated to the initial definition.

The learning task performance reached an accuracy of 84% at the end of the learning session (TR3). Results of the testing session are shown in **Figure 4** (Exp. B3). Regarding the performance of initial definitions in the cued-recall test, it is similar to the previous experiments, showing a significant effect of reactivation [χ^2 (2) = 98.85, p <0.001]. However, the observed pattern for the updated definitions is very different: it is clearly shown that in this case participants were not able to grasp the new information, as there is a nearly zero accuracy. Thus, congruency with previous information could constitute a boundary condition for the effect of reactivation on memory updating.

DISCUSSION (STUDY B)

These series of experiments addressed the influence of memory reactivation in the modification of a novel word's definition. In Experiment B1, no significant differences in memory accuracy were shown for the updated definition between the Control group and the Reactivated group. That is, the between-groups comparison does not reveal a benefit of the reminder in the incorporation of the new information. However, a within-participants analysis of the Reactivated group revealed a contrasting result: highly reactivated words (measured by the subjective ranking) presented a higher accuracy for the updated definition (**Figure 4**, Exp. B1). Thus, when a novel word's definition was ranked as highly reactivated (e.g. "CITOLA", *Ancient musical instrument*) participants were then better able to grasp the new information (*With four strings, similar to a violin*), reaching nearly a 50 percent accuracy in the cued-recall test, which is remarkable given they've only practiced it once. In addition, results reveal a positive effect of reactivation level on the initial definition, in coincidence with the previous experiments of Study A. It is interesting to discuss this puzzling discrepancy between the within-participants effect and the between-groups comparison. We suggest that this discrepancy could be inherent to the experimental design of updating experiments, of the A-B, A-C type (e.g. Schilchting & Preston, 2015). In these cases, participants first learn an association between A and B (in this case, a word and its definition), and this association is later complemented by a new association between A and C (in our case, a word and a new information). Although the participants of the Control group do not receive a reminder phase (where they actively have to access B), they are presented with the novel words during the updating phase (A-C), where they could covertly retrieve their definitions (Ozubko, Moscovitch, & Winocur, 2017). Therefore, it is possible that both groups reactivate original meanings similarly. From this, we suggest that the within-participants comparison is more appropriate to evaluate the effects of reactivation in memory updating. In addition, it is important to mention that, contrary to Study A, in this set of experiments we did not directly addressed the semantic integration of the recently learned words, as we only used a cued-recall task that allowed us to disentangle the memory for the original and the new information.

Besides, these experiments analysed the dynamics of the effect of memory reactivation on the incorporation of new information, comparing the effect of reactivating 24 h after learning (Exp. B1) or 30 min (Exp. B2). While 24 h after learning participants had a night of sleep, which is usually a crucial step for systems consolidation (Diekelmann & Born, 2010), 30 min after training is considered a short interval for memory to be consolidated (McGaugh, 2000). However, there are several reports that suggest a rapid and sleep-independent consolidation (e.g., Lindsay & Gaskell, 2013; Tamminen et al., 2020) as a result of schemas or retrieval-induced learning, thus leaving open the possibility that an effect of reactivation might be found at short intervals. Our results showed that reactivating memory 30 min after learning still produces an improvement in memory updating (**Figure 4**), i.e., higher levels of memory reactivation lead to a more accurate memory performance for updated definitions. However, when comparing overall performance between Exp. B1 and Exp. B2 (**Figure 5**), we found there were significant differences in memory accuracy, but with opposite patterns for the updated and the initial meaning. While the 30 min interval in Exp. B2 favored the memory for the initial definitions (probably because of a shorter interval between learning and testing), this was not translated into a better accuracy for the updated definition. On the contrary, memory for updated definitions was better in Exp. B1 when a 24 h interval was used between learning and reactivation.

It is interesting to frame the above results under the consolidation *versus* reconsolidation updating effects: is it possible to modify a memory trace shortly after learning? Or instead, is time after acquisition a boundary condition to obtain an updating? Regarding modifications of memory while memory is still unconsolidated, evidences are scarce, but an influential antecedent is the classical research of Izquierdo (Izquierdo & Chaves, 1988), describing the longest time interval at which new information can be added to the initial verbal memory only up to 3h after training. In this sense, a possible function for the transient short-term memory phase is to provide the organism with an opportunity to evaluate, classify and rearrange information before storing it (Dudai, 2002; Menzel, 1999), so it seems plausible that modifications during this initial phase could be incorporated to the long-term memory (Suárez, Smal, & Delorenzi, 2010). On the other hand, there is compelling evidence about the memory modifications produced after reactivating a long-term consolidated memory (i.e., using a 24 h interval), most of these are framed under the reconsolidation hypothesis (e.g., Lee, 2009). It is important to notice that the reminder used in this study would involve a prediction error (i.e, participants expect to write down the definition and receive feedback, but instead they are told to think of the definition), which is a necessary condition to trigger the labilization-restabilization process (Fernández, Bavassi, Kaczer, Forcato, & Pedreira, 2016). It has been suggested that reconsolidation opens up declarative memory to the entrance of new information (Forcato et al., 2010). Therefore, it is possible that our results showing that higher reactivation leads to strengthening of the initial memory and increased updating could be a consequence of the reconsolidation process. However, our results show that the magnitude of the updating effect is time-dependent and increases with a longer time interval, such as 24 h. Thus, the boosting effect of reactivation-reconsolidation would be time graded instead of an all-none process, although we would need to include additional time points to test this hypothesis.

Finally, results of Experiment B3 showed that participants could not recall the incongruent information (Figure 4), while their retention for the original definitions was not affected. While in Exp. B1, using a congruent information, we obtained values of nearly 50 percent accuracy for the updated definitions, in this case the results show a surprising zero memory retention. One possibility is that this result is due to a poor acquisition of the new information because of the lack of congruence with the initial definition. Previous results showed the importance of prior knowledge for incorporating new information, where it can be best assimilated into a schema and thereby expand the knowledge base (Tse et al., 2011). However, we consider that a weak training protocol is adequate for observing an effect of reactivation on memory updating, based on previous studies (Forcato et al., 2010). On the other hand, it is possible that the incongruent information might not be correctly accessed by participants during the testing session, probably due to a retrieval interference process, where the original definitions occludes the memory for the new information (Anderson & Hulbert, 2021).

GENERAL DISCUSSION

Words are very malleable memories. In the present study we focused on one possible mechanism for this remarkable memory plasticity. Specifically, our goal was to determine the influence of memory reactivation in the process of a novel word's memory formation. First, we hypothesized that memory reactivation could have a boosting effect that should be expressed in both the word-to-definition memory and also its semantic integration. Accordingly, results of Experiment A1 showed that memory reactivation increases memory retention respect to a control group, protecting memory against forgetting. This result is consistent with compelling evidence that has demonstrated that reactivating a memory by brief re-exposure to the acquired information mitigate forgetting by increasing the persistence of the memory and/or its precision (Lee, 2008; Rodríguez et al., 2013). Noteworthy, in the present study we do not use novel words as a generic type of mnemonic items, but instead we are specifically interested in the memory for words and the process of semantic integration, through which novel words can interact with other entries established in the mental lexicon. Therefore, we then asked in which way memory reactivation may promote semantic integration of a recently learned word. Results of Experiment A2 showed that reactivation facilitates a semantic decision for novel words, making it faster than a control group. Besides, we found that subjective reactivation scores were positively related to subsequent long-term memory performance such that higher reactivation of the definition led to more accurate and faster response times in the semantic decision task. These results suggest that participants' responses were associated with the strength of reactivation, which turned out to be a valid predictor of later memory performance (St. Jacques & Schacter, 2013; van Kesteren, Rignanese, Gianferrara, Krabbendam, & Meeter, 2020). All in all, results of Study A reinforce previous findings regarding the positive role of memory retrieval for subsequent memory and also provide new evidence for the specific effect of reactivation on lexical integration.

We are usually able to incorporate new information into a recently learned word, which allows us to redefine and update our knowledge. Our second hypothesis was that memory reactivation facilitates the modification of a new word's definition. In Study B we showed that a higher level of memory reactivation 24 h after learning facilitates the incorporation of new information to the original definition (Exp. B1). Importantly, in this case, the new information was not intended to replace the original definition, as it was usually the case in several updating paradigms of paired associations (Hupbach et al., 2008). On the contrary, participants were asked to add a new piece of information that was congruent with the initial definition. It is interesting to discuss whether the original and the new information constitute an integrated single memory trace or instead they are separate chunks of information that are retrieved together during the cued-recall task. In Forcato et al. (2010), using an updating procedure in a syllable pair-association task, it was established that the new information was incorporated into the single former memory, but only under certain conditions of the reminder, otherwise there was interference in retrieval of both the original and the new information, suggesting that they are encoded independently and coexist as separate memories. We argue the nature of the linguistic stimuli in our study promotes memory integration when the new information is congruent (Exp. B1 and B2), but not when it is incongruent with the previously established memory (Exp. B3). For instance, if we take into account that after only a single trial of practice of the new information participants can obtain a nearly 50 percent of accuracy (as seen in highly reactivated words in **Figure 4**), it seems plausible that the new memory becomes incorporated to the previous one. Moreover, in Study B we determined that time after training would not represent a boundary condition for updating to occur, as even a short period of 30 min after learning is enough to incorporate new information, although the effect is more pronounced with a 24 h interval. In this sense, there are several studies showing that memory consolidation could occur faster if it adapts to a previous scheme (Hebscher, Wing, Ryan, & Gilboa, 2019; Tse et al., 2011). This way, the congruence between the definition and the new information incorporated could allow an alternative consolidation route through which the memory that is incorporated does not depend crucially on the hippocampus and instead could present, to some extent, a direct integration to cortical representations.

It is interesting to discuss the cognitive mechanisms that could be responsible for the effect of memory reactivation. It has been found that reactivation provokes a state of memory instability that may lead to interference and forgetting (Fernández et al., 2016; Hupbach et al., 2007), but it also provides an opportunity for memories to interact with one another

(Robertson, 2012). Through these interactions, the shared elements between memories may activate common networks that would strengthen them, and allow their integration. This process has also been referred to as semanticization, as it allows more general memory aspects to be integrated (Ferreira, Charest, & Wimber, 2019). Emerging studies suggest that the medial prefrontal cortex (mPFC) plays an important role in the rapid formation of cortical memories, especially during retrieval practice. It has been suggested that retrieval practice reactivate related memory traces and that the mPFC can develop integrated neocortical representations of these memory traces rapidly (Antony, Ferreira, Norman, & Wimber, 2017). Consistently, the mPFC is involved in the integration and updating of reactivated memory traces (Gilboa & Marlatte, 2017; Preston & Eichenbaum, 2013; Sommer, 2017). Therefore, future studies will allow us to determine the implication of this brain region in the updating of a novel word´s meaning.

We acknowledge certain limitations of our study. First, we don't have an objective measurement of memory reactivation, but instead we asked participants to rate how much they recalled each words' definition. Although it would be important to obtain a physiological measurement of reactivation in our experiments, we based our procedure on previous findings that demonstrated that activity within the parahippocampal area predicted subjective reactivation strength (van Kesteren et al., 2020), suggesting it might correspond to neural reinstatement of the original memory. Second, we are aware that the Control and Reactivated groups differ in the number of exposures to the novel words, as the latter received an additional exposure during reactivation. However, we consider that this additional exposure does not explain our results showing a memory boosting effect, based on the following arguments. In Experiment A1, the participants in the Reactivated group that rated with low values of subjective reactivation on Day 2, then showed a low memory retention, of around 40 percent of accuracy on the final cued-recall test on Day 3 (shown in the Figure S1). Thus, it is not the mere exposure what caused the potentiation, but instead the memory reactivation caused by the reminder. In addition, it is important to note that the reminder only includes the words, not the definitions, which is the information that we evaluated on the final cued-recall test. Thirdly, although we consider the semantic judgment task used in Experiment A2 as a reliable marker of lexical integration based on previous studies (Bakker et al., 2015; Kaczer et al., 2018), it is also possible that participants can perform the task by accessing relevant episodic memories (Fang & Perfetti, 2019). Although the characteristics of the task, such as the short stimuli onset asynchrony, make it difficult to depend mostly on episodic retrieval, it is impossible to fully exclude its influence on the decision.

Finally, the results of the present study suggest that reactivation could be one of the mechanisms that allow us to better incorporate a new meaning to an existing word. Therefore, our study could have implications for the acquisition of polysemy (Rodd et al., 2012). This form of ambiguity between related word senses is very common across languages (Srinivasan & Rabagliati, 2015). In the case of polysemy, the new meaning is related to the one already known, such as when one learns “virus” is also a type of malicious software, which is distinguished from homonymy (Maciejewski, Rodd, Mon-Williams, & Klepousniotou, 2020), where the two meanings are not related, such as “bat” the animal, and the implement to hit the ball. In the former case, reactivating the original meanings may facilitate the activation of a memory schema and contribute to the integration of the novel definition, minimizing interferences between the different meanings. On the other hand, homonymy could be related to Experiment B3, where the new information was incongruent, and the positive effects of reactivation were not observed. Understanding more about how reactivation affects new learning is important in situations where effective knowledge building is key, such as in education. In this sense, the importance of memory reactivation in the classroom has already been pointed out by several authors (McDaniel, Anderson, Derbish, & Morrisette, 2007;

Roediger & Karpicke, 2006). Thus, the results of this work suggest that this practice could be extended to the teaching of words and multiple conceptual information associated with them, which is essential to build new knowledge.

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Declaration of interest statement

No potential conflict of interest was reported by the authors.

Data deposition

All data and stimuli are deposited in Open science framework: https://osf.io/rn2y9/.

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Appendix

Novel word	Definition	New information (congruent)	New information (incongruent)
BADINA	Water puddle.	Accumulates industrial waste.	Obtained from a rye fungus.
CAURO	Wind from the north-west.	It is cold and comes from the Mediterranean.	Caused by overeating.
CÍTOLA	Ancient musical instrument.	With four strings, similar to a violin.	Used to measure the diameter of the Earth.

EPINICIO	Song of victory.	Created for Olympic fighters.	Characteristic of rush hour travel.
ERGOTINA	Remedy for hemorrhages.	Obtained from a rye fungus.	Executed only by men from the Basque Country.
FISGA	Fishing spear.	Made of iron and trident shaped.	Contains antioxidants and vitamin C.
GREBA	Knee armor.	Lined with leather on the inside.	With four strings, similar to a violin.
JABARDO	Agglomeration of people.	Characteristic of rush hour travel.	Present in Gothic castles.
LASTO	Payment receipt.	Given when buying a horse.	Located in the basement of mansions.
MAINEL	Railing of a staircase.	Present in Gothic castles.	Destined for Franciscan monks.
MARMITÓN	Kitchen assistant.	Present on merchant ships.	It is fluorescent yellow.
NENIA	Funeral poem.	Recited accompanied by flutes.	Given when buying a horse.
NOMON	Sundial.	Used to measure the diameter of the Earth.	Often used in lagoons of Chubut.
PILTRO	Room of a temple.	Destined for Franciscan monks.	Lined with leather on the inside.

POSMA	Slowness to do something.	Caused by overeating.	Recited accompanied by flutes.
QUIMA	New branch of a tree.	Contains antioxidants and vitamin C.	Made of iron and trident shaped.
RETEL	Crab fishing net.	Often used in lagoons of Chubut.	Created for Olympic fighters.
SAMARUGO	Frog tadpole.	It is fluorescent yellow.	It is cold and comes from the Mediterranean.
TINELO	Dining room for servants.	Located in the basement of mansions.	Accumulates industrial waste.
ZORCICO	Type of Spanish music.	Executed only by men from the Basque Country.	Present on merchant ships.

Table 1

Mean age (± SEM) and gender ratio (male respect to female) in each experimental group of Study A.

Experiment	**Group**	**Mean Age (± SEM)**	**M:F Ratio**	**N**
A1	Control	25.7 (0.7)	0.43	43
	Reactivated	27.4 (0.7)	0.45	64
A2	Control	26.7 (1.0)	0.53	26
	Reactivated	25.7 (0.7)	0.45	32

Table 2

Mean age (± SEM) and gender ratio (male respect to female) in each experimental group of Study B.

Experiment	**Group**	**Mean Age (± SEM)**	**M:F Ratio**	**N**
B1	Control	25.1 (0.7)	0.31	46
	Reactivated	27.9 (0.8)	0.33	36
B2	Reactivated	23.0 (0.9)	0.10	22
B3	Reactivated	25.7 (1.0)	0.47	25

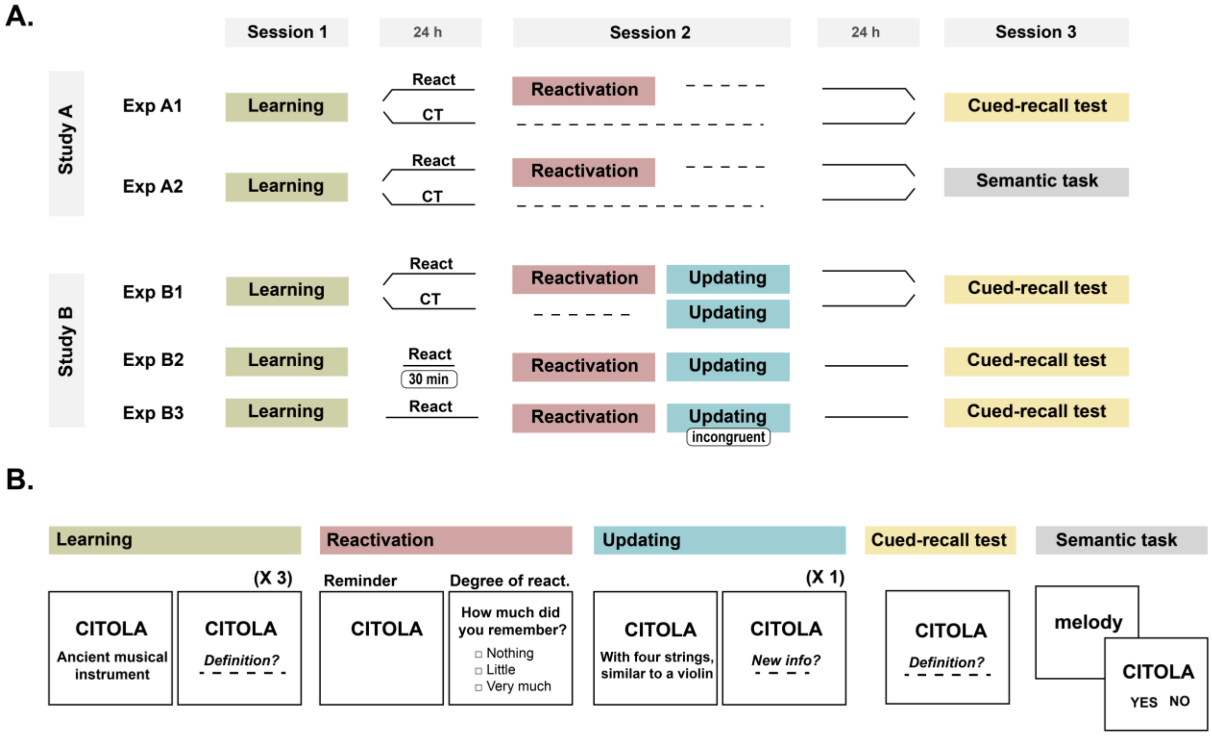

Figure 1: (**A**) Schematic diagram showing the experimental groups for Study A and Study B. All groups performed the learning task on Day 1. In Study A, reactivated groups (React) received the reactivation phase, while control groups (CT) didn't. Memory was evaluated with a cued-recall test (Exp A1) or a semantic task (Exp A2). In Study B, 24 h (Exp B1 and Exp B3) or 30 min (Exp B2) after learning, reactivated groups (React) received the reactivation followed by the updating phase for each word, while the control group (CT) only received the updating phase. The new information was congruent (Exp B1 and Exp B2) or incongruent (Exp B3) with

the initial definition. (**B**) Overview of the tasks. During the **learning** task, participants learn 20 rare words with their definitions. The **reactivation** phase included the presentation of each word and participants were instructed to remember the definition without writing it down (reminder), followed by a subjective measure of the degree of reactivation. The **updating** phase consisted of the presentation of each word together with new information and only one block of practice. For the **cued-recall test** participants had to write the definition presented in the learning task (in Study A) or the updated definition also including the new information presented in the updating phase (in Study B). For the **semantic integration task** novel words were used as targets with related or unrelated familiar words as primes and participants had to decide whether the prime and target were related or not.

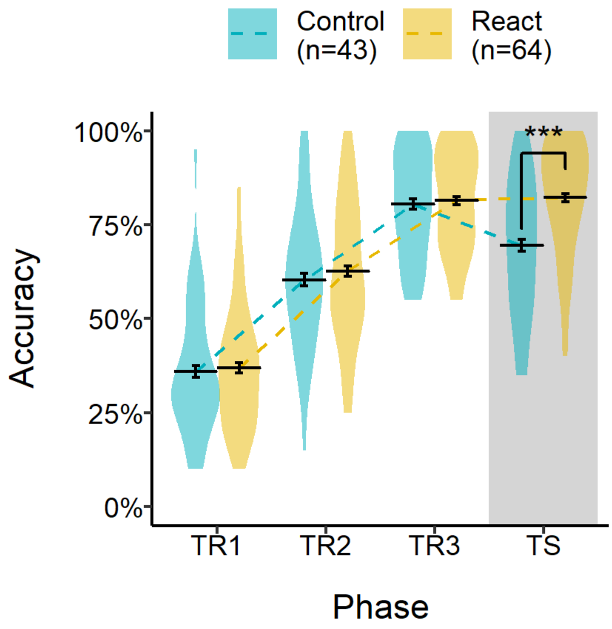

Figure 2: **Experiment A1 (between-groups analysis)**. Accuracy (percentage of correct responses) in the three blocks of practice of the learning task (TR1, TR2 and TR3) and in the cued-recall test 48 h later (TS) of the Control and Reactivated groups. Each bar provides the mean (± SEM) across each condition. The violin represents the density of the condition mean for each participant. ***: $p < 0.001$, $\Delta = -12.3\%$ (pairwise simple contrasts).

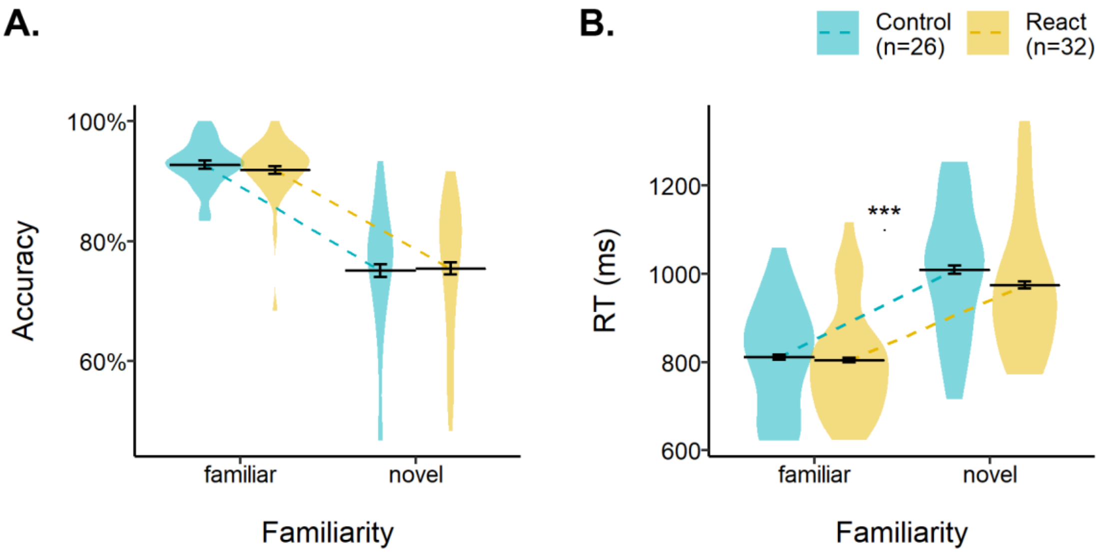

Figure 3: **Experiment A2 (between-groups analysis)**. Performance on the semantic relatedness task for familiar and novel words of the Control and Reactivated groups. Only related trials are shown. Each bar provides the mean (± SEM) across each condition. The violin represents the density of the condition mean for each participant. (A) Accuracy (percentage of correct prime-target relatedness judgments). (B) Reaction times (in milliseconds) for correct judgments measured from target offset. ***: p <0.001, (interaction between Familiarity and Reactivation factors).

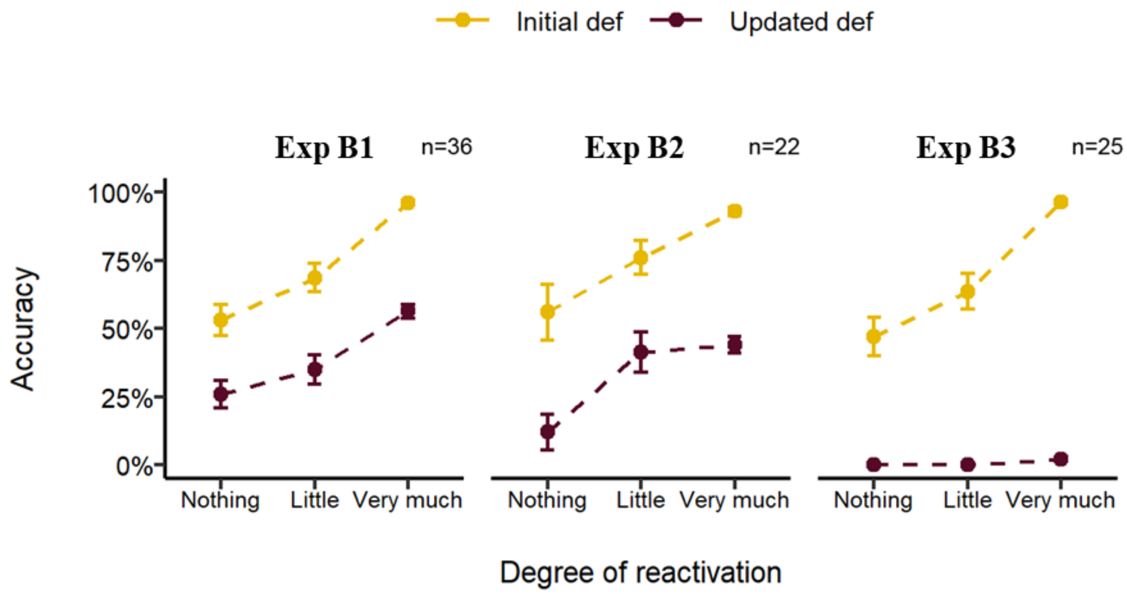

Figure 4: **Experiments B1, B2 and B3 (within-participants analysis)**. Accuracy (percentage of correct responses) in the cued-recall test. Accuracy for the initial definition (yellow curve) corresponds to all responses that correctly included the definition learnt in the learning task. Accuracy for the updated definitions (violet curve) only takes into account responses that correctly included the initial definition plus the information learnt in the updating phase. Each response was plotted according to the degree of reactivation reported by the participant for that word in the reactivation phase (Session 2). The distribution of responses of degree of reactivation were: 14% to 'nothing', 15% to 'little' and 71% to 'very much' in Experiment B1; 7% to 'nothing', 13% to 'little' and 80% to 'very much' in Experiment B2; and 12% to 'nothing', 13% to 'little' and 75% to 'very much' in Experiment B3. Each point provides the mean (± SEM) across each condition.

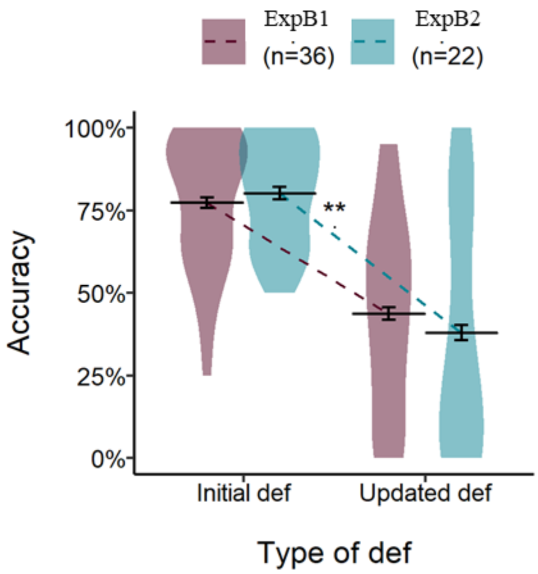

Figure 5: Experiments B1 and B2 (between-groups analysis). Accuracy (percentage of correct responses) in the cued-recall test in the initial definitions and in the updated definitions of the Experiment B1 and 4. Each bar provides the mean (± SEM) across each condition. The violin represents the density of the condition mean for each participant. **: p = 0.004, (interaction between Type of definition and Experiment factors).

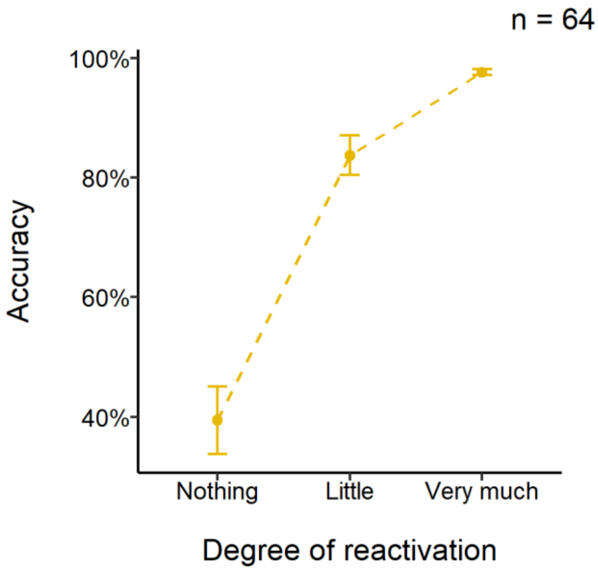

Figure S1: **Experiment A1 (within-participants analysis)**. Accuracy (percentage of correct responses) in the cued-recall test of the Reactivated group. Each response was plotted according to the degree of reactivation reported by the participant for that word in the reactivation phase (Session 2). The distribution of responses of degree of reactivation were: 7% to ‘nothing’, 12% to ‘little’ and 81% to ‘very much’. Each point provides the mean (± SEM) across each condition.

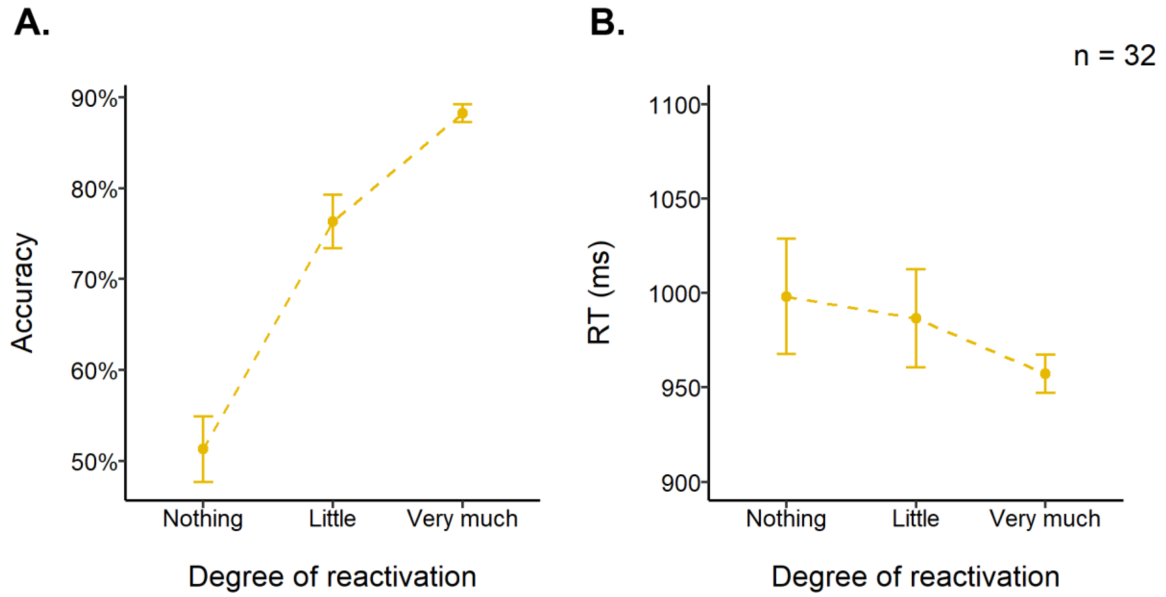

Figure S2: **Experiment A2 (within-participants analysis)**. Performance on the semantic relatedness task for novel words of the Reactivated group. Only related trials are shown. Each response was plotted according to the degree of reactivation reported by the participant for that word in the reactivation phase (Session 2). The distribution of responses of degree of reactivation were: 14% to 'nothing', 14% to 'little' and 72% to 'very much'. Each point provides the mean (± SEM) across each condition. (A) Accuracy (percentage of correct prime-target relatedness judgments). (B) Reaction times (in milliseconds) for correct judgments measured from target offset.

Supplementary Table 1

Initial learning (measured as the percentage of correct responses in the third block of practice of the learning task, TR3) and percentage of responses for each reactivation strength level in each experimental group.

Experiment	Group	Initial learning (%)	Degree of reactivation (%)		
			Nothing	Little	Very much
A1	Control	80	-	-	-
	Reactivated	81	7	12	81
A2	Control	79	-	-	-
	Reactivated	75	14	14	72
B1	Control	83	-	-	-
	Reactivated	77	14	15	71
B2	Reactivated	81	7	13	80
B3	Reactivated	84	12	13	75

Supplementary Table 2

Accuracy (percentage of correct responses) in the cued-recall test for each reactivation strength level in each experimental group.

Experiment	Group		Cued-recall test (%)			
			Total	**Nothing**	**Little**	**Very much**
A1	Control		70	-	-	-
	Reactivated		82	39	84	98
A2	Control		-	-	-	-
	Reactivated		-	-	-	-
B1	Control	**Initial**	83	-	-	-
		Updated	55	-	-	-
	Reactivated	**Initial**	77	53	69	96
		Updated	44	26	35	56
B2	Reactivated	**Initial**	80	56	76	93
		Updated	38	12	41	44
B3	Reactivated	**Initial**	79	47	64	96
		Updated	0	0	0	0