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Title

Does adding *beer* to *coffee* enhance the activation of *drinks*? An ERP study of semantic category priming

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Abstract

Categorization - whether of objects, ideas, or events - is a cognitive process that is essential for human thinking, reasoning, and making sense of everyday experiences. Categorization abilities are typically measured by the Wechsler Adult Intelligence Scale (WAIS) similarity subtest, which consists of naming the shared category of two items (e.g., "How are beer and coffee alike"). Previous studies show that categorization, as measured by similarity tasks, requires executive control functions. However, other theories and studies indicate that semantic memory is organized into taxonomic and thematic categories that can be activated implicitly in semantic priming tasks. To explore whether categories can be primed during a similarity task, we developed a double semantic priming paradigm. We measured the priming effect of two primes on a target word that was taxonomically or thematically related to both primes (double priming) or only one of them (single priming). Our results show a larger and additive priming effect in the double priming condition compared to the single priming condition, as measured by both response times and, more consistently, event-related potential. Our results support the view that taxonomic and thematic categorization can occur during a double priming task and contribute to improving our knowledge on the organization of semantic memory into categories. These findings show how abstract categories can be activated, which likely shapes the way we think and interact with our environment. Our study also provides a new cognitive tool that could be useful to understand the categorization difficulties of neurological patients.

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1. **Introduction**

Categorization is a complex cognitive process that allows brains to classify objects and events based on common characteristics (Cohen, 2005). Based on our knowledge, we categorize everything we perceive, and this allows us to make sense of our environment and experiences. This process of categorization is essential for human thinking, learning or forming general concepts, and problem-solving (Gelman and Meyer, 2011; Kotovsky and Gentner, 1996). However, the cognitive mechanisms by which we categorize or fail to categorize are poorly understood.

Categorization abilities are typically measured by the Wechsler Adult Intelligence Scale (WAIS) similarity subtest (Wechsler, 2008). In this test, subjects are asked to categorize two items (e.g., "How are an orange and a banana alike?") and name their taxonomic category ("fruits"). Previous studies report impairment in categorization tasks, such as the similarity task, in patients with frontal neurodegenerative diseases (Garcin et al., 2018; Lagarde et al., 2015), suggesting a critical role of executive control functions in this task. However, categorization has also been shown to occur automatically and to rely on semantic associations (Praß et al., 2013), suggesting that categorization depends on the organization of semantic memory. In particular, a given category seems to be implicitly pre-activated by an exemplar of this category (e.g., seeing "dog" pre-activates "animal") (Mirman et al., 2017). The critical role of executive control function in the similarity task may seem paradoxical with the notion that categorization occurs implicitly, based on semantic associations. Hence, how the category is activated during the similarity task remains an open question. More specifically, the question we raised is: do two exemplars of a given category pre-activate this category more than each exemplar would do alone, in a semantic priming paradigm? Addressing this question is essential to clarify the cognitive processes underlying categorization. It is also essential to better appreciate the cognitive difficulties of neurological patients.

The semantic priming paradigm is commonly used to explore implicit categorization and the organization of semantic memory, including the organization into categories (Chen et al., 2014; Jones and Golonka, 2012; Maguire et al., 2010) (for reviews (Hutchison, 2003; Jones and Estes, 2012; Lucas, 2000)). The principle of a semantic priming paradigm is to measure how much people are faster and/or more accurate in processing a target word when it is preceded by a semantically related prime word, as compared to an unrelated prime word. This measure reflects the semantic priming effect. The semantic priming effect is also explored with electrophysiological measures using event-related potentials (ERPs). ERPs provide temporal measures of the neural activity following stimulus presentation. Specifically, the N400 component, a negative deflection occurring approximately 400 ms after the stimulus onset and typically maximal at centro-parietal electrodes sites, is an electrophysiological landmark of semantic priming effects (for review see Kutas and Federmeier, 2011). The N400 appears very sensitive to semantic relatedness. Its amplitude is smaller when a word is preceded by a related rather than an unrelated word (Kutas and Van Petten, 1994; Lau et al., 2008). The difference in the N400 amplitude in different semantic priming conditions is referred to as the N400 priming effect, and it can occur even in the absence of response time (RT) priming effect (Chwilla et al., 2000; Chwilla and Kolk, 2003), suggesting a higher sensitivity. Many studies using a semantic priming paradigm have shown a relationship between the N400 amplitude and the strength of prime-target associative relatedness (Bentin et al., 1985; Holcomb, 1988; Rugg, 1985).

Using these behavioural and ERP measures, the semantic priming paradigm has allowed showing that different types of semantic relationships can yield priming effects. In particular, a series of studies show that both thematic (items that share a common context without necessarily sharing similar features, e.g., "rabbit" – "carrot" (Lin and Murphy, 2001) and taxonomic (items sharing specific features such as attributes and functional properties, e.g., "dog" - "cat"; Gelman and Meyer, 2011; Mirman et al., 2017; Murphy, 2002) relationships between prime and target yield a significant priming effect (Chen et al., 2014; Hagoort et al., 1996; Khateb et al., 2003; Maguire et al., 2010; Mirman et al., 2017). However, whether thematic and taxonomic relationships have distinct semantic priming characteristics, is an open question.

In addition, the behavioural and electrophysiological semantic priming effects have been shown to occur for consciously perceived primes and target, but also unconsciously perceived primes in masked-priming paradigms (Brown and Hagoort, 1993; Naccache and Dehaene, 2001; Rohaut et al., 2016; van Gaal et al., 2014). This evidence suggests that a semantic priming effect can occur unconsciously. However, a conscious context and task setting effects related to control functions can influence even unconscious priming (Naccache and Dehaene, 2001; Rohaut et al., 2016; van Gaal et al., 2014), indicating that the interplay between unconscious, implicit and controlled processes during semantic priming is complex and not entirely elucidated.

Nevertheless, the priming effect on semantic categories, whether taxonomic or thematic, suggests that categorization could occur in the context of tasks, such as the similarity task, where two presented words converge to a given category.

A few studies on semantic memory have used a "double semantic priming" paradigm to explore whether two primes impacted the processing of the target more than each prime would do alone (Balota and Paul, 1996; Chwilla and Kolk, 2005, 2003; Python et al., 2018a). In the double semantic priming paradigm, the influence of the convergence of two primes on the target processing is assessed by comparing the conditions in which the two primes are related to the target, to conditions in which only one of the two primes relates to the target. These studies demonstrated a larger double as compared to single priming effect with various primes-*target* relationships: exemplars-*taxonomic category,* e.g., copper + bronze - *metal* (Balota and Paul, 1996); associated contexts or characteristics–*object,* e.g., alley + window - *house* (Lavigne and Vitu, 1997) or naked + shy - *towel* (Chwilla and Kolk, 2005); mediated associations, e.g., lion + stripes - *tiger* (Chwilla and Kolk, 2003); exemplars-*exemplar*, e.g., helicopter + bus – *airplane* (Python et al., 2018a). Only one of these studies used exemplars of a category as primes and the category as a target (Balota and Paul, 1996) and showed a shorter RT in the double priming condition as compared to single priming, suggesting that categorization can occur implicitly.

The measurement of the N400 priming effect using multiple primes has been less explored (Chwilla and Kolk, 2003; Python et al., 2018a). To our knowledge, only two studies have explored the double semantic priming effect by combining behavioural and electrophysiological approaches. Chwilla and Kolk (Chwilla and Kolk, 2003) showed that the existence and the strength of the double priming effect depend on the behavioural task, are altered when primes are polysemous and are easier to observe in ERPs than in behaviour. Although this study did not focus on category relationships, it demonstrates the importance of exploring the neural correlates of semantic priming as a complement to behavioural data. Python and colleagues (Python et al., 2018a) examined category relationships, including thematic relationships and taxonomic relationships. In the taxonomic relationships, targets and primes were exemplars of a specific category (e.g., food or animals). The author described an increased semantic facilitation effect using multiple primes as compared to single primes. Although single semantic priming studies did not show differences in priming effect between taxonomic and thematic relationships (Chen et al., 2014; Hagoort et al., 1996; Khateb et al., 2003; Maguire et al., 2010), in this double priming study, the behavioural priming effect was larger for thematic than taxonomic relationships. In contrast, the ERP priming effect was similar for both relationships. Hence, these findings suggest that categorization can be studied in semantic priming paradigms and may depend on the type of relationships between primes and target. However, this study does not allow to directly test whether exemplars of a category activate the name of that category because the targets used were exemplars of categories, not category names. Whether the double priming effect can be observed in the context of the similarity task, i.e., whether several exemplars prime the category name, is an unresolved question.

The current study aims to explore whether categorization - as it occurs in the similarity task - can also occur in a semantic priming paradigm, i.e., without explicit instructions. We explore more specifically whether two exemplars of a given category activate this category name more than each exemplar would do alone in a semantic priming paradigm. For this purpose, we designed a double semantic priming task. This task allowed us to test whether two words belonging to the same taxonomic category (e.g., "banana" – "orange") elicited a stronger priming effect on the target category word (e.g., "fruits") than each exemplar separately did. Given the observed differences in priming paradigms between distinct types of relationships, we also examined this effect for thematic relationships where the target was contextually associated with the primes (e.g., primes "banana" and "cage" with the target "monkey"). We measured both the behavioural (RTs) and ERPs (N400) priming effects. We expected a larger priming effect in double-prime trials as compared to single-prime ones.

2. Materials and Methods

2.1 Participants:

Forty subjects (20 women) with a mean age of 23 years old (± standard deviation (S.D.) = 1.31) participated in this study and performed the priming task and other cognitive tasks. One participant was excluded because she did not carry out the task until the end. Thirty-nine subjects were included in the behavioural analyses (n = 39, 19 women, mean age = 22.5 ± 1.3 years old). Electrophysiological data were recorded in a subgroup of 24 participants (13 women, mean age = 23 ± 1.19 years old).

Subjects were French native speakers, right-handed, and all had a normal or corrected-to-normal vision. Participants had no medical history of neurological or psychiatric disorders, no cognitive impairment (Mini mental State test score > 28) and were free of any drug or psychotropic medication. The local ethical committee (Comité de Protection des Personnes "CPP Ile de France V", approval n° C14-17) approved the study. All sections of the experiment were performed in accordance with relevant guidelines and regulations. All participants provided written informed consent and received financial compensation for their participation.

2.2 Experimental paradigm

2.2.1 *General principle*

We developed a priming paradigm based on a Lexical Decision Task (LDT), in which participants decided whether a displayed chain of letters (the target) was a word or not. This target was preceded by two prime words, each of which could be either semantically related or unrelated to the target, so that there were three semantic relatedness to the target fell into three possibilities: 1) they were both semantically related to the target, 2) one was related and one unrelated, or 3) none was related to the target. Two types of relationships were explored: taxonomic (e.g., "coffee" – "drink") and thematic (e.g., "banana" – "monkey") relationships, using a distinct verbal material. The participants performed two blocks of thematic trials and two blocks of taxonomic trials. We followed the general principles proposed by Balota and Paul (Balota and Paul, 1996) to design the double semantic priming paradigm: considering the relatedness between the prime and the target (related – unrelated) and the position of the prime (first - second), four different conditions were compared: Related-Related (*RR*), Related-Unrelated (*RU*), Unrelated-Related (*UR*), Unrelated-Unrelated (*UU*). The influence of the convergence of multiple primes on target processing was assessed by comparing the effect (either behavioural or electrophysiological) in the multiple prime condition (*RR*) with the effect of both single prime conditions (*RU* and *UR*). Three different effects can be observed: additive, over-additive, or under-additive effects. A simple additive effect occurs when the facilitation of the target processing in *RR* condition (double priming effect) corresponds to the sum of the facilitation in *RU* and *UR* conditions (sum of single priming effects). Over-additivity indicates that the double priming effect is larger than the sum of the single priming effects. Conversely, under-additivity means that the double priming effect is smaller than the sum of the single priming effects.

2.2.2 Experimental conditions:

We created a set of words for taxonomic relationships and another one for thematic relationships (see word lists in Supplementary Table S1). Each set consisted of 26 triplets of one category target word and two prime words. The prime words had a taxonomic relationship with the target (taxonomic set) or a thematic relationship with the target (thematic set). Four different conditions were obtained for both sets by recombining all the elements in each set and considering the relation between the primes and the target (related or unrelated). First, a double priming condition or *RR* condition consisted of each of the original lists of 26 triplets of words in which the two primes were related to the target. Second, *RU* and *UR* conditions were single priming conditions, in which only the first or the second prime, respectively, was related to the target word (the other prime being unrelated to this target). Finally, we created a fourth condition, *UU*, in which neither the first nor the second prime word were related to the target. This last condition was the baseline condition.

Overall, each condition (*RR*, *RU*, *UR,* and *UU* for taxonomic and thematic relationships) included 26 trials. To operationalize the LDT, we also created trials with pseudowords as targets. These pseudoword targets were pseudo-randomly combined with the same prime pairs as in the *RR* (13 trials), *RU* (13 trials), *UR* (13 trials), and *UU* (13 trials). When the target was not a word, the relatedness to the target did not make sense anymore (*UU*, *UR,* and *RU* are equivalent), and only the relatedness between primes made sense (*RR* as opposed to *UU*, *RU*, *UR*). Hence, the combination of primes with pseudowords defined two conditions for pseudowords targets: *RR* (13 trials) and *UU* (39 trials) conditions (see Table 1 and Supplementary Table S2 and S3). Therefore, the probability of a pseudoword target occurring after two related (*RR*) or after two unrelated primes (*UU*) was identical (1/3). In total, this first set of trials included 156 taxonomic and 156 thematic trials (including word and pseudoword trials).

Another set of trials was obtained by reversing the order of the first and second prime words (which were displayed sequentially) for all the trials described above, while keeping the other parameters identical. This second set was built to counterbalance the order of the primes over conditions and allowed us to double the total number of trials. Overall, the participants performed four blocks of trials corresponding to the four sets of 156 trials that were formed: two taxonomic blocks (that differed in the order of the primes in each trial) and two thematic blocks (that also differed in prime order). Each prime was repeated six times: three times in the first position and three times in the second position (see Supplementary Table S3), and each target was repeated four times (Table 1). The order of the trials was pseudo-randomized in each session of 156 trials, with the constraint so that at least nine trials separated two repetitions of the same target. We used the software Mix (van Casteren and Davis, 2006) to pseudo-randomize the trials. Each session lasted about 15 minutes. The order of the sessions was counterbalanced between subjects using the following latin square pattern: 1-2-3-4 / 2-3-4-1 / 3-4-1-2 / 4-1-2-3. Before the task, each participant completed a training session of 6 trials with different triplets of words than those used in the main task. The task was coded and administered with MATLAB 2016b (The MathWorks, Inc., Natick, MA) using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007).

Condition	Prime 1	Prime 2	Target	Number of Trials
RR-word	coffee *(café)*	beer *(bière)*	drink *(boisson)*	26 Trials
RU-word	beer *(bière)*	pigeon *(pigeon)*	drink *(boisson)*	26 Trials
UR-word	boot *(botte)*	coffee *(café)*	drink *(boisson)*	26 Trials
UU-word	copper *(cuivre)*	sight *(vue)*	drink *(boisson)*	26 Trials
RR-pseudo-word*	coffee *(café)*	beer *(bière)*	asimum	13 Trials
UU-pseudo-word	sorbet *(sorbet)*	sight *(vue)*	disseya	39 Trials

Table 1. Examples of the six different conditions used as stimuli. The table contains real trials used in the taxonomic session. Each condition included two primes and one target, and this table provides the number of trials presented in one session. In *RR*-pseudoword trials, the two primes belong to the same category while in the *UU*-pseudoword trials the two primes are not related. The proportion of primes that belong to the same category is thus similar for words and pseudo-words trials (0.25). Trials were created from the original list of 26 triplets of words and a total 156 trials were used for each session (Four sessions in total: taxonomic and thematic; prime order 1-2 or 2-1). French words are presented in brackets.

2.2.3 Selection of the verbal material:

We used nouns or adjectives that were concrete, composed of 3 syllables or less, and with a reasonably high lexical frequency (lemma frequency > 1 per million occurrences in the Lexicon book database; www.lexique.org; New et al., 2004).

Three databases of free association norms in French were used to select the words presented as primes and as targets: the norms of verbal associations for concrete words and abstract words (Ferrand, 2001; Ferrand and Alario, 1998) and a dictionary of French verbal associations accessible online (Debrenne, 2010). These tools allowed us to assess the association strength between different pairs of words for the creation of word triplets (two primes and one target). The association strength is the probability that a cue word elicits a specific target word in a verbal free association task. It is measured as the percentage of participants who produced the target in response to the cue word. We ensured that each prime word alone was not strongly associated with the target word (less than 15% of association strength), to avoid a ceiling effect and prevent the priming effect from being significantly boosted by direct verbal associations beyond the semantic relationship itself (Tyler and Moss, 2001).

Pseudowords were created by modifying target words using the Wuggy® software (Keuleers and Brysbaert, 2010). This software allowed us to create pseudowords that matched the target words in terms of the number of syllables and letters, and the frequency of letters. Pseudowords were words that do not belong to the French language, but pronounceable under French phonological rules. Pseudowords were then pseudo-randomly combined with pairs of primes to form trials so that a given target and the pseudoword generated from this target did not occur in the same trial.

2.2.4 Experimental task (Figure 1):

Participants were seated in front of the screen and asked to perform the LDT using two mouse buttons. Subjects who participated in the electrophysiological recording were seated inside an electrically shielded room (Faraday cage). Stimuli were presented in white letters on a black background. Each trial started with the presentation of a fixation cross displayed at the centre of the monitor. After 500 ms, the first prime was presented during 300 ms and was followed by a fixation cross for 100 ms. Then, the second prime was displayed during 300 ms and was followed by a new fixation cross during 800 ms, and then by the target that was displayed in bold font for 2 seconds. Hence, the total Stimulus-Onset Asynchrony (SOA) in all the trials was 1500 ms. During this period, participants were instructed to decide whether the target was a word or a pseudoword, by doing a left- or right- click on the mouse to select their response with the right hand. An inter-trial-interval whose duration was jittered from 1.8 to 2.2 seconds (with steps of 2.6 ms) followed. Subjects were instructed to focus only on bold words and to answer, "as accurately and as fast as possible". The mouse buttons corresponding to the answer "word" and "pseudoword" were counterbalanced between participants.

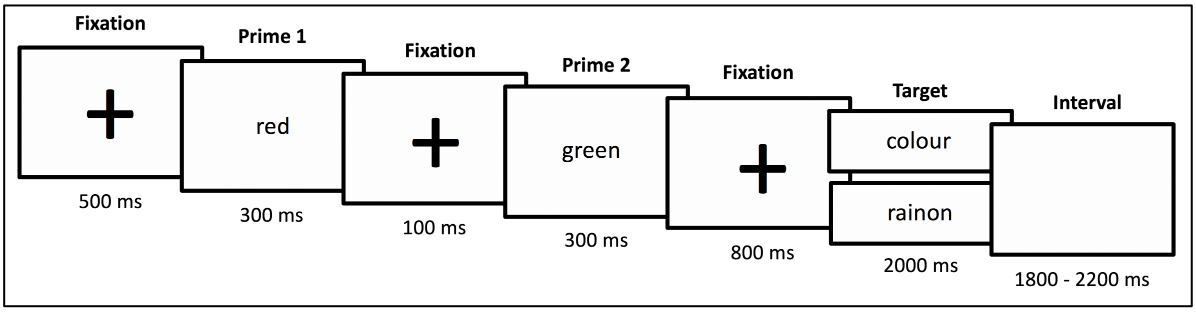

Figure 1. Experimental model. Each trial starts with the presentation of a fixation cross. Each prime is presented during 300 ms, separated by 100 ms of cross fixation. The target is presented during 2000 ms, and it can be a word (e.g., "colour") or a pseudoword (e.g., "rainon").

2.3 EEG data acquisition and preprocessing

For a subset of 24 subjects, EEG data were recorded on 66 electrodes using BRAINAMP DC system (Brain Products GmbH, Münich, Germany) with actiCAP64-active electrodes mounted in an elastic cap according to the extended International 10–20 system and including a row of low fronto-temporo-occipital electrodes (PO9/10, TP9/10, FT9/10). The FCz electrode was the reference during the recording, and the AFz electrode was the ground. Additional electrodes placed above and below the right or left eye and lateral to the outer canthus of both eyes recorded vertical and horizontal EOG, respectively. Electrode impedances were at or below ten kOhm. The EEG data were recorded at 1 kHz with an online 0.016-250 Hz bandpass filter.

The EEG signal was downsampled offline to 250 Hz, and filtered with a zero-phase, third order high pass and low pass Butterworth filter (0.5 to 30 Hz). Epochs of 200 ms before and 1000 ms after target onset were considered for the analysis. Independent Component Analysis (ICA) was used to detect and remove artefacts caused by eye-blinks. On average, two independent components were removed after a visual inspection of the time series and topographies. Noisy channels were interpolated using the averaged signal of neighbouring channels. A mean of 5.6 electrodes (± S.D. = 1.1) was interpolated among the participants. Trials containing more than 10% of noisy channels were removed. A mean of 13.7 trials per subject was rejected (± S.D. = 19.6; Range = 0-77) among the total number of trials. After the rejection of the noisy trials, 96.4% (± S.D. = 3.3) of all trials remained for the analysis. For the remaining trials, we performed baseline correction between -200 ms to 0 ms relative to the target onset and the signal was re-referenced to the average of all electrodes (retrieving the FCz electrode signal that was initially used as the reference). EEG signals were averaged for each experimental condition (*RR*, *UR*, *RU*, *UU*) separately. Only correct response trials with a word as a target were considered for the analysis. Note that our experimental design was optimized to analyze the target-evoked responses, minimizing contamination by the primes-evoked responses. Thus, the ERPs analysis did not consider the exploration of the priming effects triggered by the primes, which would be difficult to disambiguate from one another. We provide a figure of the ERP time course across the whole trial period in Supplementary Figure S1. All EEG preprocessing and analyses were performed using the FieldTrip toolbox running under MATLAB 2016b (Oostenveld et al., 2011).

2.4 Behavioural and electrophysiological analyses

2.4.1 Behavioural measures

Reaction time was measured as the duration from the target onset to the participants' button press. Median RTs on correct trials with a word as a target were computed for each condition and each participant. We chose median RTs for the analyses to limit the influence of extreme values in the results. The priming effect was measured by subtracting RT in the baseline condition (*UU*) to RT in the related conditions (*UR*, *RU*, or *RR*). The difference in RTs between *RR* and *UU* measured the double priming effect. We also calculated the overall single priming effect by averaging RTs from both single priming conditions (*RU* and *UR*) — labelled as *RUR* RT — and subtracting it to *UU*.

2.4.2 ERP measures

Our a priori hypothesis focuses on the N400 component that typically occurs between 300-500 ms after the target onset (Kutas and Hillyard, 1984). A predetermined time-window of interest between 300-500 ms after the target onset was thus selected and analyzed. However, to provide a more comprehensive analysis of the evoked response, we analyzed other time windows of 200 ms duration each, going from 100 ms to 900 ms after the target onset. Therefore, in total we analyzed the following time windows: 100-300 ms, 300-500 ms, 500-700 ms and 700-900 ms.

For each condition, we measured the mean amplitude of ERPs in the different time windows, averaging ERP data across nine electrodes around the central Cz position (FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, CP2). We selected a priori the frontocentral and centroparietal sites because the N400 component is maximal at this location (Martin et al., 2009). To assess the N400 priming effect, we subtracted the N400 component of each of the conditions containing a related prime (*RR*, *RU* and *UR*) to the baseline condition (*UU*). We also computed the overall N400 single priming effect by averaging priming effects across both single priming conditions (*UR* and *RU*).

2.4.3 Statistical analyses

The following procedure was used for the behavioural data (RTs) and ERPs (N400s). We first tested for the semantic priming effect and for the differences according to the semantic category type (taxonomic or thematic). We performed a two-way repeated-measures ANOVA with semantic category type (2 levels, taxonomic and thematic) and condition (4 levels, *RR, UR, RU, UU*) as within-subject factors. For the ERPs analyses, independent ANOVAs were performed for each time window, and a Bonferroni correction was used for multiple comparisons. Then, as our interest was the existence of a double priming effect and the additivity properties of double as compared to single priming, we performed two additional two-way repeated-measures ANOVAs, in order to compare single and double priming effect (priming factor) across semantic category types (thematic vs taxonomic). In the first set of ANOVAs, we tested for a double priming effect in each time window (with a Bonferroni correction for this multiple comparison). For this, the two levels of the priming factor corresponded to the priming effects computed separately for the single *(RUR - UU)* and the double (*RR* - *UU*) priming conditions. When a double priming effect was significant, we tested for additivity or over-additivity of the priming effect. For this, the two levels of the priming factor corresponded to i) the sum of the priming effect for the two single priming conditions (that is, (*RU* - *UU*) + (*UR* - *UU*)) and ii) the double (*UU* - *RR*) priming conditions. For comparisons with more than one degree of freedom, we used the Mauchly's test to verify the assumption of sphericity and the Greenhouse-Geisser coefficient ε to correct for deviations to this assumption. We report the Greenhouse-Geisser corrected p-values but the original, uncorrected degrees of freedom. The Greenhouse-Geisser epsilon (ε) value is reported in cases where the assumption of sphericity was violated. When the main effect of priming condition was significant, we performed post-hoc pairwise comparisons between conditions with Bonferroni correction for multiple comparisons.

Finally, to explore whether the ERPs priming effects were significant in electrodes that we did not consider a priori in our analysis, we employed a cluster-based permutation approach in the Fieldtrip toolbox (Oostenveld et al., 2011). We examined whether the priming effect in the double priming condition *RR* was significantly different from the baseline condition *UU*. This statistical procedure can optimally correct for the problem of multiple comparisons in EEG data.

All statistical analyses were performed using SPSS software (v22.0; LEAD Technologies, Inc.).

3. Results

3.1 Behavioural analysis:

Mean accuracy reached 98.4% (± S.D. = 1.2; Range = 95-100) of all trials. Only the correct trials were kept and analyzed. The mean and standard deviations of the median RTs are provided for all conditions in Supplementary Table S4. We first performed a two-way repeated-measures ANOVA with semantic category type (2 levels, taxonomic and thematic) and condition (4 levels, *RR, UR, RU, UU*) to explore priming effects across conditions. There was no significant main effect of semantic category type (taxonomic vs thematic) on median RTs ($F < 1$). However, there was a main effect of the priming condition ($F(3,114) = 15.53$; $\varepsilon = 0.75$; $p < 0.001$). Post-hoc pairwise comparisons with Bonferroni correction for multiple comparisons revealed that RT was longer in the baseline condition *UU* when compared to double priming condition *RR* ($p < 0.001$) and to each single priming condition *UR* ($p = 0.007$) and *RU* ($p < 0.001$). RT was shorter in the double priming condition *RR* compared to the single priming condition *UR* ($p = 0.005$) but not compared to the single priming condition *RU* ($p = 0.068$) (Figure 2a). The interaction between semantic category type and conditions was not significant ($F(3,114) = 1.61$; $p = 0.2$).

To examine whether there was a double priming effect and whether it was over-additive, we ran two additional ANOVAs on the single and double priming effects. In the first ANOVA, the double priming effect (*RR* - *UU*) was compared to the average of the single priming effects (*RUR* - *UU*) to explore the existence of a double priming effect. There was no main effect of semantic category type ($F < 1$) but a significant effect of priming type (double versus single) ($F(1,38) = 7.66$; $p = 0.009$). The interaction between semantic category type and priming type was significant ($F(1,38) = 4.58$; $p = 0.04$). Post-hoc comparisons revealed that RT was significantly shorter in the double priming than the single priming condition for taxonomic $t(38) = -4.26$; $p < 0.001$) but not thematic ($t(38) = -0.82$; $p = 0.26$) categories (Figure 2b). In the second ANOVA, we tested over-additivity by examining if the priming effect in the double priming condition (*RR* - *UU*) was larger than the sum of the priming effect in the single priming conditions (*RU* - *UU* + *UR* - *UU*). This final ANOVA did not reveal any significant main effect or interaction (all F < 1). Thus, the double priming effect was not significantly larger than the sum of the single priming effects, indicating that the double priming effect was only additive.

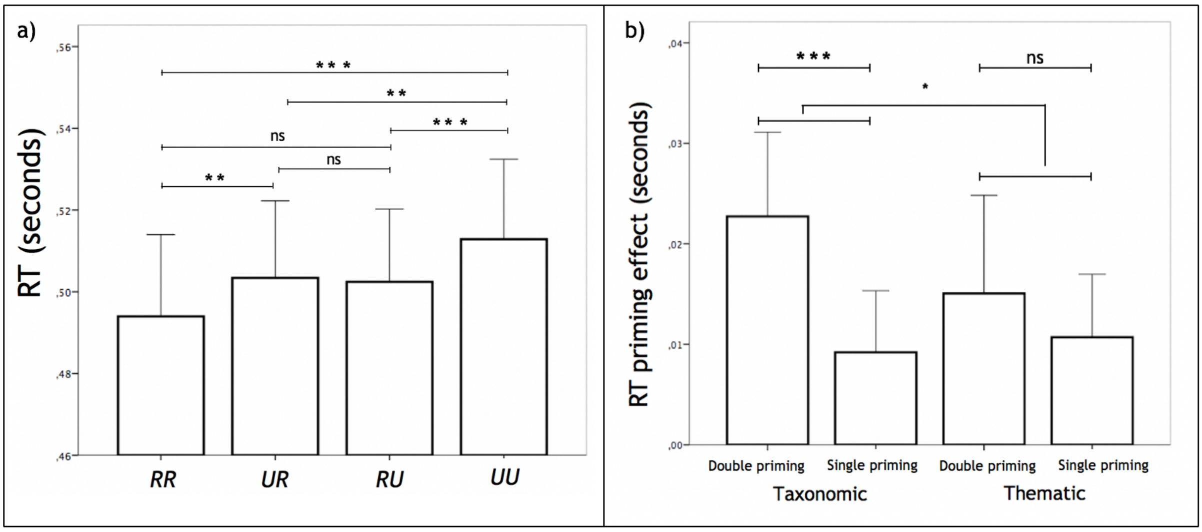

Figure 2. Behavioural data. a) Mean of the median RTs across subjects in the four priming conditions (taxonomic and thematic conditions pooled together). b) Priming effects in double and single priming conditions for the taxonomic and thematic conditions are represented as the difference in RTs between *RR* and *UU*, and between *RUR* and *UU*, respectively. There is a significant interaction between category and priming effect.
*** p < .001; ** p <.01; * p <.05; ns: not significant. Error bars correspond to 95% confidence intervals.
UU: unrelated-unrelated; *RU*: related-unrelated; *UR*: unrelated-related; *RR*: related-related.

3.2 <u>ERP analysis</u>

We measured the mean amplitude of the N400 component in all conditions in both types of semantic relationships. The N400 mean amplitudes and standard deviations for all conditions are provided in the Supplementary Table S5. Figure 3 shows the individual time course of the N400 component for the nine electrodes averaged for the analyses, and the scalp distribution. The statistical analysis followed the same strategy as for the behavioural data. First, for each time window, we performed an ANOVA with semantic category type (2 levels, taxonomic and thematic) and condition (4 levels, *RR, UR, RU, UU*) as within-subject factor allowed us to explore priming effects across conditions. This analysis did not show any effect of the semantic category type (taxonomic versus thematic) (F < 1) in any of the four time windows. A significant effect of the priming conditions (F(3,69) = 11.60; $\varepsilon = 0.65$; p < 0.001) was found in the 300-500 ms time window, but not in the other time windows (F < 1). The post-hoc pairwise comparisons with Bonferroni correction for multiple comparisons performed in the 300-500 ms time window showed that the N400 component was larger in the baseline condition *UU* compared to the double priming condition *RR* (p = 0.001) and to both single priming conditions *UR* (p = 0.029) and *RU* (p = 0.002) (Figure 4a). Moreover, double priming condition *RR* showed a significantly lower amplitude of the N400 component compared to single priming condition *UR* (p = 0.014), but not compared to *RU* (p = 0.2). There was no significant interaction between semantic category type and priming condition factors in any of the time windows (F < 1).

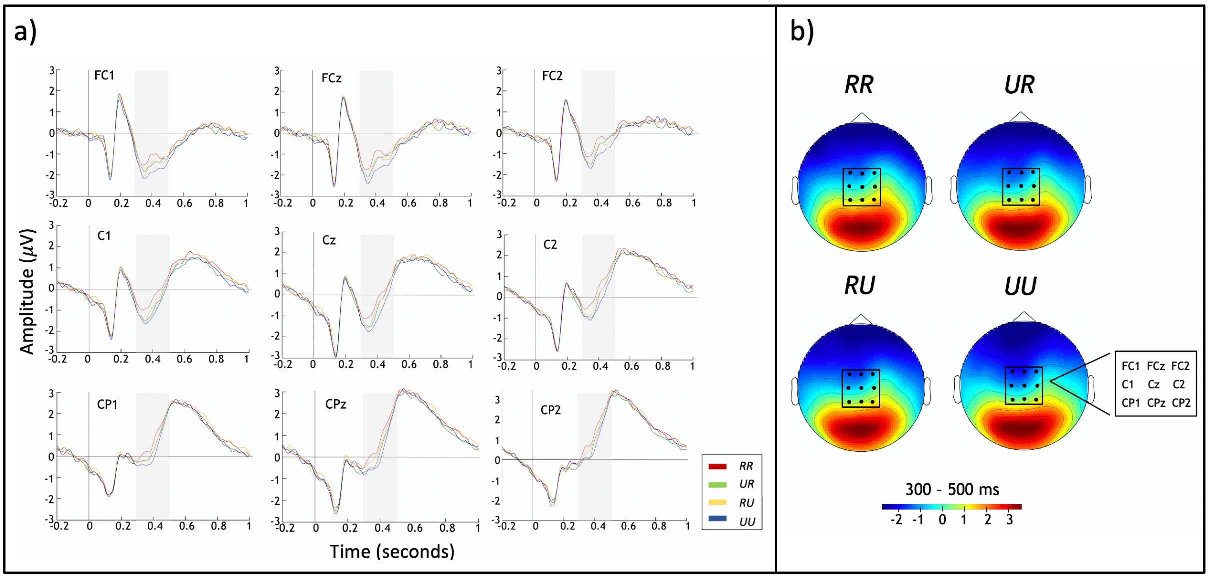

Figure 3. ERP grand average over the nine electrodes separately and N400 scalp distribution. a) The ERP grand average elicited by the four conditions is provided for the nine electrodes separately. Time 0 corresponds to the target presentation, and the grey area represents the studied time window. b) Topographic maps show the mean N400 amplitude (μV) for the studied time window for all the conditions. Black dots indicate the nine electrodes considered in the ERP analysis.

RR: related-related; *RU*: related-unrelated; *UR*: unrelated-related; *UU*: unrelated-unrelated.

To examine whether there was a double priming effect, we ran additional ANOVAs on single and double priming effects computed as the differences in amplitude for *RUR* and *RR* relative to the *UU* conditions for each time window. These analyses revealed a significant difference between the single and double priming effects (F(1,23) = 8.780; p = 0.007) in the 300-500 ms time window. Participants presented a larger N400 priming effect in the double semantic priming condition compared to the averaged single semantic priming condition

(Figure 4). This effect was not significant in any other time window (F < 1). No significant effect of semantic category type (F < 1) and no significant interaction between semantic category and priming effect types (F < 1) was observed in any of the time windows.

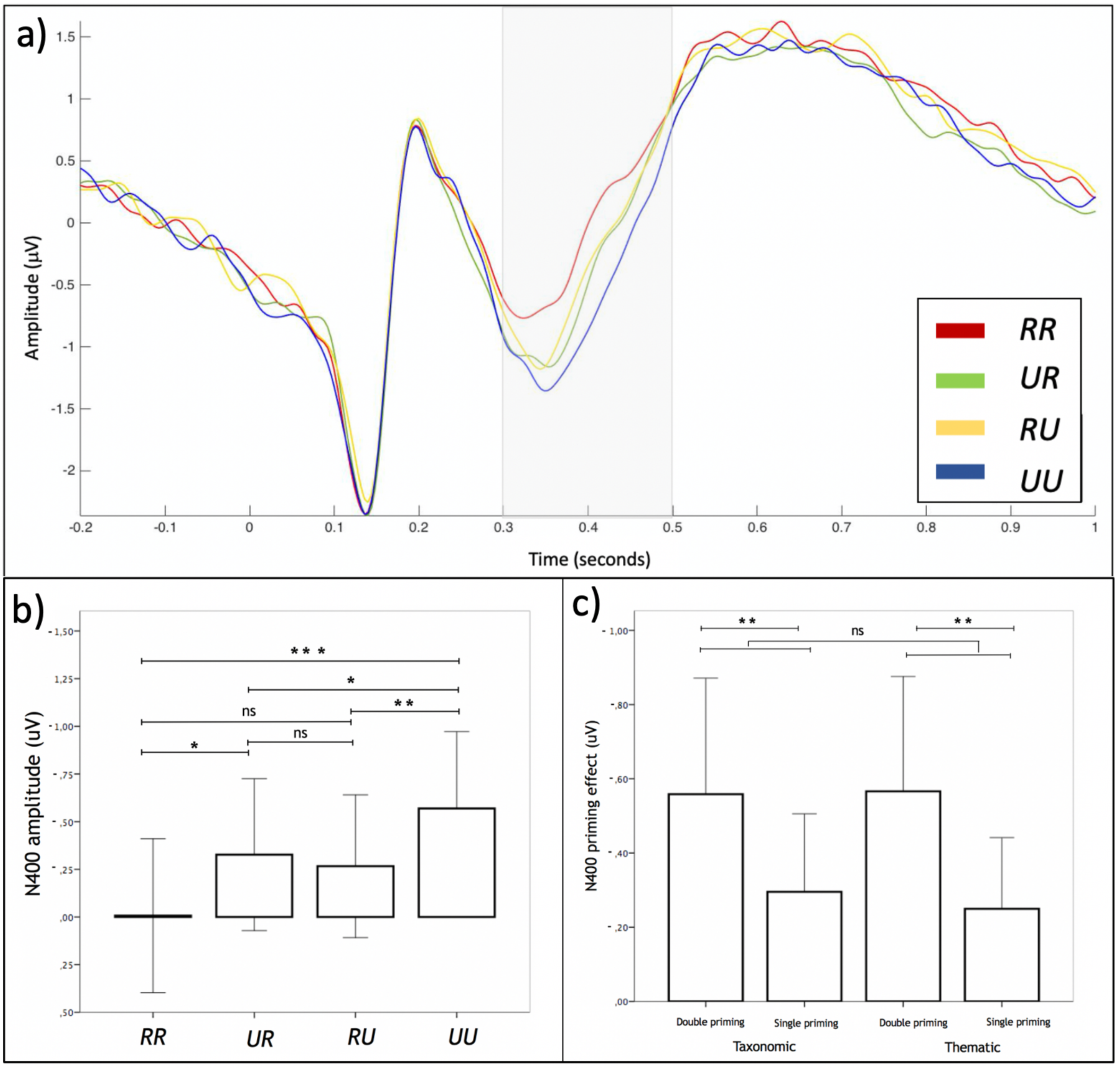

Figure 4. N400 time course over the nine averaged electrodes and N400 analysis per condition. a) The ERP grand average is displayed for the four conditions. Amplitude (µV) corresponds to the average of the nine electrodes considered in the analysis. Time 0 corresponds to the target presentation, and the grey area represents the studied time window. b) N400 measurements (average signal in the 300-500 ms time window) for the four different conditions (taxonomic and thematic trials averaged). c) N400 priming effects in double and single priming conditions for the taxonomic and thematic trials. Here, priming effects are the difference in the N400 amplitude between *RR* and *UU* (double priming), and between *RUR* and *UU* (single priming) in the 300-500 ms time window.

Significance of the post hoc tests conducted on the 300-500 ms time window are indicated as follows: *** p < .001; ** p <.01; * p <.05; ns: not significant. Error bars correspond to 95% confidence intervals.

RR: related-related; *RU*: related-unrelated; *UR*: unrelated-related; *UU*: unrelated-unrelated.

To explore whether the ERPs priming effects were restricted to the a priori selected electrodes for the analysis, we employed a cluster-based permutation approach. We examined whether the priming effect in the double priming condition *RR* was significantly different from the baseline condition *UU* in other electrodes in any of the time windows from 0.1 to 0.9 seconds after target onset. The analysis revealed that the double priming effect *RR* was significantly different from the baseline condition *UU* (p < 0.01) between the times 0.34 to 0.48 seconds over the frontocentral and centroparietal electrodes (Figure 5). This result is consistent with the a priori hypothesized N400 effect.

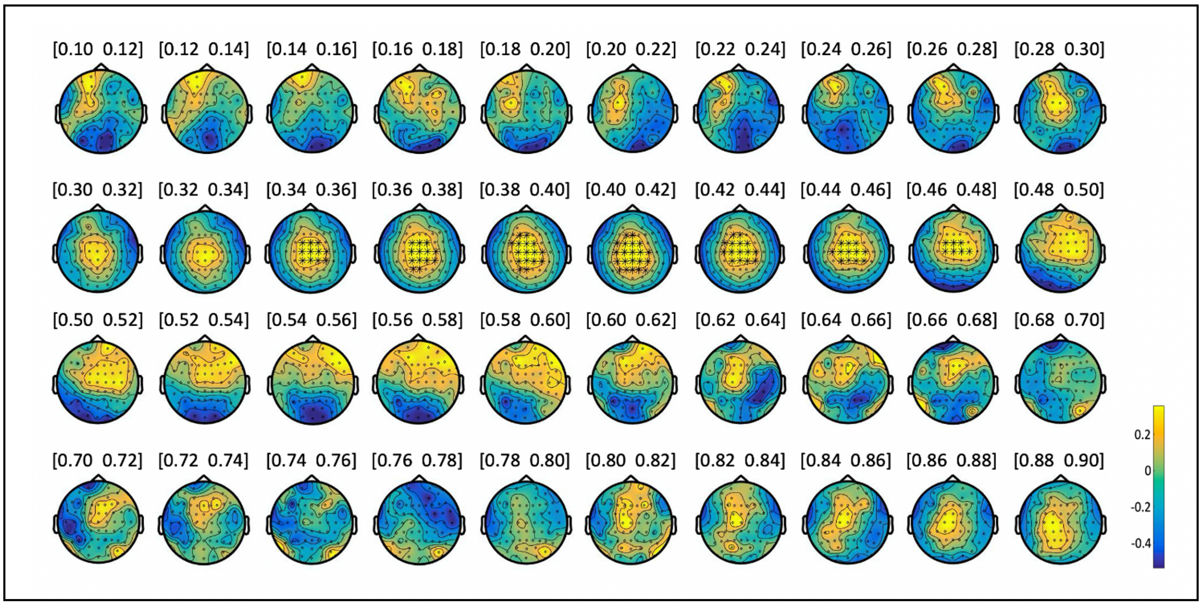

Figure 5. Cluster-based permutation analysis. Testing for the N400 effect and the ERPs effect in the whole epoch of analysis (0.1 to 0.9 seconds after the target onset), the cluster-based permutation tests revealed a significant difference between the double priming condition *RR* and the baseline condition *UU* (p < 0.01). The forty topographic plots equally spaced between 0.1 to 0.9 seconds are displayed, the black dots represent the 65 electrodes, and the significant clusters are indicated with stars. A single cluster was observed, indicating a significant difference between 0.34 and 0.48 seconds over the frontocentral and centroparietal electrodes.

Then, to explore over-additivity, we examined if the N400 double priming effect (*RR-UU)* was larger than the sum of the N400 single priming effects ((*RU* – *UU*) + (*UR* – *UU*)). This analysis was performed in the 300-500 ms time window in which the double priming effect was significantly larger that the single priming effect. This final ANOVA did not reveal any significant effect or interaction (all F < 1). Thus, the N400 priming effect for the double priming condition was not significantly different from the sum of the priming effect for the single priming conditions, indicating a mere additivity of the priming effects.

4. Discussion

In the present study, we used a double semantic priming task to explore categorization of taxonomically and thematically related multiple primes in humans. We explored the priming effects through behaviour (as a time decrease to process the primed compared to the unprimed targets) and electrophysiology (as a decreased amplitude of the N400 in the primed conditions). Our study yielded three essential results. First, both behavioural and ERP measures showed robust single (*RU* and *UR*) and double (*RR*) priming effects. Second, both behavioural and ERP measures demonstrated a larger priming effect for double priming than for single priming conditions. However, there was no evidence for an over-additivity of double priming compared to single priming. Finally, the more substantial priming effect of double compared to single primes was observed for both taxonomic and thematic relationships in the N400 analysis, whereas it was observed only for the taxonomic relationships in the behavioural analysis.

4.1. Categorization in a double vs single priming condition

Our results showed a greater priming effect with two primes than with single primes on both behavioural and ERP measures. We observed additivity but no over-additivity of multiple primes: the facilitation induced by multiple primes was not significantly larger than the sum of the facilitation yielded by each prime separately, for both behavioural and electrophysiological analyses.

4.1.1 Underlying processes of multiple priming effect

Our study confirms the additivity of two primes at the behavioural level in an LDT task. This finding is consistent with previous studies showing an additive effect in multiple priming conditions at the behavioural level, in both semantic category types (Balota and Paul, 1996; Chwilla and Kolk, 2003; Lavigne and Vitu, 1997).

Consistent with behavioural results, the ERP findings also revealed an additive pattern of double priming. We are aware of only one study that explored ERPs in a multiple priming task using a LDT paradigm. Chwilla and Kolk (Chwilla and Kolk, 2003) showed different N400 additivity patterns varying according to the task (LDT or relatedness judgment task) and the type of words used as primes (ambiguous or unambiguous). In the LDT, the results showed an additive effect using both ambiguous and unambiguous words, which is consistent with our findings. In the relatedness judgment task, there was an over-additive effect with unambiguous words but an under-additive effect with ambiguous words. Another study that explored ERPs in a multiple priming task used a picture naming task (Python et al., 2018a). Although the authors did not explore additivity, they described an increased semantic facilitation effect with multiple primes compared to a single prime in both taxonomic and thematic categories. Overall, these findings suggest that a double priming effect can occur in priming paradigms that use different tasks, i.e., naming, LDT, relatedness judgement tasks, suggesting that distinct mechanisms can be involved and combined both at the semantic, lexical, and strategic levels. The task and material used to explore a double priming effect are both critical and an over-additivity effect might be difficult to observe using an LDT, possibly due to its reliance on processes not optimally captured by this task.

The putative mechanisms of additivity remain debated. First, the multiple priming effect might depend on an enhanced influence of one of the primes. It refers to an associative "boost" (Moss et al., 1995) in which the presence of a semantic association between each prime and the target generates a larger priming effect by "accumulation". We controlled the association strength between primes and target, to ensure that verbal associations beyond the semantic relationship itself did not boost the priming effect (Tyler and Moss, 2001). For this reason, we consider that it is unlikely that the double priming effect was due to two separate priming effects or to an enhanced influence of the second prime on the target. We suggest that the multiple priming effect instead reflects the pre-activation of the target induced by primes that have convergent semantic relationships with this target. Previous studies using masked semantic primes and attentional blink paradigms have shown the sensitivity of the N400 priming effect to automatic semantic processes (Deacon et al., 2000; Kiefer, 2002; Kiefer and Spitzer, 2000; Rolke et al., 2001). Hence, the higher facilitation in multiple primes conditions may reflect the organization of concepts into categories.

Second, top-down processes such as controlled strategies might be involved in the multiple priming effect. Several authors have argued against the involvement of purely automatic processes in priming experiments using long SOA (> 300 ms), because such duration allows controlled processing and strategies during task performance (Lucas, 2000; Neely, 1977). In the present study, we used a long SOA (1500 ms) to avoid the ERPs in response to target words to be affected by the ERPs in response to the second prime. Therefore, it is possible that both automatic and controlled processes contributed to the semantic priming effect.

More specifically, two controlled processes may be involved, the expectancy generation and semantic matching. Expectancy generation (Becker, 1980, 1979; Neely, 1991; Neely et al., 1989) is defined as the use of the semantic information of the prime to activate a set of potential words that could correspond or strongly relate to the following target. To limit the impact of the expectation component, we instructed participants not to pay attention to primes. However, as the target was a category, participants may make correct expectations about the following target. This expectation is more likely to be correct in the *RR* condition were the two primes belong to the same category, and especially in the taxonomic condition where there are fewer options than in the thematic condition. The expectation is less likely to be correct in the *RU* or *UR* conditions as the *R* and *U* primes do not belong to the same category. However, in our experiment, the relatedness proportion of *RR* trials (i.e., the proportion of related trials among the total of trials (including related and unrelated conditions) was low (25%), which does not typically favour the occurrence of strategic expectation processes during priming paradigms (de Groot, 1984; Neely et al., 1989). Another controlled process that can be involved in semantic priming is semantic matching (Colombo and Williams, 1990; den Heyer et al., 1983; Neely, 1991, 1977; Neely et al., 1989), in which the participants verify the relation between the prime and the target. It is induced by the type of target-prime relatedness, and primarily occurs when most unrelated prime-target trials use pseudoword targets. With such proportion, unrelated pairs could bias the lexical decision to a "pseudoword" response, and related words, to a "word" response (Neely et al., 1989). In our paradigm, there were as many related as unrelated primes in both words and pseudowords trials, and it is thus less likely that semantic matching processes explain our results. It is noteworthy that the facilitation effect of the first word prime appeared greater than the effect of the second word prime, with a larger difference between RR and UR than between RR and RU conditions. Although this result is difficult to interpret due to a lack of statistical difference between RU and UR, it may suggest that the first prime played a larger role in the semantic facilitation effect than the second one. This tendency might however be better explained by expectancy generation triggered by the first prime than by semantic matching.

Furthermore, some masked priming paradigms showed that unconscious semantic processes are affected by the conscious context and engagement of executive attention (Greenwald et al., 2003; Naccache et al., 2002; Rohaut et al., 2016), highlighting the complexity of the role of controlled processes in implicit priming. Additionally, the increased activation of semantic associations in schizophrenic patients ("hyperpriming") with impaired frontal functions also suggests the role of control functions on semantic priming (Dehaene et al., 2003; Kreher et al., 2008; Spitzer et al., 1993). "Hyperpriming" has also been described in neurological patients, including semantic dementia (Laisney et al., 2011) and Alzheimer disease (Borge-Holthoefer et al., 2011; Giffard et al., 2002, 2001; Ober and Shenaut, 1995), but also patients with post-stroke aphasia and left frontal lesions (Dyson et al., 2020; see also Python et al., 2018b). Among other interpretations, this effect had been explained by a decreased competition or interference among fewer pre-activated or available knowledge. It may also be related to attentional or controlled deficits. The left inferior frontal region may be critical to shaping semantic facilitation by thresholding lexical selection. These studies highlight the complex intricacy of controlled and automatic processes during implicit priming. Hence, we cannot exclude that the categorization we observe also involves controlled processes exerted on implicit priming, and thus may engage at least in part the frontal lobe functions.

Overall, we show a double priming effect on both taxonomic (both behaviourally and on ERPs) and thematic (on ERPs only) relationships in a similarity priming task. These results indicate that some of the processes involved in the similarity task - allowing to activate the shared category between two items - can occur during a semantic priming task. Such processes may include automatic semantic processes and (mostly pre-lexical) controlled processes. The results also suggest that the N400 can be considered as an electrophysiological marker of such primed categorization.

4.1.2 Additive but not over-additive effect

The double priming effect was additive but not over-additive. One putative explanation relates to the design of our paradigm. According to the spreading activation theory, the activation of concepts decays with time. The long SOA used in our task may have allowed a decay in the pre-activation of the target over time, thus decreasing the double priming effect.

Another potential factor is the repetition of the primes (six times) and targets (four times) within the same session that can impact the semantic priming effect. The repetition of each word can yield to a higher baseline level of activation of the concepts, generating a lower semantic priming effect (see Kutas and Federmeier, 2011). However, to limit this effect, we ensured that each word was presented only once for each condition, and we ensured that at least nine trials separated any target repetition. We also created two lists for each type of semantic association to counterbalance the order of the primes, and the order of the sessions alternated between the participants, which allowed us to balance the number of times each of the primes was presented in the first and in the second position.

Hypothetically, an additive rather than the over-additive effect in our double priming task might have a behavioural significance, because it could reflect an adaptive balance between over-constraining the activation of one given concept in response to given stimuli (over-additivity) and failing to activate the appropriate converging concept between them (under-additivity).

4.2 The amount of behavioural double priming effect varies with the type of semantic association.

In the behavioural analysis, the double priming effect was larger when primes were taxonomically related to the target, than when they were thematically related. Based on the results of Python and colleagues (Python et al., 2018a), we were instead expecting a larger behavioural priming effect for thematic than for taxonomic relationships. The reason for a lower double priming effect of thematic relationships remains unclear. Both automatic and controlled mechanisms can explain this result.

In the framework of the spreading activation model, when the first prime is presented, its activation propagates to neighbouring nodes. We propose that as taxonomically related concepts share various features, they are highly interlinked and close to each other in semantic memory. Therefore, a given target category could be primed by the cumulative effect of pre-activation provoked by many neighbouring nodes, resulting in an increased target facilitation. In contrast, thematically related words do not necessarily share similar features. Therefore, the presentation of thematically related primes may activate a much broader set of concepts that are not necessarily interlinked to each other. Thus, there may be no (or less) cumulative effect yielded by multiple primes.

In addition, and as mentioned above, although most factors were controlled in the paradigm to counteract the effect of controlled processes, some factors such as the long SOA and the conscious perception of the stimuli may have allowed controlled processes to occur. We believe that the expectancy generation process could have contributed to the difference in double priming RT between taxonomic and thematic categories. It is possible that due to the presentation of the same type of trials in the taxonomic sessions, namely, exemplars (primes) – category (target) relation, the set of words activated according to the expectancy generation hypothesis was more limited than in thematic trials. In addition, thematic items included different types of functional relations and participants could have generated a broader set of expected targets. Then, the probability that the real target of the task corresponds to the expected one may have been lower for the thematic condition, which may have decreased the influence of expectancy generation in the semantic priming effect.

Regarding more typical effects such as the single priming effect, our findings are in agreement with several studies that have shown no difference in the RT priming effect between taxonomic and thematic (Chen et al., 2014; Hagoort et al., 1996; Khateb et al., 2003; Maguire et al., 2010). This result suggests that the semantic facilitation yielded by a single prime involves similar processes in both types of semantic categories. However, multiple primes may favour the access to taxonomic relationships behaviourally, which should be interpreted with caution since we did not observe differences between semantic category types in N400 amplitudes.

5. **Conclusion**

The present study provides evidence for an additive effect of double priming of taxonomic and thematic categories and suggests that categorization can occur without explicit instructions in a semantic priming task. At the behavioural level, the effect of double priming suggested that taxonomic relations may be stronger or more easily accessed than thematic relations. In contrast, the N400 double priming effect was equivalent for both types of semantic relations, highlighting the importance of the N400 as an electrophysiological marker of categorization. Our findings have implications in understanding the cognitive processes at play during the similarity task in particular, and in categorization in general. The results also place our “similarity priming task” in a promising position as a tool to better characterize the patients' difficulties in abstract thinking, especially in the context of a frontal or temporal degenerative disease or in patients with schizophrenia. Finally, our research has broad significance in understanding how semantic memory is organized and accessed to, and how it shapes the way humans think and generate abstract concepts.

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Supplementary material

Does adding *beer* to *coffee* enhance the activation of *drinks*? An ERP study of semantic category priming

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Prime 1		Prime 2		Target		Prime 1		Prime 2		Target	
iron	(plomb)	copper	(cuivre)	metal	(métal)	emotion	(émotion)	tear	(larme)	sadness	(tristesse)
beer	(bière)	coffee	(café)	drink	(boisson)	head	(tête)	foot	(pied)	body	(corps)
rice	(riz)	corn	(maïs)	cereal	(céréale)	thread	(fil)	button	(bouton)	sewing	(couture)
boot	(botte)	sandal	(sandale)	shoe	(chaussure)	pen	(stylo)	sheet	(feuille)	writing	(écriture)
ball	(ballon)	puzzle	(puzzle)	game	(jeu)	skirt	(jupe)	breast	(sein)	women	(femme)
arm	(bras)	leg	(jambe)	limb	(membre	pig	(cochon)	hen	(poule)	farm	(ferme)
armchair	(fauteuil)	bed	(lit)	furniture	(meuble)	cold	(froid)	mitten	(moufle)	winter	(hiver)
saw	(scie)	shovel	(pelle)	tool	(outil)	garden	(jardin)	chimney	(cheminée)	house	(maison)
tulip	(tulipe)	cactus	(cactus)	plant	(plante)	anchor	(ancre)	sailboat	(voilier)	boat	(bateau)
knife	(couteau)	spoon	(cuillère)	cutlery	(couvert)	dark	(noir)	moon	(lune)	night	(nuit)
red	(rouge)	green	(vert)	colour	(couleur)	handcuffs	(menottes)	escape	(évasion)	jail	(prison)
cake	(tarte)	sorbet	(sorbet)	dessert	(dessert)	zebra	(zèbre)	plains	(plaine)	savanna	(savane)
hatred	(haine)	friendship	(amitié)	feeling	(sentiment)	ladder	(échelle)	truck	(camion)	fireman	(pompier)
shirt	(chemise)	dress	(robe)	clothes	(vêtement)	suitcase	(valise)	beach	(plage)	holiday	(vacances)
horse	(cheval)	frog	(grenouille)	animal	(animal)	breath	(souffle)	blood	(sang)	life	(vie)
ax	(hache)	bow	(arc)	weapon	(arme)	game	(gibier)	gun	(pistolet)	hunting	(chasse)
ring	(bague)	necklace	(collier)	jewel	(bijou)	motor	(moteur)	wing	(aile)	plane	(avion)
fire	(feu)	earth	(terre)	element	(élément)	war	(guerre)	troop	(troupe)	army	(armée)
pear	(poire)	grape	(raisin)	fruit	(fruit)	magic	(magie)	broom	(balai)	witch	(sorcière)
bee	(abeille)	ant	(fourmi)	insect	(insecte)	dress	(robe)	white	(blanc)	bride	(mariée)
sweet pepper	(poivron)	carrot	(carotte)	vegetable	(légume)	day	(jour)	star	(astre)	sun	(soleil)
January	(janvier)	April	(avril)	month	(mois)	bald	(chauve)	redheaded	(roux)	hair	(cheveu)
owl	(hibou)	pigeon	(pigeon)	bird	(oiseau)	banana	(banane)	cage	(cage)	monkey	(singe)
winter	(hiver)	spring	(printemps)	season	(saison)	tongue	(langue)	smile	(sourire)	mouth	(bouche)
sight	(vue)	taste	(goût)	sense	(sens)	music	(musique)	bird	(oiseau)	song	(chant)
ski	(ski)	football	(football)	sport	(sport)	child	(enfant)	notebook	(cahier)	school	(école)

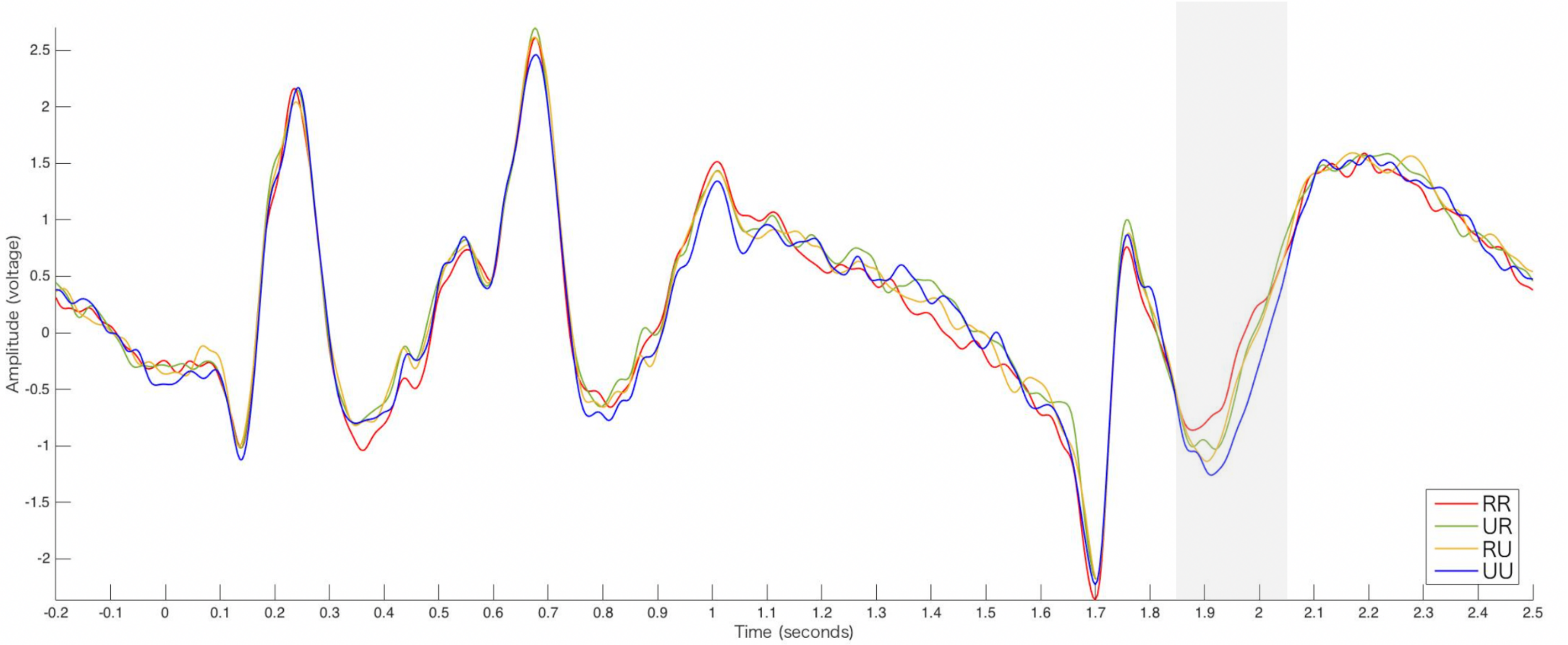
Supplementary Table S1. List of words for both taxonomic and thematic associations translated in English (French in brackets). Twenty-six triplets of words were created for taxonomic and thematic relationships, containing one target and two related primes. The triplets in the present list were used as stimuli for the *RR*-word condition. The combination of all words in the list allowed us the creation of *UR*, *RU* and *UU* conditions.

Taxonomic					Thematic				
word	pseudoword				word	pseudoword			
métal	mélax	méril	bélal	sétol	tristesse	printasse	primmesse	chattesse	prantesse
boisson	meusson	baussin	biossin	muisson	corps	coyal	coxon	dorps	concs
céréale	cémuole	cémurle	cévurle	cémuane	couture	saicure	saipure	soivure	soinure
chaussure	blousture	bleussore	draisture	drainsure	écriture	éscodère	escodore	éscogyre	éscosore
jeu	jee	jui	keu	seu	femme	fulme	faîme	fampe	famde
membre	murbre	beuvre	meltre	bimbre	ferme	farpe	fenre	forve	terde
meuble	moiple	muivre	meivre	beuple	hiver	niper	jimer	zimer	zider
outil	oulol	ourim	ouryl	outaf	maison	bainon	maunon	vauson	saivon
plante	drende	pronte	dranle	flonte	bateau	batoub	batué	batioc	bariau
couvert	pouvexe	coumart	pouset	pouvort	nuit	niot	nuif	juit	nuet
couleur	counour	coutier	poulier	cousuir	prison	plinon	brinon	brivon	clisan
dessert	dassecs	disseon	disseng	disseya	savane	parale	pacene	sarele	patale
sentiment	sennisant	senlisant	sesrident	pontident	pompier	pombeur	pempoir	pemmier	purpier
vêtement	nytament	tâtegent	tômement	tytament	vacances	nacondes	galences	lamences	nacorces
animal	asimum	asimom	asimié	asigol	vie	vio	hie	bie	vei
arme	esme	erte	erne	anle	chasse	cresse	bresse	trosse	blâsse
bijou	bizoï	bizoa	bifau	bifui	avion	anain	anéon	anoen	anien
élément	écèvent	érénent	écésant	évècent	armée	ercée	erbée	ancée	anbée
fruit	frout	friat	fruiz	fruif	sorcière	serboire	serlière	servaure	serloire
insecte	incuote	incoste	incuate	incirte	mariée	marong	maroyé	marorn	maropé
légume	néduge	nésude	hénude	téduge	soleil	soreul	sotial	rolial	roteil
mois	moil	moinf	mias	mias	cheveu	chumeu	chemoa	chuvio	truveu
oiseau	oisiag	oiniau	oiviau	eusiou	singe	cirge	rinde	minde	simbe
saison	saivin	rainon	moiron	maisan	bouche	tougne	cougne	cauche	coubre
sens	hens	bens	dens	nens	chant	chint	brant	chacs	chont
sport	spoya	gnort	spoll	spolt	école	évuse	épune	ésune	éruse

Supplementary Table S2. List of pseudowords for both taxonomic and thematic associations. Two pseudowords for target word were created for each session. In total, fifty-two pseudowords were used for each session in the *UU*-pseudoword and *RR*-pseudoword trials conditions.

	Taxonomic (first session)			Taxonomic (second session)		
Condition	Prime 1	Prime 2	Target	Prime 1	Prime 2	Target
RR-word	**beer**	coffee	drink	coffee	**beer**	drink
RU-word	copper	**beer**	metal	**beer**	pigeon	drink
UR-word	pigeon	**beer**	drink	**beer**	copper	metal
UU-word	**beer**	football	sense	football	**beer**	sense
RR-pseudoword	**beer**	coffee	asimom	coffee	**beer**	asimum
UU-pseudoword	frog	**beer**	baussin	**beer**	frog	meusson

Supplementary Table S3. Trials organization to counterbalance the order of the primes over conditions. The table contains real trials that were used in the taxonomic sessions. In the first session, each prime (e.g., beer) was repeated six times: three times in the first position and three times in the second position. The additional set of trials (second session) was constructed by reversing the order of the primes of each trial of the first session.



Supplementary Figure S1. Time course of the ERPs during the full trial period. The time course of the averaged ERP data of the four priming conditions across the nine frontocentral and centroparietal electrodes (FC1, FCz, FC2, C1, Cz, C2, CP1, CPz, CP2) is displayed. The time course starts with the fixation cross onset (time = 0) and considers the 2.5 seconds of the entire trial period. We considered 0.2 seconds before the cross onset as the baseline period. The onset of the first prime was at 0.05 seconds and the second prime onset was at 0.45 second. The target onset was at 1.55 second. Our a priori period of interest was between 1.85 and 2.05 seconds (0.3 to 0.5 seconds after the target onset).

	Taxonomic				Thematic			
Condition	Mean	SD	Min	Max	Mean	SD	Min	Max
RR	490	87	377	757	497	91	381	822
UR	505	86	406	755	502	82	402	766
RU	503	82	415	770	501	77	388	747
UU	513	91	394	780	513	83	409	795
RUR	504	79	413	763	502	79	395	757

Supplementary Table S4. Descriptive statistics of RTs. Mean, Standard Deviation (SD), Minimum (Min) and Maximum (Max) of the median RTs of all participants are presented in milliseconds. Data are shown for the two types of semantic associations and for the four conditions analyzed. The average between *UR* and *RU* conditions is included in the table as *RUR*.

Taxonomic	[100 - 300]				[300 - 500]				[500 - 700]				[700 - 900]			
Condition	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
RR	-0.52	0.92	-2.40	1.70	0.03	1.28	-2.33	3.02	1.59	1.11	-0.46	3.94	1.06	0.85	-0.60	2.68
UR	-0.56	0.91	-1.89	1.96	-0.23	1.32	-2.77	3.25	1.38	0.96	-0.24	3.25	0.84	0.80	-0.97	2.28
RU	-0.53	1.00	-2.20	2.53	-0.25	1.40	-2.85	3.8	1.41	1.16	-0.49	3.78	0.99	0.98	-0.83	3.05
UU	-0.65	0.86	-1.85	1.86	-0.53	1.29	-3.58	3.16	1.39	0.90	-0.01	2.93	0.95	0.74	-0.30	2.11
RUR	-0.55	0.92	-2.04	2.24	-0.24	1.34	-2.81	3.52	1.40	1.05	-0.36	3.52	0.92	0.87	-0.90	2.37

Thematic	[100 - 300]				[300 - 500]				[500 - 700]				[700 - 900]			
Condition	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
RR	-0.46	0.81	-2.11	1.80	-0.04	1.52	-2.84	3.21	1.37	0.99	-0.12	4.48	1.04	0.77	-0.11	2.76
UR	-0.55	1.01	-2.61	2.09	-0.43	1.45	-3.69	3.07	1.33	1.08	-0.15	4.58	0.90	0.74	-0.20	3.16
RU	-0.34	0.89	-1.71	2.28	-0.28	1.20	-3.14	2.48	1.49	1.01	-0.11	4.52	1.06	0.76	-0.31	2.85
UU	-0.44	0.96	-1.80	2.04	-0.61	1.51	-3.93	3.01	1.34	1.06	-0.03	4.28	0.92	0.68	-0.28	2.74
RUR	-0.44	0.91	-2.16	2.19	-0.36	1.29	-3.41	2.78	1.41	1.00	-0.13	4.55	0.98	0.71	-0.03	3.01

Supplementary Table S5. Descriptive statistics of the N400 component. Mean, Standard Deviation (SD), Minimum (Min) and Maximum (Max) of the N400 amplitude are presented in microVolts (μV) for each time window. Data are shown for the two types of semantic associations and the four conditions analyzed. The average between *UR* and *RU* conditions is represented in the table as *RUR*.