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HAL Authorization

1 **Title**

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

5

6 **Authors list**

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35 **Abstract**

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

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103 **1. Introduction**

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

112 Categorization abilities are typically measured by the Wechsler Adult Intelligence Scale
113 (WAIS) similarity subtest (Wechsler, 2008). In this test, subjects are asked to categorize two
114 items (e.g., "How are an orange and a banana alike?") and name their taxonomic category
115 ("fruits"). Previous studies report impairment in categorization tasks, such as the similarity task,
116 in patients with frontal neurodegenerative diseases (Garcin et al., 2018; Lagarde et al., 2015),
117 suggesting a critical role of executive control functions in this task. However, categorization
118 has also been shown to occur automatically and to rely on semantic associations (Praž et al.,
119 2013), suggesting that categorization depends on the organization of semantic memory. In
120 particular, a given category seems to be implicitly pre-activated by an exemplar of this category
121 (e.g., seeing "dog" pre-activates "animal") (Mirman et al., 2017). The critical role of executive
122 control function in the similarity task may seem paradoxical with the notion that categorization
123 occurs implicitly, based on semantic associations. Hence, how the category is activated during
124 the similarity task remains an open question. More specifically, the question we raised is: do
125 two exemplars of a given category pre-activate this category more than each exemplar would
126 do alone, in a semantic priming paradigm? Addressing this question is essential to clarify the
127 cognitive processes underlying categorization. It is also essential to better appreciate the
128 cognitive difficulties of neurological patients.

129 The semantic priming paradigm is commonly used to explore implicit categorization and
130 the organization of semantic memory, including the organization into categories (Chen et al.,
131 2014; Jones and Golonka, 2012; Maguire et al., 2010) (for reviews (Hutchison, 2003; Jones and
132 Estes, 2012; Lucas, 2000)). The principle of a semantic priming paradigm is to measure how
133 much people are faster and/or more accurate in processing a target word when it is preceded by
134 a semantically related prime word, as compared to an unrelated prime word. This measure
135 reflects the semantic priming effect. The semantic priming effect is also explored with
136 electrophysiological measures using event-related potentials (ERPs). ERPs provide temporal

137 measures of the neural activity following stimulus presentation. Specifically, the N400
138 component, a negative deflection occurring approximately 400 ms after the stimulus onset and
139 typically maximal at centro-parietal electrodes sites, is an electrophysiological landmark of
140 semantic priming effects (for review see Kutas and Federmeier, 2011). The N400 appears very
141 sensitive to semantic relatedness. Its amplitude is smaller when a word is preceded by a related
142 rather than an unrelated word (Kutas and Van Petten, 1994; Lau et al., 2008). The difference in
143 the N400 amplitude in different semantic priming conditions is referred to as the N400 priming
144 effect, and it can occur even in the absence of response time (RT) priming effect (Chwilla et
145 al., 2000; Chwilla and Kolk, 2003), suggesting a higher sensitivity. Many studies using a
146 semantic priming paradigm have shown a relationship between the N400 amplitude and the
147 strength of prime-target associative relatedness (Bentin et al., 1985; Holcomb, 1988; Rugg,
148 1985).

149 Using these behavioural and ERP measures, the semantic priming paradigm has allowed
150 showing that different types of semantic relationships can yield priming effects. In particular, a
151 series of studies show that both thematic (items that share a common context without
152 necessarily sharing similar features, e.g., "rabbit" – "carrot" (Lin and Murphy, 2001) and
153 taxonomic (items sharing specific features such as attributes and functional properties, e.g.,
154 "dog" - "cat"; Gelman and Meyer, 2011; Mirman et al., 2017; Murphy, 2002) relationships
155 between prime and target yield a significant priming effect (Chen et al., 2014; Hagoort et al.,
156 1996; Khateb et al., 2003; Maguire et al., 2010; Mirman et al., 2017). However, whether
157 thematic and taxonomic relationships have distinct semantic priming characteristics, is an open
158 question.

159 In addition, the behavioural and electrophysiological semantic priming effects have been
160 shown to occur for consciously perceived primes and target, but also unconsciously perceived
161 primes in masked-priming paradigms (Brown and Hagoort, 1993; Naccache and Dehaene,
162 2001; Rohaut et al., 2016; van Gaal et al., 2014). This evidence suggests that a semantic priming
163 effect can occur unconsciously. However, a conscious context and task setting effects related
164 to control functions can influence even unconscious priming (Naccache and Dehaene, 2001;
165 Rohaut et al., 2016; van Gaal et al., 2014), indicating that the interplay between unconscious,
166 implicit and controlled processes during semantic priming is complex and not entirely
167 elucidated.

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

171 A few studies on semantic memory have used a "double semantic priming" paradigm to
172 explore whether two primes impacted the processing of the target more than each prime would
173 do alone (Balota and Paul, 1996; Chwilla and Kolk, 2005, 2003; Python et al., 2018a). In the
174 double semantic priming paradigm, the influence of the convergence of two primes on the target
175 processing is assessed by comparing the conditions in which the two primes are related to the
176 target, to conditions in which only one of the two primes relates to the target. These studies
177 demonstrated a larger double as compared to single priming effect with various primes-*target*
178 relationships: exemplars-*taxonomic category*, e.g., copper + bronze - *metal* (Balota and Paul,
179 1996); associated contexts or characteristics-*object*, e.g., alley + window - *house* (Lavigne and
180 Vitu, 1997) or naked + shy - *towel* (Chwilla and Kolk, 2005); mediated associations, e.g., lion
181 + stripes - *tiger* (Chwilla and Kolk, 2003); exemplars-*exemplar*, e.g., helicopter + bus - *airplane*
182 (Python et al., 2018a). Only one of these studies used exemplars of a category as primes and
183 the category as a target (Balota and Paul, 1996) and showed a shorter RT in the double priming
184 condition as compared to single priming, suggesting that categorization can occur implicitly.

185 The measurement of the N400 priming effect using multiple primes has been less explored
186 (Chwilla and Kolk, 2003; Python et al., 2018a). To our knowledge, only two studies have
187 explored the double semantic priming effect by combining behavioural and
188 electrophysiological approaches. Chwilla and Kolk (Chwilla and Kolk, 2003) showed that the
189 existence and the strength of the double priming effect depend on the behavioural task, are
190 altered when primes are polysemous and are easier to observe in ERPs than in behaviour.
191 Although this study did not focus on category relationships, it demonstrates the importance of
192 exploring the neural correlates of semantic priming as a complement to behavioural data.
193 Python and colleagues (Python et al., 2018a) examined category relationships, including
194 thematic relationships and taxonomic relationships. In the taxonomic relationships, targets and
195 primes were exemplars of a specific category (e.g., food or animals). The author described an
196 increased semantic facilitation effect using multiple primes as compared to single primes.
197 Although single semantic priming studies did not show differences in priming effect between
198 taxonomic and thematic relationships (Chen et al., 2014; Hagoort et al., 1996; Khateb et al.,
199 2003; Maguire et al., 2010), in this double priming study, the behavioural priming effect was
200 larger for thematic than taxonomic relationships. In contrast, the ERP priming effect was similar
201 for both relationships. Hence, these findings suggest that categorization can be studied in
202 semantic priming paradigms and may depend on the type of relationships between primes and
203 target. However, this study does not allow to directly test whether exemplars of a category
204 activate the name of that category because the targets used were exemplars of categories, not

205 category names. Whether the double priming effect can be observed in the context of the
206 similarity task, i.e., whether several exemplars prime the category name, is an unresolved
207 question.

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

220

221 **2. Materials and Methods**

222

223 2.1 Participants:

224

225 Forty subjects (20 women) with a mean age of 23 years old (\pm standard deviation (S.D.) =
226 1.31) participated in this study and performed the priming task and other cognitive tasks. One
227 participant was excluded because she did not carry out the task until the end. Thirty-nine
228 subjects were included in the behavioural analyses ($n = 39$, 19 women, mean age = 22.5 ± 1.3
229 years old). Electrophysiological data were recorded in a subgroup of 24 participants (13 women,
230 mean age = 23 ± 1.19 years old).

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

238

239 2.2 Experimental paradigm

240

241 2.2.1 General principle

242

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

265

266 2.2.2 Experimental conditions:

267

268 We created a set of words for taxonomic relationships and another one for thematic
269 relationships (see word lists in Supplementary Table S1). Each set consisted of 26 triplets of
270 one category target word and two prime words. The prime words had a taxonomic relationship
271 with the target (taxonomic set) or a thematic relationship with the target (thematic set). Four
272 different conditions were obtained for both sets by recombining all the elements in each set and

273 considering the relation between the primes and the target (related or unrelated). First, a double
274 priming condition or *RR* condition consisted of each of the original lists of 26 triplets of words
275 in which the two primes were related to the target. Second, *RU* and *UR* conditions were single
276 priming conditions, in which only the first or the second prime, respectively, was related to the
277 target word (the other prime being unrelated to this target). Finally, we created a fourth
278 condition, *UU*, in which neither the first nor the second prime word were related to the target.
279 This last condition was the baseline condition.

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

292 Another set of trials was obtained by reversing the order of the first and second prime words
293 (which were displayed sequentially) for all the trials described above, while keeping the other
294 parameters identical. This second set was built to counterbalance the order of the primes over
295 conditions and allowed us to double the total number of trials. Overall, the participants
296 performed four blocks of trials corresponding to the four sets of 156 trials that were formed:
297 two taxonomic blocks (that differed in the order of the primes in each trial) and two thematic
298 blocks (that also differed in prime order). Each prime was repeated six times: three times in the
299 first position and three times in the second position (see Supplementary Table S3), and each
300 target was repeated four times (Table 1). The order of the trials was pseudo-randomized in each
301 session of 156 trials, with the constraint so that at least nine trials separated two repetitions of
302 the same target. We used the software Mix (van Casteren and Davis, 2006) to pseudo-
303 randomize the trials. Each session lasted about 15 minutes. The order of the sessions was
304 counterbalanced between subjects using the following latin square pattern: 1-2-3-4 / 2-3-4-
305 1 / 3-4-1-2 / 4-1-2-3. Before the task, each participant completed a training session of 6 trials
306 with different triplets of words than those used in the main task. The task was coded and

307 administered with MATLAB 2016b (The MathWorks, Inc., Natick, MA) using the
 308 Psychophysics Toolbox extensions (Brainard, 1997; Kleiner et al., 2007).

309

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

310

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

319

320 2.2.3 Selection of the verbal material:

321

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

325 Three databases of free association norms in French were used to select the words presented as
 326 primes and as targets: the norms of verbal associations for concrete words and abstract words
 327 (Ferrand, 2001; Ferrand and Alario, 1998) and a dictionary of French verbal associations
 328 accessible online (Debrenne, 2010). These tools allowed us to assess the association strength
 329 between different pairs of words for the creation of word triplets (two primes and one target).
 330 The association strength is the probability that a cue word elicits a specific target word in a
 331 verbal free association task. It is measured as the percentage of participants who produced the
 332 target in response to the cue word. We ensured that each prime word alone was not strongly
 333 associated with the target word (less than 15% of association strength), to avoid a ceiling effect

334 and prevent the priming effect from being significantly boosted by direct verbal associations
335 beyond the semantic relationship itself (Tyler and Moss, 2001).

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

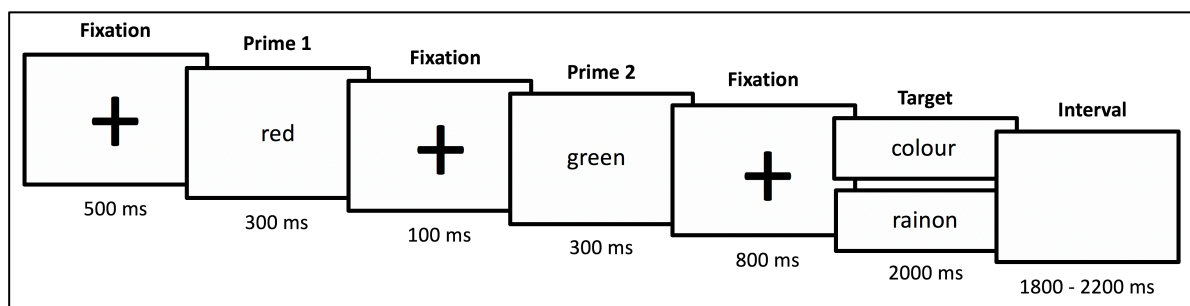
343

344 2.2.4 *Experimental task (Figure 1):*

345

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

360



361

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

365

366 2.3 EEG data acquisition and preprocessing

367

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

377 The EEG signal was downsampled offline to 250 Hz, and filtered with a zero-phase, third
378 order high pass and low pass Butterworth filter (0.5 to 30 Hz). Epochs of 200 ms before and
379 1000 ms after target onset were considered for the analysis. Independent Component Analysis
380 (ICA) was used to detect and remove artefacts caused by eye-blinks. On average, two
381 independent components were removed after a visual inspection of the time series and
382 topographies. Noisy channels were interpolated using the averaged signal of neighbouring
383 channels. A mean of 5.6 electrodes (\pm S.D. = 1.1) was interpolated among the participants.
384 Trials containing more than 10% of noisy channels were removed. A mean of 13.7 trials per
385 subject was rejected (\pm S.D. = 19.6; Range = 0-77) among the total number of trials. After the
386 rejection of the noisy trials, 96.4% (\pm S.D. = 3.3) of all trials remained for the analysis. For the
387 remaining trials, we performed baseline correction between -200 ms to 0 ms relative to the
388 target onset and the signal was re-referenced to the average of all electrodes (retrieving the FCz
389 electrode signal that was initially used as the reference). EEG signals were averaged for each
390 experimental condition (*RR*, *UR*, *RU*, *UU*) separately. Only correct response trials with a word
391 as a target were considered for the analysis. Note that our experimental design was optimized
392 to analyze the target-evoked responses, minimizing contamination by the primes-evoked
393 responses. Thus, the ERPs analysis did not consider the exploration of the priming effects
394 triggered by the primes, which would be difficult to disambiguate from one another. We provide

395 a figure of the ERP time course across the whole trial period in Supplementary Figure S1. All
396 EEG preprocessing and analyses were performed using the FieldTrip toolbox running under
397 MATLAB 2016b (Oostenveld et al., 2011).

398

399 2.4 Behavioural and electrophysiological analyses

400

401 2.4.1 Behavioural measures

402

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

411

412 2.4.2 ERP measures

413

414 Our a priori hypothesis focuses on the N400 component that typically occurs between 300-
415 500 ms after the target onset (Kutas and Hillyard, 1984). A predetermined time-window of
416 interest between 300-500 ms after the target onset was thus selected and analyzed. However, to
417 provide a more comprehensive analysis of the evoked response, we analyzed other time
418 windows of 200 ms duration each, going from 100 ms to 900 ms after the target onset.
419 Therefore, in total we analyzed the following time windows: 100-300 ms, 300-500 ms, 500-
420 700 ms and 700-900 ms.

421

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

429

430 2.4.3 Statistical analyses

431

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

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

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

464

465 **3. Results**

466

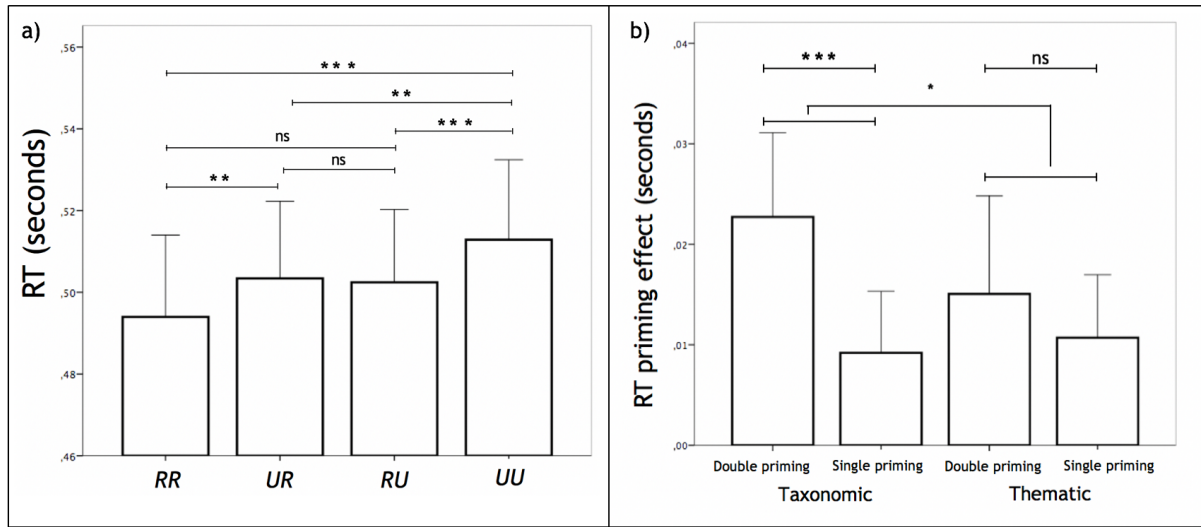
467 3.1 Behavioural analysis:

468

469 Mean accuracy reached 98.4% (\pm S.D. = 1.2; Range = 95-100) of all trials. Only the correct
470 trials were kept and analyzed. The mean and standard deviations of the median RTs are
471 provided for all conditions in Supplementary Table S4. We first performed a two-way repeated-
472 measures ANOVA with semantic category type (2 levels, taxonomic and thematic) and
473 condition (4 levels, *RR*, *UR*, *RU*, *UU*) to explore priming effects across conditions. There was
474 no significant main effect of semantic category type (taxonomic vs thematic) on median RTs
475 ($F < 1$). However, there was a main effect of the priming condition ($F(3,114) = 15.53$; $\epsilon = 0.75$;
476 $p < 0.001$). Post-hoc pairwise comparisons with Bonferroni correction for multiple comparisons
477 revealed that RT was longer in the baseline condition *UU* when compared to double priming
478 condition *RR* ($p < 0.001$) and to each single priming condition *UR* ($p = 0.007$) and *RU* ($p <$
479 0.001). RT was shorter in the double priming condition *RR* compared to the single priming
480 condition *UR* ($p = 0.005$) but not compared to the single priming condition *RU* ($p = 0.068$)
481 (Figure 2a). The interaction between semantic category type and conditions was not significant
482 ($F(3,114) = 1.61$; $p = 0.2$).

483 To examine whether there was a double priming effect and whether it was over-additive,
484 we ran two additional ANOVAs on the single and double priming effects. In the first ANOVA,
485 the double priming effect (*RR* - *UU*) was compared to the average of the single priming effects
486 (*RUR* - *UU*) to explore the existence of a double priming effect. There was no main effect of
487 semantic category type ($F < 1$) but a significant effect of priming type (double versus single)
488 ($F(1,38) = 7.66$; $p = 0.009$). The interaction between semantic category type and priming type
489 was significant ($F(1,38) = 4.58$; $p = 0.04$). Post-hoc comparisons revealed that RT was
490 significantly shorter in the double priming than the single priming condition for taxonomic $t(38)$
491 $= -4.26$; $p < 0.001$) but not thematic ($t(38) = -0.82$; $p = 0.26$) categories (Figure 2b). In the
492 second ANOVA, we tested over-additivity by examining if the priming effect in the double
493 priming condition (*RR* - *UU*) was larger than the sum of the priming effect in the single priming
494 conditions (*RU* - *UU* + *UR* - *UU*). This final ANOVA did not reveal any significant main effect

495 or interaction (all $F < 1$). Thus, the double priming effect was not significantly larger than the
 496 sum of the single priming effects, indicating that the double priming effect was only additive.
 497



498
 499 **Figure 2. Behavioural data.** a) Mean of the median RTs across subjects in the four priming
 500 conditions (taxonomic and thematic conditions pooled together). b) Priming effects in double
 501 and single priming conditions for the taxonomic and thematic conditions are represented as the
 502 difference in RTs between *RR* and *UU*, and between *RUR* and *UU*, respectively. There is a
 503 significant interaction between category and priming effect.

504 *** $p < .001$; ** $p < .01$; * $p < .05$; ns: not significant. Error bars correspond to 95% confidence
 505 intervals.

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

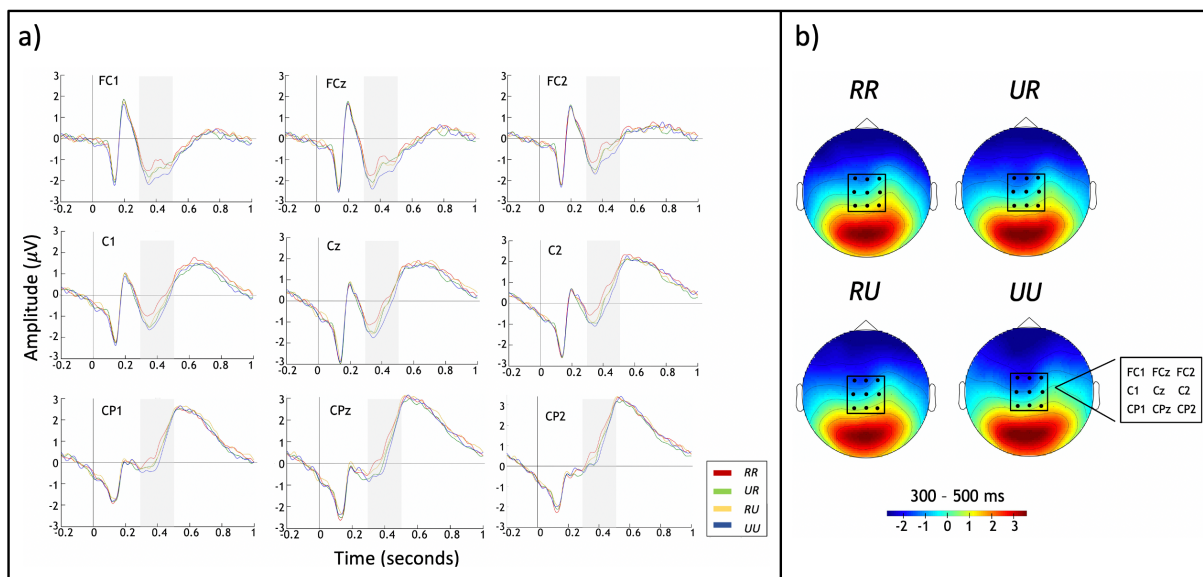
507

508 3.2 ERP analysis

509

510 We measured the mean amplitude of the N400 component in all conditions in both types
 511 of semantic relationships. The N400 mean amplitudes and standard deviations for all conditions
 512 are provided in the Supplementary Table S5. Figure 3 shows the individual time course of the
 513 N400 component for the nine electrodes averaged for the analyses, and the scalp distribution.
 514 The statistical analysis followed the same strategy as for the behavioural data. First, for each
 515 time window, we performed an ANOVA with semantic category type (2 levels, taxonomic and
 516 thematic) and condition (4 levels, *RR*, *UR*, *RU*, *UU*) as within-subject factor allowed us to
 517 explore priming effects across conditions. This analysis did not show any effect of the semantic
 518 category type (taxonomic versus thematic) ($F < 1$) in any of the four time windows. A
 519 significant effect of the priming conditions ($F(3,69) = 11.60$; $\epsilon = 0.65$; $p < 0.001$) was found in

520 the 300-500 ms time window, but not in the other time windows ($F < 1$). The post-hoc pairwise
 521 comparisons with Bonferroni correction for multiple comparisons performed in the 300-500 ms
 522 time window showed that the N400 component was larger in the baseline condition *UU*
 523 compared to the double priming condition *RR* ($p = 0.001$) and to both single priming conditions
 524 *UR* ($p = 0.029$) and *RU* ($p = 0.002$) (Figure 4a). Moreover, double priming condition *RR* showed
 525 a significantly lower amplitude of the N400 component compared to single priming condition
 526 *UR* ($p = 0.014$), but not compared to *RU* ($p = 0.2$). There was no significant interaction between
 527 semantic category type and priming condition factors in any of the time windows ($F < 1$).
 528

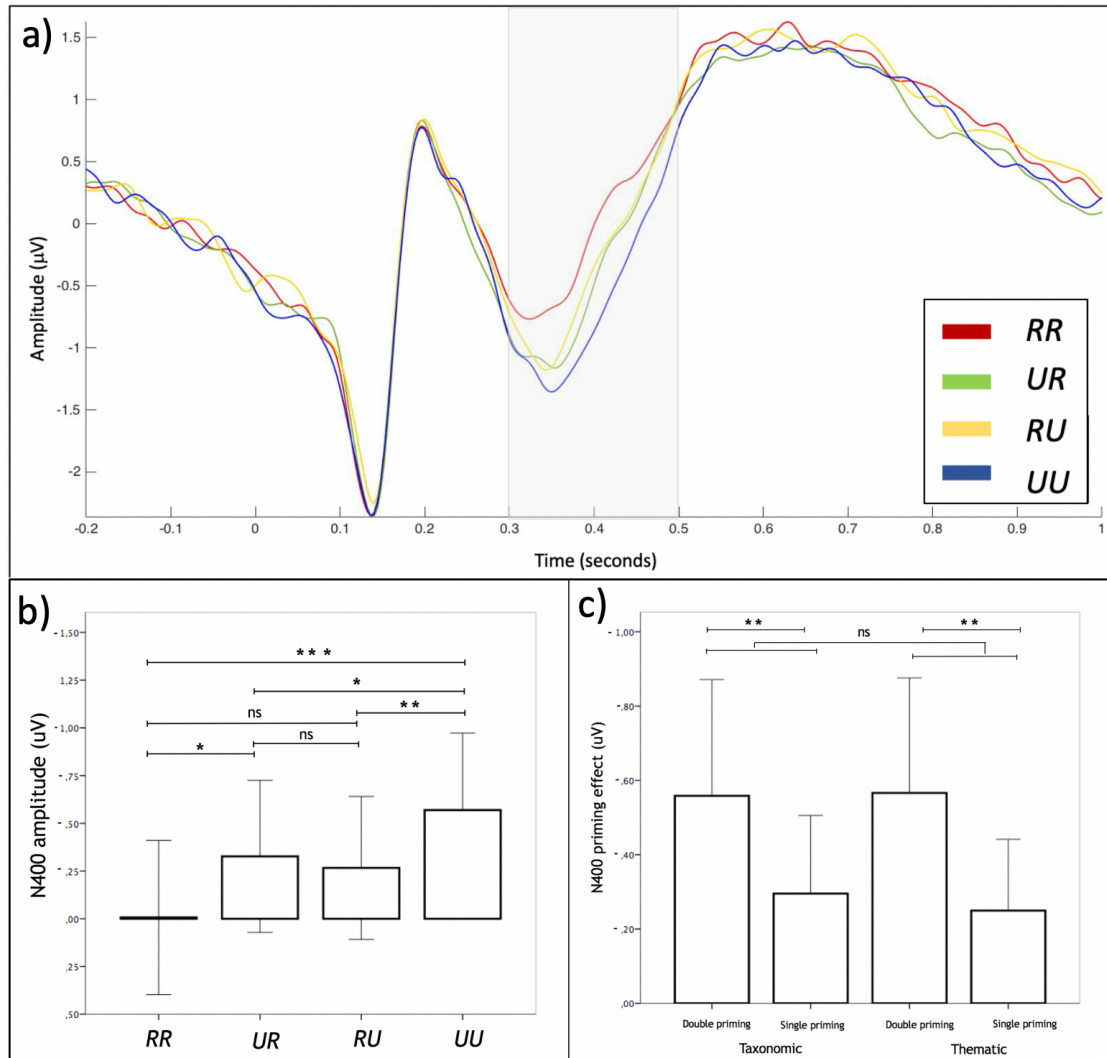


529 **Figure 3. ERP grand average over the nine electrodes separately and N400 scalp**
 530 **distribution.** a) The ERP grand average elicited by the four conditions is provided for the nine
 531 electrodes separately. Time 0 corresponds to the target presentation, and the grey area
 532 represents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

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

536
 537
 538 To examine whether there was a double priming effect, we ran additional ANOVAs on
 539 single and double priming effects computed as the differences in amplitude for *RUR* and *RR*
 540 relative to the *UU* conditions for each time window. These analyses revealed a significant
 541 difference between the single and double priming effects ($F(1,23) = 8.780$; $p = 0.007$) in the
 542 300-500 ms time window. Participants presented a larger N400 priming effect in the double
 543 semantic priming condition compared to the averaged single semantic priming condition

544 (Figure 4). This effect was not significant in any other time window ($F < 1$). No significant
 545 effect of semantic category type ($F < 1$) and no significant interaction between semantic
 546 category and priming effect types ($F < 1$) was observed in any of the time windows.
 547



548
 549 **Figure 4. N400 time course over the nine averaged electrodes and N400 analysis per**
 550 **condition.** a) The ERP grand average is displayed for the four conditions. Amplitude (μV)
 551 corresponds to the average of the nine electrodes considered in the analysis. Time 0 corresponds
 552 to the target presentation, and the grey area represents the studied time window. b) N400
 553 measurements (average signal in the 300-500 ms time window) for the four different conditions
 554 (taxonomic and thematic trials averaged). c) N400 priming effects in double and single priming
 555 conditions for the taxonomic and thematic trials. Here, priming effects are the difference in the
 556 N400 amplitude between *RR* and *UU* (double priming), and between *RUR* and *UU* (single
 557 priming) in the 300-500 ms time window.

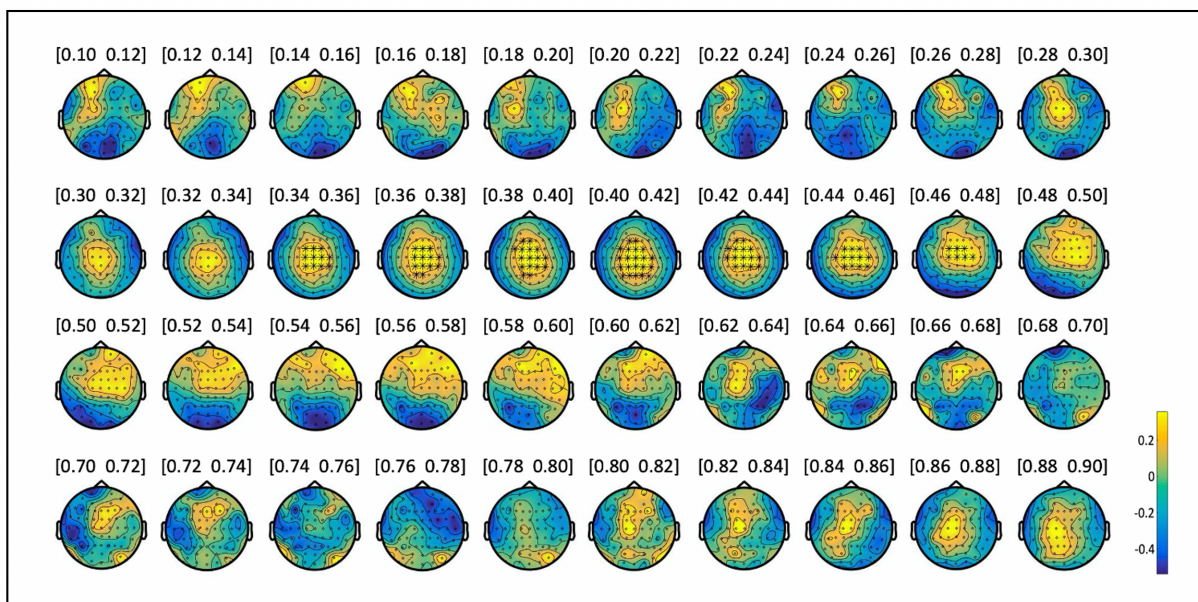
558 Significance of the post hoc tests conducted on the 300-500 ms time window are indicated as
559 follows: *** $p < .001$; ** $p < .01$; * $p < .05$; ns: not significant. Error bars correspond to 95%
560 confidence intervals.

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

562

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

571



572

573 **Figure 5. Cluster-based permutation analysis.** Testing for the N400 effect and the ERPs
574 effect in the whole epoch of analysis (0.1 to 0.9 seconds after the target onset), the cluster-based
575 permutation tests revealed a significant difference between the double priming condition *RR*
576 and the baseline condition *UU* ($p < 0.01$). The forty topographic plots equally spaced between
577 0.1 to 0.9 seconds are displayed, the black dots represent the 65 electrodes, and the significant
578 clusters are indicated with stars. A single cluster was observed, indicating a significant
579 difference between 0.34 and 0.48 seconds over the frontocentral and centroparietal electrodes.

580

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

588

589 **4. Discussion**

590

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

602 4.1. Categorization in a double vs single priming condition

603

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

609

610 4.1.1 Underlying processes of multiple priming effect

611

612 Our study confirms the additivity of two primes at the behavioural level in an LDT task.
613 This finding is consistent with previous studies showing an additive effect in multiple priming

614 conditions at the behavioural level, in both semantic category types (Balota and Paul, 1996;
615 Chwilla and Kolk, 2003; Lavigne and Vitu, 1997).

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

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

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

654 More specifically, two controlled processes may be involved, the expectancy generation
655 and semantic matching. Expectancy generation (Becker, 1980, 1979; Neely, 1991; Neely et al.,
656 1989) is defined as the use of the semantic information of the prime to activate a set of potential
657 words that could correspond or strongly relate to the following target. To limit the impact of
658 the expectation component, we instructed participants not to pay attention to primes. However,
659 as the target was a category, participants may make correct expectations about the following
660 target. This expectation is more likely to be correct in the *RR* condition were the two primes
661 belong to the same category, and especially in the taxonomic condition where there are fewer
662 options than in the thematic condition. The expectation is less likely to be correct in the *RU* or
663 *UR* conditions as the *R* and *U* primes do not belong to the same category. However, in our
664 experiment, the relatedness proportion of *RR* trials (i.e., the proportion of related trials among
665 the total of trials (including related and unrelated conditions) was low (25%), which does not
666 typically favour the occurrence of strategic expectation processes during priming paradigms
667 (de Groot, 1984; Neely et al., 1989). Another controlled process that can be involved in
668 semantic priming is semantic matching (Colombo and Williams, 1990; den Heyer et al., 1983;
669 Neely, 1991, 1977; Neely et al., 1989), in which the participants verify the relation between the
670 prime and the target. It is induced by the type of target-prime relatedness, and primarily occurs
671 when most unrelated prime-target trials use pseudoword targets. With such proportion,
672 unrelated pairs could bias the lexical decision to a "pseudoword" response, and related words,
673 to a "word" response (Neely et al., 1989). In our paradigm, there were as many related as
674 unrelated primes in both words and pseudowords trials, and it is thus less likely that semantic
675 matching processes explain our results. It is noteworthy that the facilitation effect of the first
676 word prime appeared greater than the effect of the second word prime, with a larger difference
677 between *RR* and *UR* than between *RR* and *RU* conditions. Although this result is difficult to
678 interpret due to a lack of statistical difference between *RU* and *UR*, it may suggest that the first
679 prime played a larger role in the semantic facilitation effect than the second one. This tendency

680 might however be better explained by expectancy generation triggered by the first prime than
681 by semantic matching.

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

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

706

707 *4.1.2 Additive but not over-additive effect*

708

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

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

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

727

728 4.2 The amount of behavioural double priming effect varies with the type of semantic 729 association.

730

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

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

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

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

766

767 **5. Conclusion**

768

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

780 understanding how semantic memory is organized and accessed to, and how it shapes the way
781 humans think and generate abstract concepts.
782

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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)

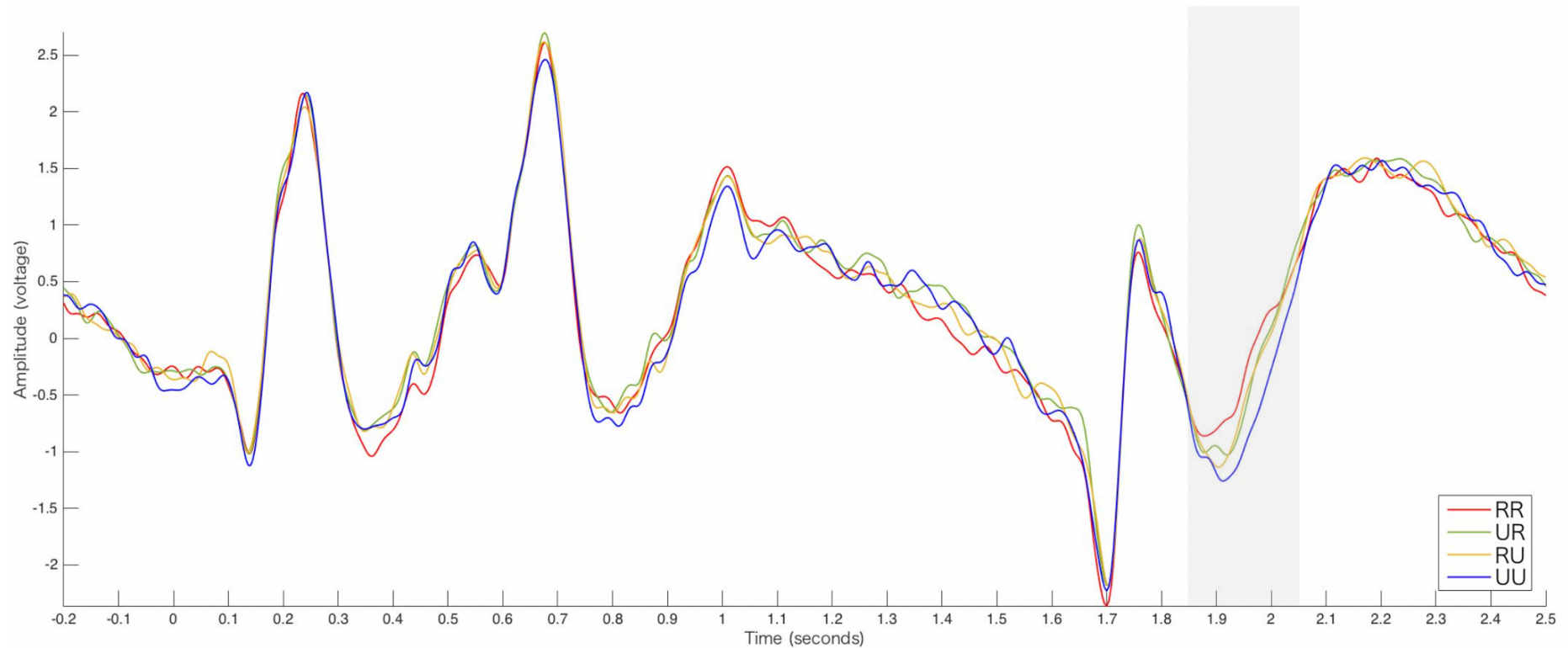
Supplementary Table S1. List of words for both taxonomic and thematic associations translated in English (French in brackets). Twenty-six triplets of words were created for taxonomic and thematic relationships, containing one target and two related primes. The triplets in the present list were used as 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	ménil	bélal	sétol	tristesse	printasse	primmesse	chattesse	prantesse
boisson	meusson	baussin	bioassin	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	érément	écésant	évècent	armée	ercée	erbée	ancée	anbée
fruit	frouit	friat	fruiiz	fruiif	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.

Condition	Taxonomic (first session)			Taxonomic (second session)		
	Prime 1	Prime 2	Target	Prime 1	Prime 2	Target
<i>RR</i> -word	beer	coffee	drink	coffee	beer	drink
<i>RU</i> -word	copper	beer	metal	beer	pigeon	drink
<i>UR</i> -word	pigeon	beer	drink	beer	copper	metal
<i>UU</i> -word	beer	football	sense	football	beer	sense
<i>RR</i> -pseudoword	beer	coffee	asimom	coffee	beer	asimum
<i>UU</i> -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).

Condition	Taxonomic				Thematic			
	Mean	SD	Min	Max	Mean	SD	Min	Max
<i>RR</i>	490	87	377	757	497	91	381	822
<i>UR</i>	505	86	406	755	502	82	402	766
<i>RU</i>	503	82	415	770	501	77	388	747
<i>UU</i>	513	91	394	780	513	83	409	795
<i>RUR</i>	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*.