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Subliminal syntactic priming

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ABSTRACT

Subliminally presented words have been shown to cause priming at orthographic and semantic levels. Here, we investigate whether subliminal priming can also occur at the syntactic level, and use such priming as a tool to probe the architecture for processing the syntactic features of written words. We studied the impact of masked and unmasked written word primes on response times to a subsequent visible target that shared or did not share syntactic features such as grammatical category and grammatical number. Methodological precautions included the use of distinct lists of subliminal primes that were never consciously seen, and the verification that participants were at chance in a prime-classification task. Across five experiments, subliminal priming could be induced by the repetition of the same grammatical category (e.g. a noun followed by another noun), by the transition between two categories (e.g. a determiner followed by a noun), or by the repetition of a single grammatical feature, even if syntax is violated (e.g. "they lemons", where the expression is ungrammatical but the plural feature is repeated). The orthographic endings of prime words also provided unconscious cues to their grammatical category. Those results indicate the existence of a representation of abstract syntactic features, shared between several categories of words, and which is quickly and unconsciously extracted from a flashed visual word.

Written and spoken sentences can be understood without much effort, suggesting that several aspects of word processing proceed automatically, unconsciously, and in an encapsulated manner (Fodor, 1983; Ullman, 2001). Indeed, at the single-word level, a series of subliminal priming experiments have demonstrated unconscious processing at orthographic (Kouider, Dehaene, Jobert, & Le Bihan, 2007) semantic (Dehaene et al., 1998; Van den Bussche & Reynvoet, 2007; Yeh, He, & Cavanagh, 2012) and morphological levels (Frost, Deutsch, Gilboa, Tannenbaum, & Marslen-Wilson, 2000; Giraudo & Grainger, 2001). Subliminal priming even occurs at the emotional (Gaillard et al., 2006; Naccache et al., 2005; van Gaal et al., 2014) and possibly the phonological levels (Wilson, Tregellas, Slason, Pasko, & Rojas, 2011), although the latter remains somewhat debated (Kouider et al., 2007).

One type of processing which has received comparatively little attention, however, is the extraction of the syntactic features of words, such as determining whether a word is a noun or a verb, whether it is masculine or feminine, plural or singular, etc. In the present work, we aimed to examine whether the syntactic properties of words and their grammatical relationships can also be extracted in the absence of conscious perception, and to propose a model of the first steps of syntax processing.

Syntax is a core computational component of language which is necessary to properly construct the meaning of sentences (Friedmann & Shapiro, 2003). Several behavioral and brain-imaging experiments support a "syntax-first" model (Friederici, 2012) in

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which syntactic properties are quickly extracted, using a dedicated cortical circuit (Pallier, Devauchelle, & Dehaene, 2011), and guide the subsequent computation of sentence meaning (Friederici, Gunter, Hahne, & Mauth, 2004). Relatively few studies, however, have examined the relations between syntactic processing and conscious perception. Early studies with dichotic listening suggested that unattended sentences may still be processed at a deep level (Aydelott, Baer-Henney, Trzaskowski, Leech, & Dick, 2012, p. 201; Bentin, Kutas, & Hillyard, 1995; Cherry, 1953; Eich, 1984; Mackay, 1973; Moray, 1959; Rivenez, Darwin, & Guillaume, 2006), although subsequent research has questioned both this conclusion (Aydelott, Jamaluddin, & Pearce, 2015; Dupoux, Kouider, & Mehler, 2003) and the unconscious nature of the stimuli (Holender, 1986; Newstead & Dennis, 1979). Using event-related potentials (ERPs), violations of grammatical agreement in gender or number were found to elicit a mismatch negativity even when attention was distracted away from the auditory stimuli (Pulvermüller & Assadollahi, 2007; Pulvermüller & Shtyrov, 2003). Again, however, the unconscious nature of the stimuli could be questioned.

More recently, experimenters have used better controlled paradigms of subliminal masking, attentional blink or continuous flash suppression to ensure non-consciousness at the single-trial level. Several teams used continuous flash suppression (CFS) to present an entire sequence of words in one eye and rendering it invisible by presenting flickering color patterns to the other eye. Axelrod, Bar, Rees, and Yovel (2014) showed that, during CFS, meaningful sentences caused slightly larger brain activity than lists of pseudowords in language-related areas of the inferior frontal and superior temporal cortex. Sklar et al. (2012) presented a series of experiments suggesting that sentences containing semantic violations break through CFS and become conscious quicker than expressions without semantic violations, but this result failed to be replicated (Rabagliati, Robertson, & Carmel, 2018). Hung and Hsieh (2015) used CFS to hide a single word or morphologically complex pseudoword, and showed that this item popped into conscious awareness faster when it was syntactically incongruent with two previous conscious words or pseudowords. This methodology has been criticized, however (Stein, Hebart, & Sterzer, 2011), and CFS no longer appears as a useful means of eliciting deep unconscious language processing (Rabagliati et al., 2018).

Turning to other methods, Batterink and Neville (2013) used the attentional blink to distract attention from a critical word that rendered a sentence ungrammatical, and showed that even an undetected syntactic anomaly still induced a left anterior negativity in ERP recordings, presumably reflecting an unconscious processing of syntax. Finally, three studies used subliminal priming with masked written words to explore the syntactic representation of words. The first one reported priming from a subliminal determiner onto a conscious noun, as a function of whether the two words shared the same grammatical gender in German (Ansorge, Reynvoet, Hendler, Oettl, & Evert, 2013), although in the stimuli, gender was partially confounded with plural. The second study showed that the morphological features of a masked conjugated verb (indicating active, passive, or reflexive) could prime another verb with the same features (Deutsch, Frost, & Forster, 1998). The third study reported magneto-encephalography evidence that Japanese participants were sensitive to the unconscious agreement between a conscious noun, a subliminal transitive or intransitive verb, and a subsequent conscious verb (Iijima & Sakai, 2014), although no behavioral evidence of subliminal priming was obtained. Here we aimed to systematize those prior results by performing a series of experiments assessing the impact of conscious and unconscious primes on a grammatical categorization task in healthy controls. In five successive experiments, we asked whether the processing of a syntactic feature (e.g. plural) could be facilitated by an unconscious prime. If we could demonstrate such subliminal priming, it would not only extend the range of cognitive operations known to occur without consciousness, but also, importantly, provide information about the organization of the representation(s) and processes that underlie the extraction of the syntactic features of words. Contemporary linguistic theorizing postulates that, for the purpose of unification with other words during sentence parsing, each word must be labeled according to a set of positive or negative syntactic features. For instance, the verb "rained" may be labeled as +verb, −transitive, +singular, +past, etc. (as reviewed e.g. by Sportiche, Koopman, & Stabler, 2013). In the present work, we propose to use priming as a tool to study (1) the psychological reality of syntactic features, and (2) the various cue and cognitive architecture by which such features are extracted.

Our research is guided by a theoretical framework, shown in Fig. 1, which derives from a careful consideration of the various cues available to the participant in order to determine the syntactic features of a word: pseudo-morphology, lexicon, and prior context. We now present each of those levels in turn.

The presentation of a written word is thought to quickly induce an automatic analysis of its orthographic features, culminating in an invariant representation of abstract letter identities and their order (visual word form). Following this stage, our framework tentatively proposes that two routes to syntax are available. The first route provides a tentative morphological analysis of the incoming string: it detects the presence of potential morphemes such as prefixes and suffixes that often provide highly consistent cues about grammatical category and other syntactic features (for instance, the *-ed* ending suggests a verb in the past tense). We label this route as "pseudomorphological" because it needs not suffice to converge on the proper morphological analysis ("biped" is a noun, not the past tense of the verb "bip"). Considerable behavioral and brain-imaging analysis suggests that such morphological analysis occurs at a high speed (Beyersmann et al., 2016; Bick, Frost, & Goelman, 2010; Devlin, Jamison, Matthews, & Gonnerman, 2004; Frost, Deutsch, Gilboa, et al., 2000) and, importantly, even when it is inappropriate (e.g. the word *brother* may be automatically parsed as *broth*+*er*, see Rastle, Davis, & New, 2004).

The second route to syntax postulated in our theoretical framework is lexical. In parallel to pseudo-morphological analysis, the syntactic identity of the word would be retrieved from the "syntactic lexicon", a representation that stores the syntactic features of known words. The postulation of such a representation is necessary, and must eventually override the preceding shallow analysis of pseudo-morphemes, because there are many words whose syntactic features are unmarked morphologically (e.g. *women* = +noun, +plural; *ran* = +verb, +past-tense), or whose initial morphological decomposition is misleading (such as *biped*). The syntactic lexicon would therefore correspond to an internal memory store that specifies, for each word, its grammatical category as well as all the syntactic features necessary to assign it a precise role in the parse tree (grammatical number, gender, tense, number and type of

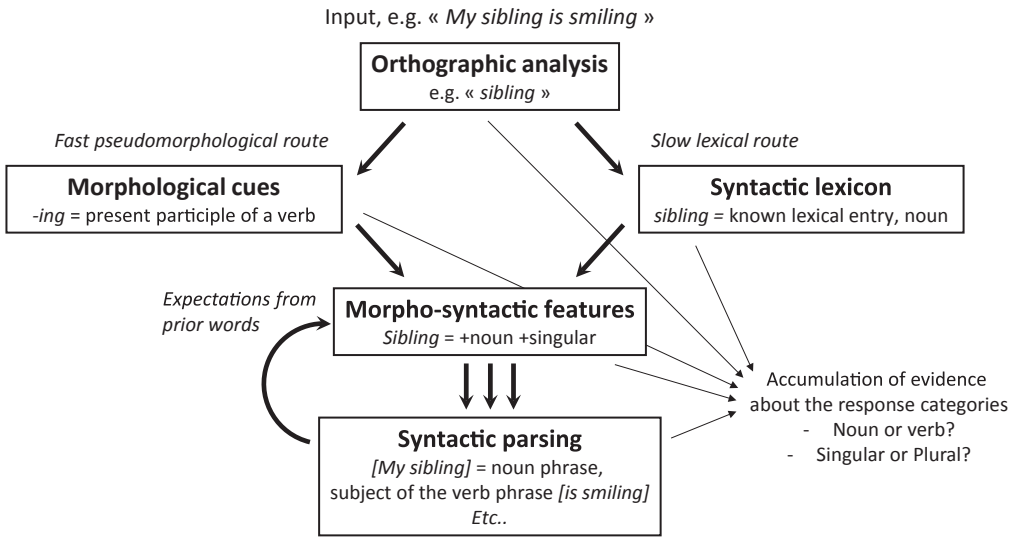

Fig. 1. Tentative theoretical framework for syntactic categorization of a visually presented word. We propose that syntactic features are retrieved via two parallel routes: pseudo-morphological (left) and lexical (right). Following orthographic analysis, morphological cues are quickly extracted and cause a bias towards specific grammatical features (e.g. in English, a word ending with *ing*, such as *smiling*, suggests a present participle of a verb or a nominalized verb). In parallel, a slower lexical route retrieves the stored syntactic features of known words. This route can override the fast one (for instance ***sibling*** ends with -ing, suggesting a verb, but the lexicon correctly encodes it as a noun). Information from the two routes is combined with the current sentence context to yield an estimate of the syntactic features of the current word which is then used for sentence parsing. In turn, parsing creates a syntactic context that biases the processing of subsequent words (i.e. may induce priming). The present experiments test the hypothesis that, in a syntactic categorization task, participants' decisions reflect a combination of multiple sources of evidence arising from each of these representational levels.

arguments, etc.). Explicit models of lexical-syntactic representations of words have been previously proposed and suggest that words having irregular forms are stored as full forms (e.g. *feet* is directly stored as a plural noun) while regular forms would be stored as lemma that can be associated with morphological signals (e.g. *cats* can be decomposed in *cat* noun + *-s* plural) (Amenta & Crepaldi, 2012; Fieder, Nickels, & Biedermann, 2014; Lavric, Pizzagalli, Forstmeier, & Rippon, 2001; Marslen-Wilson & Tyler, 1998; Nickels, Biedermann, Fieder, & Schiller, 2015; Pinker, 1991). Moreover, these models posit that some grammatical features are ultimately associated with conceptual representations (e.g. singular/plural with unique/multiple, noun/verb with entity/event, etc.) (Nickels et al., 2015).

Finally, the third cue to syntactic features is the context of preceding words. The sentence context, once parsed, can induce syntactic expectations about the upcoming word and help to resolve ambiguities due to homographs (e.g. *the walk* versus *they walk*). When contextual expectations contradict the morphological or lexical features of the incoming word, a mismatch signal may arise (Batterink & Neville, 2013; Friederici et al., 2004; Neville, Nicol, Barss, Forster, & Garrett, 1991; Pulvermüller & Shtyrov, 2003).

In normal sentences, the three types of information provided by morphological cues, the syntactic lexicon, and sentential context, must ultimately be reconciled in order to yield a unified interpretation of the most likely syntactic features of the current word in the current context. This interpretation is passed on to the syntactic parser and may, in turn, bias the syntactic categorization of subsequent words (Fig. 1).

Given this theoretical framework, the present experiments had two major goals. First, we wanted to test the postulated architecture for syntactic feature retrieval, and particularly the existence of distinct pseudo-morphological and lexical contributions to syntactic feature retrieval. The framework proposes that multiple cues are computed in parallel and may converge or, on the contrary, diverge in their conclusions. To test this idea, we used priming as a tool, asking whether a syntactic categorization task (e.g. decide whether a target word is a noun or a verb, or is singular or plural) could be primed by another word (the prime). Primes and targets never shared the same orthography, but in different experiments, they could (1) possess congruent or incongruent pseudo-morphemic cues (e.g. both ending with verb cues); (2) share the same category in the syntactic lexicon, or not (e.g. both being verbs); and (3) create a contextual expectation convergent or divergent with the target's genuine category (e.g. determiner followed by noun, pronoun followed by verb). In this way, we tested the existence and efficiency of each of the three routes to syntactic features proposed in our framework.

Second, we also probed whether some or all of the postulated architecture could operate unconsciously. Thus, we compared the effect of conscious primes versus subliminal primes that were masked below the threshold for conscious identification (both at short SOAs). Because masking reduces the activation evoked by a written word at all stages of the reading circuit (Dehaene & Changeux, 2011), the unmasked, conscious condition provided the best chance of obtaining strong priming effects that probe the postulated architecture for syntactic-feature extraction (Fig. 1). However, only the masked, unconscious condition provides a specific test of the fast and unconscious nature of the observed effects. Studying unconscious processing is important because according to the main

theories of consciousness (Baars, 1993; Dehaene & Naccache, 2001; Dennett, 2017; Tononi, 2004), once a word is conscious, any information it conveys can become globally broadcast throughout the cognitive processing system. Only subliminal priming provides a specific test of the hypothesis that the three types of postulated information (pseudomorphological, lexical and contextual knowledge) are quickly extracted and processed even when the incoming stimulus is unable to gain access into the vast stores of the participants' conscious knowledge.

In detail, we conducted a total of five behavioral studies in French. On each trial, a masked or unmasked prime was briefly flashed and followed by a visible target word. Participants had to classify the target either according to its grammatical category (noun or verb; experiments 1–4) or to its grammatical number (singular or plural; experiment 5). Experiment 1 and 2 tested grammatical category priming, i.e. the ability of a prime belonging to a grammatical category to accelerate the processing of a target belonging to the same grammatical category (e.g. a noun followed by a noun, or a verb followed by a verb), and examined the respective contributions of pseudomorphological versus lexical information. Experiment 3 explored whether syntactic priming could also be induced by the contextual relationship between two words (e.g. a determiner followed by a noun, or a pronoun followed by a conjugated verb). In experiments 4 and 5, we examined whether individual syntactic features, rather than syntactic categories, could induce priming. Experiment 4 evaluated whether a determiner could prime a noun, or a pronoun a verb, even when their grammatical number disagreed (e.g. "they cooperates"). Conversely, experiment 5 evaluated whether a singular word could prime another singular word, or a plural another plural, even when their categories formed an ungrammatical phrase (e.g. "they lemons"). To anticipate on the results, all experiments provided evidence that grammatical categories and grammatical features can induce conscious as well as unconscious priming effects.

1. Experiment 1

Experiment 1 evaluated whether masked and unmasked words cause grammatical category priming. We used French verbs and nouns as primes and targets and studied whether a noun could prime another noun, and a verb another verb.

To specifically study such grammatical category priming, several methodological precautions were taken. All verbs were in the infinitive form, thus sidestepping any issues of agreement or grammaticality (all of the two-word combinations that we presented were ungrammatical in French). Because orthographic (Kouider et al., 2007) and possibly phonological (Wilson et al., 2011) features can be processed subliminally, we excluded all words that were homophones or homographs of words from other grammatical categories, and we built pairs of nouns and verbs that were well matched in orthography, length, and frequency. Because emotional valence can be subliminally processed (Gaillard et al., 2006; Naccache et al., 2005; van Gaal et al., 2014), we chose words with neutral emotional valence.

Most importantly, the experiment was designed to test the respective contribution of pseudomorphological and lexical information in determining the syntactic category of primes and targets, by orthogonally varying them. In French, word ending is a strong cue to grammatical category (Arciuli & Monaghan, 2009), especially in French where many verbs end in "er", and such affixes have been shown to induce priming (Frost, Deutsch, & Forster, 2000; Giraudo & Grainger, 2001). Thus, we used pairs of nouns and verbs that were matched according to their ending. Furthermore, in each prime-target pair, the prime ending differed from the target ending. Those precautions ensured that (1) the task could only be performed by retrieving the category of the target from the syntactic lexicon, because word-ending information alone did not suffice; (2) similarly, syntactic-category priming (noun-noun or verb-verb), if observed, could only be explained by retrieval of the prime's syntactic category from the syntactic lexicon; (3) our experiment also allowed measurement of the putative effects induced by word endings alone, i.e. through the pseudo-morpho-syntactic route, and this separately for the prime and for the target. The dual-route model presented in Fig. 1 predicted that both the word-ending (pseudo-morphological route) and the true syntactic category (lexical route) of the prime, as well as the irrelevant morphological indication provided by the target ending, would influence the categorization of the target word, and we probed whether they did so for unconscious as well as conscious primes.

1.1. Material and methods

1.1.1. Participants

Twenty-two right-handed native French speakers (8 males; mean age 23.9 years old; range 18–30 years old) were tested. All participants had normal or corrected-to-normal vision and were naive to the purpose of the experiment. No participant took part in more than one experiment. Participants gave informed consent before taking part, and received financial compensation (10€ for a session of 45 min). Six participants were excluded: 4 had an error rate of more than 10% and two could not see the unmasked prime in the visibility task (their d′ measures for unmasked primes were 0.6 and −0.2 respectively).

1.1.2. Stimuli

Sixty French masculine nouns and sixty infinitive verbs served as prime and target stimuli. We created pairs consisting of one noun and one verb that were similar in orthography, ending ("er", "ir" or "re"), number of letters (mean 7.1; range 3–10), and frequency in French (mean 19 per million; range 0.09–232), for instance "écuyer" ("rider", noun) and "écumer" ("to skim", verb). We excluded words belonging to more than one grammatical category, homophones or homographs of words from other grammatical categories, words having a strong emotional valence and nouns having a verb-like pseudo-morphology. For instance, the noun "berger " ("shepherd") was excluded because it could have been construed as a verb constructed from the noun "berge" and the ending "er" (see e.g. Rastle et al., 2004).

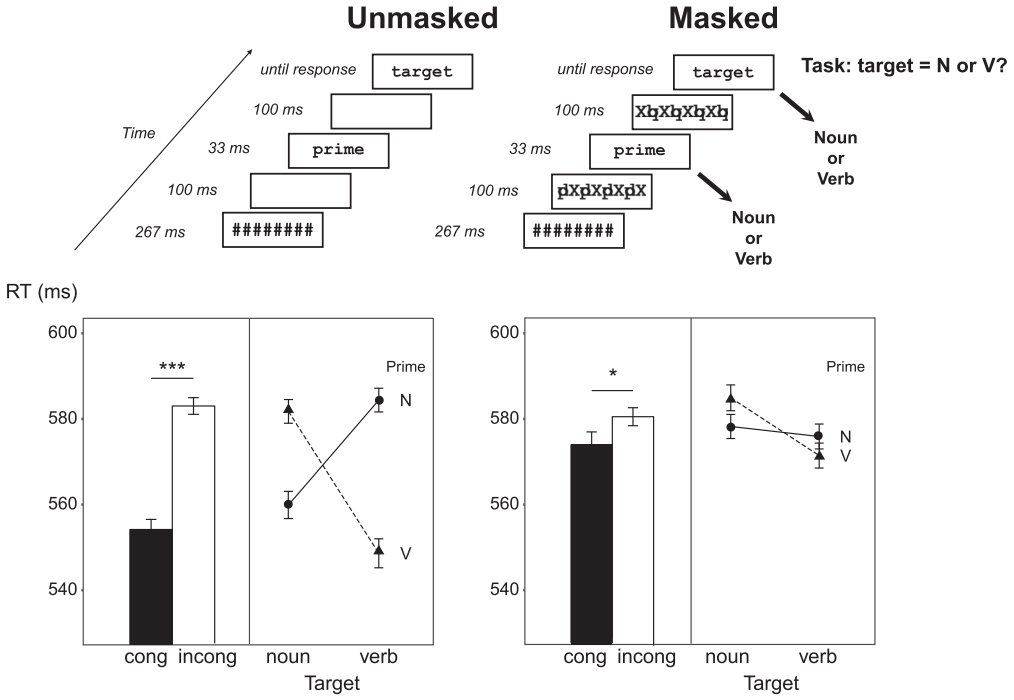

Fig. 2. Procedure and results of experiment 1. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked noun or verb prime. On the left: unmasked conditions, on the right: masked conditions. At the bottom, barplots show response times for congruent (black bars) and incongruent (white bars) trials, lineplots show response times as a function of prime category (N = noun, solid line; V = verb, dashed line) and target category. Error bars represent one standard error of the mean (*SEM*). *** = $p < 0.001$; * = $p < 0.05$.

For each participant, 30 noun-verb pairs out of 60 were randomly selected to serve as masked primes, while the others served both as targets and as unmasked primes. This methodological precaution is important as it implies that the masked primes were never consciously seen and, therefore, could not induce direct sensori-motor priming (see e.g. Abrams & Greenwald, 2000; Naccache & Dehaene, 2001). Consequently, both primes and targets consisted of very similar words such as “écuyer” and “écumer”, which could only be distinguished by their (arbitrary) assignment to the noun or verb grammatical category in the French lexicon. The final list of stimuli was generated by randomly pairing primes and targets, with the further constraint that they should not share the same initial letter nor the same ending (last three letters). All target words appeared equally often in each of the congruent and incongruent conditions, for a total of 240 masked trials and 240 unmasked trials. All trial types were randomly intermixed.

1.1.3. Procedure

Each trial consisted of a precisely timed sequence of a prime presented for 33 ms and a target presented until the participant answered. The presentation of the prime could be masked or unmasked depending on the masking conditions. On masked trials, the prime was preceded by a first forward mask (i.e., “############”) for 267 ms and a second forward mask (i.e., “dXpdXpdXpdX”) for 100 ms, and followed by a backward mask (i.e., “XhXhXhXh”) presented for 100 ms prior to the target. On unmasked trials, the two masks surrounding the prime (i.e., the second forward mask and the backward mask) were replaced by blank screens (see Fig. 2). Such a masking technique (a variant of Kouider et al., 2007) was required in order to contrast conscious versus unconscious trials with the same prime duration (33 ms) and prime-target stimulus onset asynchrony (SOA, 133 ms). With standard techniques such as the Forster paradigm (Forster & Davis, 1984), where prime-target asynchrony is very short, it is very difficult to obtain complete invisibility in the masked condition and full visibility in the conscious condition while keeping timing variable constant. We run pilot experiments and empirically adapted the masks and timing to the specific words used, taking into account that they varied in length and frequency. All stimuli appear at the center of screen in the same fixed-size font (courier new bold, subtending 1.15 degree of vertical visual angle) in lowercase black letters on a white background.

Participants were asked to determine as quickly as possible the grammatical category of the target word (noun or verb) by pressing a right-hand or left-hand button (buttons were assigned at the beginning of the experiment, and their assignment was counterbalanced between participants). They were asked to pay attention solely to the word that stayed on screen (i.e., target) and to ignore any other event (i.e., prime or masks). Each participant performed a training block of 60 trials, where each target word was presented once, then 8 blocks of 60 trials, with a short pause after every block. The aim of the training (also used in previous studies, e.g. Dehaene et al., 2001) was to familiarize participants with the procedure and the target words so that their subsequent performance would be better and more uniform.

After the main experiment, participants performed a forced-choice test (visibility task) in order to check whether the specific

syntactic feature tested (i.e. grammatical category) could be consciously perceived. Participants were told about the presence of a hidden prime preceding each target word, and were asked to guess whether it was a noun or a verb. They were told that only response accuracy was important, not response speed, and that they had to venture an answer even if they did not see the prime. They were informed that the target grammatical category was incongruent with the prime grammatical category 50% of the time. Each trial comprised the same sequence of masks and stimuli as in the experiment, except that the target stayed on screen for 500 ms. In addition, just after the target, the response words "NOM" (noun) and "VERBE" (verb) appeared. To avoid response priming, those categories were randomly assigned to the right and left of the fixation point. Participants responded by pressing the button on the side of the word they wanted to select. The two alternatives remained on screen until a response was made.

1.2. Results

1.2.1. Behavioral priming in response times

Overall error rate was 7% (range 2–10%). We performed an analysis of variance (ANOVA) on median of correct response times for each participant (excluding response times above 1200 ms or $+/-3$ standard deviations away from the mean for each participant) during the grammatical categorization task, with factors of visibility (masked/unmasked), prime category (noun/verb) and target category. This analysis revealed a main effect of visibility (masked vs. unmasked; $F_{1,15} = 34.83$, $p < 0.001$): responses were 10 ms faster overall in the unmasked condition (567 ms versus 577 ms), presumably because removal of the masks rendered the target easier to process. There was no main effect of the category of the target ($F_{1,15} = 1.87$, $p = 0.19$) and of the prime ($F_{1,15} = 1.54$, $p = 0.23$). Crucially, a prime category × target category interaction indicated the presence of an overall grammatical category priming effect (congruent: 563 ms; incongruent: 580 ms, difference: 17 ms, $F_{1,15} = 59.45$, $p < 0.001$). Furthermore, a triple interaction with visibility ($F_{1,15} = 29.12$, $p < 0.001$) indicated greater priming in the unmasked compared to the masked condition. Nevertheless, grammatical category priming was found under both unmasked (552 ms versus 581 ms, difference: 29 ms, $F_{1,15} = 67.64$, $p < 0.001$) and masked conditions (574 ms versus 580 ms, difference: 6 ms, $F_{1,15} = 4.68$, $p = 0.048$) (see Fig. 2).

1.2.2. Prime visibility

Data from the forced-choice prime categorization task was used to evaluate prime visibility. Measures of d′ values for each participant confirmed that they were unable to consciously categorize the primes in the masked condition (50.6% correct; $d' = 0.03$; $t_{15} = 0.4$; $p = 0.69$), whereas they could do so in the unmasked condition (93.6% correct; $d' = 3.06$; $t_{15} = 26.1$; $p < 0.001$). There was no positive correlation between the size of the priming effect and the prime visibility in the masked condition, but if anything a negative correlation (Pearson $r = -0.5$, $t_{14} = -2.17$, $p = 0.048$) and the intercept of this regression was significant (5.4 ms, $t_{14} = 2.50$, $p = 0.025$), indicating that priming remained significant even at null d′ (see Greenwald, Draine, & Abrams, 1996).

1.2.3. Word ending analysis

We next evaluated whether word-ending cues had an independent impact on the noun-verb categorization task, thus testing the existence of a pseudo-morphological level of processing that biases the retrieval of syntactic features. The words we used ended with one of seven possible endings ("er", "ier", "ir", "ire", "oir", "re", "tre"), each of which was used for at least ten words. We first examined if those endings biased responses towards the verb or the noun category. An ANOVA on median response time showed a significant interaction between grammatical category and target ending ($F_{6,48} = 8.88$, $p < 0.001$; note that this analysis was restricted to the 9 participants without any missing measures in each condition), suggesting that some endings cued specific grammatical categories. For instance, participants were significantly faster to answer "verb" than "noun" for words ending in "er" (difference: 84 ms, $t_8 = -4.26$, $p = 0.003$) but faster to answer "noun" than "verb" for a word ending by "re" (difference: 16 ms, $t_8 = 2.71$, $p = 0.027$). Thus, target ending influenced the syntactic categorization task, even though by design it was orthogonal to the genuine category of the target word.

Next, we evaluated whether *prime* ending had an effect on the target-based decision. First, we used the target-based RTs to compute a variable that we called the "ending-induced bias" (EIB) for each of our seven endings in French. EIB was defined as the mean difference RT_{noun}-RT_{verb} for each target ending (see Fig. 3, left panel). It was therefore positive for endings such as "er" or "oir" which favor a "verb" response, and negative for endings such as "re" or "ir" which favor a "noun" response. Second, we applied this variable to the prime words, and used a mixed-effect regression model to examine whether the prime-related EIB biased the speed of responding to the target. The variable of interest, called "prime ending congruity" was the prime-ending variable multiplied by a $+1/-1$ variable coding for target category, thus measuring the congruity between the amount of noun-verb bias induced by the prime ending and the correct noun/verb response induced by the target. Other variables of non-interest were the category of the prime, the presentation condition (masked/unmasked), their interaction between themselves and with other variables of interest, and the frequency of the target word in French. We again observed a target-ending effect ($t = -5.70$, $p < 0.001$; trivially reflecting the fact that EIB was derived from the same data), but we did not find any significant prime ending congruity effect, neither for unmasked ($t = 0.23$, $p = 0.38$) nor for masked primes ($t = -0.28$, $p = 0.38$).

Our model assumes that the pseudo-morphological route is fast and eventually over-ridden by the genuine information provided by the lexical route. To explore whether prime ending affected only the earliest stages of grammatical category processing, we analyzed separately short and long RT trials (respectively inferior and superior to the median). Still, no effect was found in this analysis neither for unmasked nor for masked conditions (short RT unmasked: $t = -0.15$, $p = 0.39$; masked: $t = -0.34$, $p = 0.37$; long RT unmasked: $t = 0.50$, $p = 0.34$; masked: $t = 1.02$, $p = 0.23$).

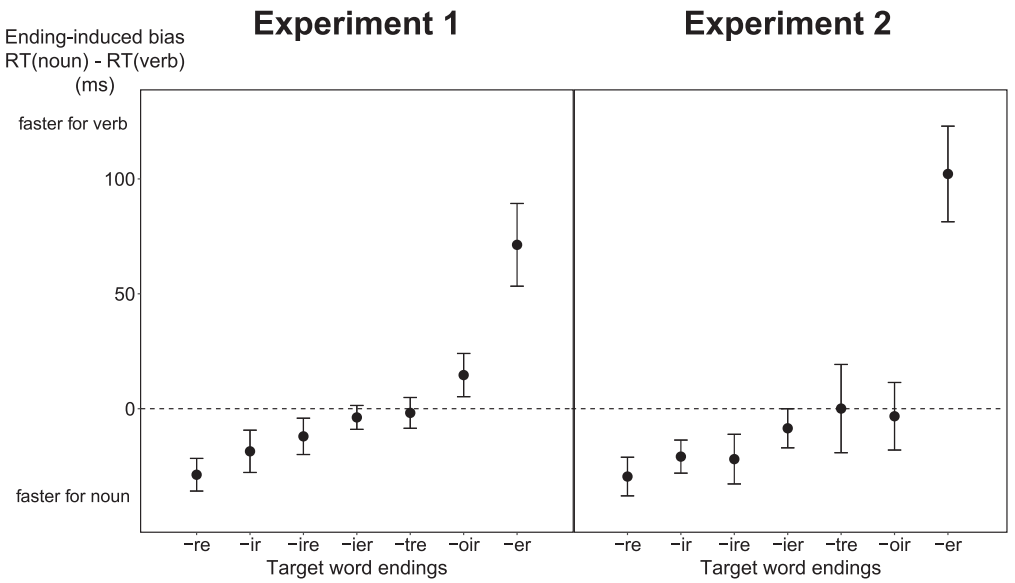

Fig. 3. Word endings modulate the speed with which target words are classified as nouns or verbs. For each ending, the y axis shows the bias towards verbs, as measured by the difference in mean response time (RT) to nouns and to verbs. Positive values indicate a faster response to verbs than to nouns. On the x axis, word endings have been sorted according to the biases measured in experiment 1. In both experiments 1 and 2, word endings induced reproducible and highly similar biases towards one or the other response (r = 0.97). Error bars represent one *SEM*.

1.3. Discussion

A significant grammatical category priming was found in both unmasked and masked conditions. In the latter, participants were unable to consciously perceive the primes and were at chance in discriminating their grammatical category. Furthermore, the prime-target word pairs were specifically chosen to avoid any bias due to orthographic, phonological, syntactic, semantic, or morphological priming. Finally, in the masked condition, a distinct list of prime words was used, which were never seen nor categorized as targets. This design allowed us to formally exclude the possibility that priming arose from automatized stimulus-response mappings (Abrams & Greenwald, 2000; Damian, 2001). We therefore concluded that the grammatical category of a word (noun or verb) can be subliminally extracted from masked words and can prime the noun-verb judgment for another word of the same category. Because grammatical category was manipulated independently of word ending, with minimal pairs such as *écuyer* (N) vs *écumer* (V), prime category information could only have arisen from a stored lexicon, and we therefore conclude that the lexical route to syntactic category can be activated consciously as well as unconsciously. Unsurprisingly, and in accordance with many prior studies, conscious priming was parallel to, but significantly greater than, subliminal priming (Cheesman & Merikle, 1986; Dehaene et al., 2001; Kouider & Dehaene, 2007; Kouider et al., 2007; Merikle, Smilek, & Eastwood, 2001).

The dual-route model of syntactic-feature extraction also predicted that word ending would have an independent influence on the syntactic categorization task. In agreement with this prediction, we found that, independently of the target's grammatical category, the target's final letters, which carry pseudomorphological information in French, biased participants towards the verb or noun response. This finding strongly supports the dual-route model, as it indicates that two different variables, genuine word category and the (often erroneous) category induced by pseudo-morphemes, had orthogonal influences on syntactic categorization.

Surprisingly, however, no such word-ending effect was found on the prime. We will discuss this finding after the presentation of experiment 2, where we examined one possible cause for its absence.

2. Experiment 2

Experiment 2 aimed to replicate experiment 1 with a few changes. Most crucially, we reasoned that the relatively long stimulus-onset-asynchrony (SOA) separating the prime and the target (133 ms) could have weakened the priming effects and, in particular, might explain why we found a target-ending effect but not prime-ending effect. If the pseudo-morphological route is fast and quickly overridden by the slower lexical route, as postulated in our theoretical framework, then the prime effect induced specifically by the prime ending might be very short-lived. In experiment 2, the prime-target SOA under masked condition was therefore reduced to 50 ms. This required small changes to the masking paradigm (Fig. 4), and piloting also showed that we could maintain prime invisibility while relaxing the strong masking conditions imposed in experiment 1 (one forward mask instead of two), again in the hope of increasing the amount of priming.

Another limit of experiment 1 is that the unmasked prime word could appear as targets, thus affording the possibility that their response (left or right) was automatized and led to stimulus-response priming. This was not true for masked primes, which never appeared as conscious targets. As a consequence, the larger difference between masked and unmasked priming in experiment 1 (29

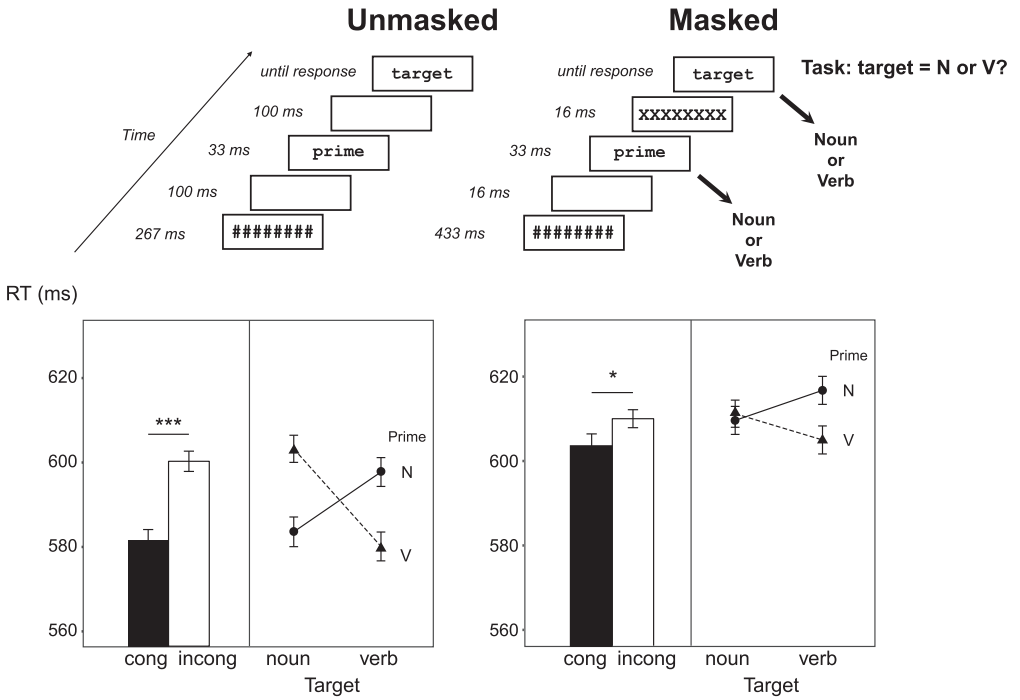

Fig. 4. Procedure and results of experiment 2. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked noun or verb prime. Same format as Fig. 2. Error bars represent one *SEM*. *** = p < 0.001; * = p < 0.05.

vs. 6 ms) could have arisen in part from a difference in stimulus-response priming. We corrected this small problem in experiment 2 by using three separate lists of words (randomly varied across participants) that served respectively as masked primes, unmasked primes, and target words.

2.1. Material and methods

2.1.1. Participants

Twenty-one right-handed native French speakers (6 males; mean age 23.3 years old; range 19–29 years old), fulfilling the same criteria as in experiment 1, were tested. Two participants were excluded: one had an error rate of more than 10% and one had a mean response time (RT) of over 800 ms.

2.1.2. Stimuli

The same 120 words as in experiment 1 were used. For each participant 20 pairs of matched nouns and verbs were randomly assigned to serve as masked primes, 20 as unmasked primes and the remaining 20 as targets.

2.1.3. Procedure

On unmasked trials, the visual sequence was exactly the same as in experiment 1 (267 ms forward mask "############", 100 ms blank screen, 33 ms prime, 100 ms blank screen, and finally the target presented until the response). On masked trials, the sequence comprised a 433 ms forward mask "############", 16 ms blank screen, 33 ms prime, 16 ms backward mask "XXXXXXXXXXX", and target. This procedure ensured that prime duration (33 ms) was equal and identical to experiment 1, but that the masking was lighter (see Fig. 4). Note that the SOA between prime and target was now shorter on masked compared to unmasked trials (50 ms versus 133 ms). The task was the same as in experiment 1, i.e. determining as quickly as possible the grammatical category of the target word (noun or verb).

The procedure was as in experiment 1 except that a control repetition-priming block was inserted before the final visibility task. During this block, using the same task, 160 masked-only trials were used. The masked primes were identical to the targets on 25% of the trials, different but congruent for grammatical category on another 25%, and incongruent on the remaining 50%, so that overall 50% of the trials were congruent and 50% were incongruent. In this block, both prime and target words were the 20 nouns and 20 verbs used as targets in the main block.

2.2. Results

2.2.1. Behavioral priming in response times

Overall error rate was 5% (range 1–8%). For the main block, an analysis of variance (ANOVA) on the median of correct response times for each participant, with the same exclusion criterion as in experiment 1, revealed results similar to experiment 1. There was a main effect of presentation type (masked vs. unmasked; $F_{1,18} = 53.26$; $p < 0.001$): responses were 20 ms faster overall in the unmasked condition (591 ms versus 611 ms). There was no main effect of the category of the target ($F_{1,18} = 0.15$, $p = 0.70$) and of the prime ($F_{1,18} = 0.64$, $p = 0.43$). Crucially, there was a significant grammatical category priming effect (interaction of prime category and target category; congruent 595 ms versus incongruent 607 ms, difference: 12 ms, $F_{1,18} = 20.07$, $p < 0.001$). As expected, a triple interaction with visibility ($F_{1,18} = 8.21$, $p = 0.010$) indicated greater priming in the unmasked compared with the masked condition. The grammatical category priming was found both in unmasked (582 ms versus 600 ms, difference: 18 ms, $F_{1,18} = 20.8$, $p < 0.001$) and masked conditions (607 ms versus 614 ms, difference: 7 ms, $F_{1,18} = 5.55$, $p = 0.030$) (see Fig. 4). In a comparison of experiments 1 and 2, the size of the grammatical category priming effect was similar, both in the unmasked condition (29 ms vs. 18 ms; Welch $t_{df = 32.8} = -1.79$; $p = 0.082$) and in the masked condition (6 ms vs. 7 ms; Welch $t_{df = 33} = 0.284$; $p = 0.78$).

2.2.2. Prime visibility

Measures of d′ values for each participant confirmed that they were unable to consciously perceive the category of the primes under masked condition, as they performed slightly below chance (45.5% correct; $d' = -0.24$; $t_{18} = -2.60$; $p = 0.018$), whereas they performed well in the unmasked condition (89.5% correct; $d' = 2.70$; $t_{18} = 17.47$; $p < 0.001$). There was no significant correlation between the priming effect and the prime visibility in the masked condition ($t_{17} = -0.34$, $p = 0.74$) and the intercept of this regression was significant in the expected direction (8.3 ms, $t_{17} = 2.00$, one-tailed $p = 0.031$), indicating that grammatical priming occurred at null visibility.

2.2.3. Word ending analysis

An ANOVA on median response time again showed a significant interaction between grammatical category and target ending ($F_{6,78} = 9.93$, $p < 0.001$), indicating that some endings cued specific grammatical categories. We again calculated the ending-induced bias (EIB) as the mean difference RT_{noun}-RT_{verb} (see Fig. 3, right panel). EIB variables were highly correlated between experiments 1 and 2 (correlation coefficient $r = 0.97$, $t_{12} = 14.07$, $p < 0.0001$), showing that the same endings reproducibly biased decisions towards nouns or towards verbs. We then used the same mixed-effect regression model as in experiment 1 to examine whether prime ending biased RTs to the target. This time, we could use the EIB calculated from the independent data in experiment 1, thus avoiding any circularity in the analysis. There was a highly significant effect of target EIB ($t = -5.70$, $p < 0.001$). Furthermore, crucially, there was now a highly significant prime-ending congruity effect for masked primes ($t = -3.23$, $p = 0.005$). For unmasked primes, the effect was non-significant ($t = -1.08$, $p = 0.22$), but a median split suggested a marginal effect in the appropriate direction when we analyzed only the fast response times (below each participant's median; $t = -2.04$, one-tailed $p = 0.027$).

2.3. Discussion

Experiment 2 replicated the presence of grammatical category priming with unmasked primes that had never been explicitly categorized by the participants (which was not the case in experiment 1). The size of this unmasked priming effect was 18 ms, only slightly and non-significantly smaller than the 29 ms in experiment 1. Most crucially, under masked condition, the grammatical category priming effect was replicated and was comparable to experiment 1 (7 ms versus 6 ms). Modifying the masks and reducing the prime-target SOA thus did not affect the amount of category priming. Overall, the results suggest that, even though unconscious syntactic-category priming is a small effect, it is a robust and reproducible phenomenon that resists variations in prime-target SOA and masking type. This finding confirms that the grammatical category of a subliminal word can be subliminally retrieved from the lexicon and can prime another word of the same category.

Independently of this category effect, we also found a prime ending effect: masked words primed the noun or verb response in direct proportion to how their endings, when present in the target words, biased RTs towards the noun or verb category. Those results indicate that word-endings may unconsciously bias responses toward the verb or noun category, independently of the word's true category. Changes in prime-target SOA between experiments 1 and 2 may explain the fluctuations of this effect. Indeed, it was only found when the SOA was very short (50 ms), i.e. for masked primes in experiment 2, but not in the other conditions where SOA was longer (133 ms) i.e. masked and unmasked primes in experiment 1, and unmasked primes in experiment 2. When we selected only the shortest responses (RTs < median), a marginal prime-ending effect reappeared for unmasked primes in experiment 2.

These results are fully compatible with the proposed theoretical framework for syntactic-feature extraction (Fig. 1): the prime-ending effect arises only as a fast and transient effect, quickly replaced in time by the effect of the true grammatical category of the word in the French lexicon. Remember that, according to the proposed dual-route model, grammatical category is retrieved through two parallel routes. A tentative category is activated based on morphological cues, particularly word ending (fast pseudo-morphological route). Later, the correct grammatical category is retrieved from the syntactic lexicon (slow lexical route). In case of a mismatch between those two categories, the real grammatical category supersedes the one hypothesized from morphological cues. The existence of the two routes is supported by the presence of two independent and orthogonal effects in our data, while the superseding assumption is supported by the fact that participants performed at a very high level (95% correct) even on trials where target ending conflicted with target category.

The speed of the slow lexical pathway is likely to be modulated by the familiarity and the conditions of word presentation (the more familiar and visible, the faster). The latter property fits with the absence of prime-ending effect in experiment 1 under unmasked condition, even for short RTs, given that the unmasked prime words had also been presented as targets. It also fits with prior findings of "pseudo-morphological decomposition" according to which a word such as "brother" is transiently decomposed into its apparent morphemes "broth" and "er" (Rastle et al., 2004). Our results complement those prior findings by showing that the terminal morpheme of a noun or word can cue a specific grammatical category.

3. Experiment 3

In experiment 3, we sought to test the third postulated source of syntactic information in our theoretical framework (Fig. 1): the syntactic context provided by previous words. Thus, whereas experiments 1 and 2 studied word-end and category-based repetition priming (noun-noun or verb-verb), experiment 3 probed whether priming could be induced by syntactic context in the absence of any repetition of a given syntactic category. The task still was to categorize a visible target word as a noun or a verb, but the prime word was either a determiner or a pronoun. Determiners are generally followed by nouns, and pronouns by verbs – and conversely, a determiner followed by a verb or a pronoun followed by a noun are ungrammatical constructions in French. Thus, the presence of a determiner should induce a strong and possibly unconscious grammatical expectation for a noun, and a pronoun should lead participants to expect a verb. We therefore expected that the grammatical pairings (determiner-noun and pronoun-verb) would cause priming relative to the ungrammatical pairings.

This design also allowed us to address another issue. In experiments 1 and 2, participants were actively engaged in a grammatical categorization task on target words. Thus, the category priming that we observed could be due to a subliminal accumulation of evidence towards one of the two imposed response categories. The results undoubtedly imply that subliminal words provided unconscious evidence towards the noun and verb categories, but we cannot exclude that this categorization was, at least in part, induced by the task itself which, as proposed in Fig. 1, may rely on an accumulation of all available sources of evidence. In other words, experiments 1 and 2 do not necessarily imply that the noun and verb categories are automatically and unconsciously extracted whenever a word is processed, only that they *can* be extracted when required (for a similar discussion, see e.g. Dehaene et al., 1998; Greenwald, Abrams, Naccache, & Dehaene, 2003). However, if we observed priming by determiners and pronouns in experiment 3, even though the target categories are noun versus verb, it would strongly suggest that at least part of the observed priming effect is due to an automatic categorization of the primes even when their category is irrelevant for the task.

3.1. Material and methods

3.1.1. Participants

Twenty-two right-handed native French speakers (6 males; mean age 24 years old; range 19–30 years old) were tested. Six participants were excluded: three had an error rate of more than 10%, two had a mean response time of over 800 ms and one did not respect instructions.

3.1.2. Stimuli

Primes were either a singular masculine determiner "un" ("a") or "le" ("the"), or a masculine 3rd person singular personal pronoun "on" ("one") or "il" ("he"). As in the first two experiments, we created pairs of noun and verb similar in orthography, length, frequency and ending, for instance "rôle" ("role") and "rôde" ("prowls"). We identified thirty French countable masculine nouns and thirty verbs conjugated in the 3rd person singular present tense, paired so that they were similar in orthography, ending, number of letters (mean 6.6; range 4–9), and frequency in French on average (mean 15.6 per million; range 1.29–392). We excluded all words that were homophones or homographs of words from other grammatical categories, words with a strong emotional valence, and nouns derived from verbs, for example "blocage" ("blocking") derived from "bloquer" ("to block"). We also excluded direct transitive verbs. Also note that the primes formed pairs ("il/le" and "on/un") that were similar in orthography, number of letters, and frequency (mean 11887.4 per million, range 8586–13653).

Participants all saw the same 60 target words (30 nouns and 30 verbs), but half of the participants had "le" ("the") and "il" ("he") as unmasked primes and "un" ("a") and "on" (pronoun "one") as masked primes, while the other half had the reverse assignment. Primes and targets could form a noun phrase, for instance "le sport" ("the sport"), a verb phrase, for instance "il dort" ("he sleeps"), or an ungrammatical pairing such as "il sport" ("he sport") or "le dort" ("the sleeps"). Since direct transitive verbs were excluded, the pronoun-verb pairing was ungrammatical even when considered as part of a larger sentence (with a direct transitive verb such as "manger" ("eat"), phrases such as "il le mange" would be grammatical).

We excluded target words starting with a vowel, because in this case the determiner "le" would have had to be elided to "l'". We also excluded mass nouns, for example "pétrole" ("fuel"), because they cannot be utilized with the indefinite determiner "un"; and impersonal verbs (for example "rain") which could not be conjugated with the pronoun "on" in French.

3.1.3. Procedure

Task, stimulus presentation, timing and procedure were exactly as in experiment 2 (see Fig. 5).

During the forced-choice test (visibility task), participants were asked to guess whether the word presented before the target was a determiner or a pronoun. They were informed that the target grammatical category was incongruent with the prime grammatical category 50% of the time. Each trial comprised the same sequence of masks and stimuli as in the experiment but the target stayed on

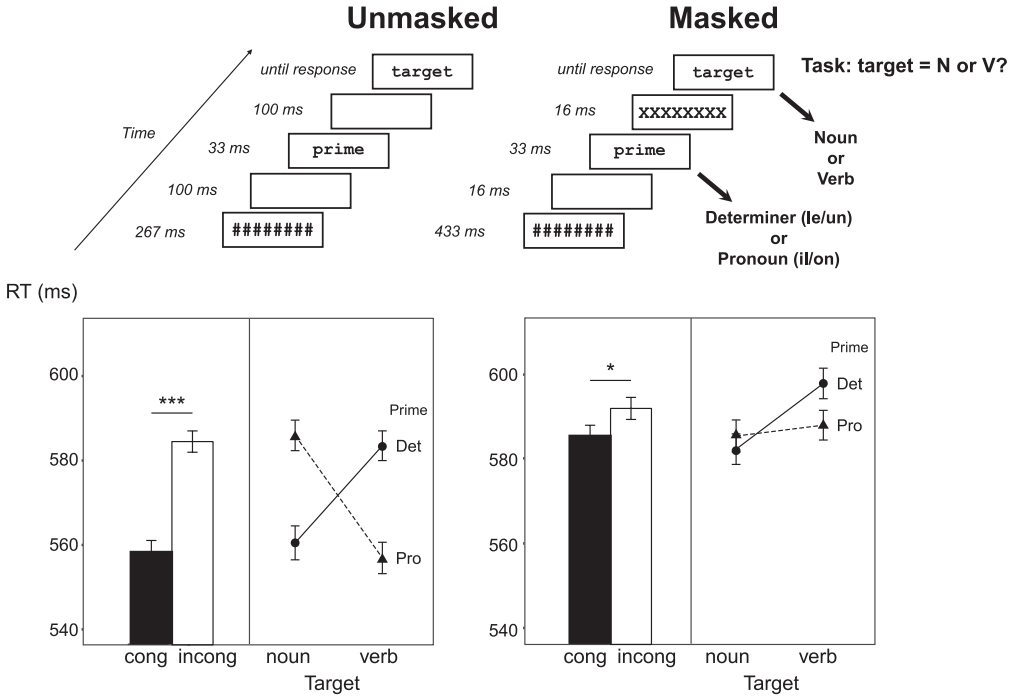

Fig. 5. Procedure and results of experiment 3. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked determiner or pronoun prime. At the bottom, barplots show response times for congruent (black bars) and incongruent (white bars) trials, lineplots show response times as a function of prime category (Det = determiner, solid line; Pro = pronoun, dashed line) and target category. Error bars represent one *SEM*. *** = $p < 0.001$; * = $p < 0.05$.

screen for 500 ms. In addition, just after the target, the words “PRONOM (il, on)” and “DETERMINANT (le, un)” were randomly presented left and right of fixation. Participants responded by pressing the button on the side of the response they selected. The two alternatives remained on screen until a response was made.

In the final repetition-priming block, noun and verb targets were replaced by the four words “il”, “le”, “un” and “on”. The participant’s task was to classify them into “determiner” versus “pronoun” categories (randomly assigned to right versus left buttons, counterbalanced across participants).

Each participant first performed the main task, including a training block of 60 trials and 8 blocks of 60 trials (with all possible pairings of primes and targets presented twice), then two blocks of the forced-choice test (60 trials each).

3.2. Results

3.2.1. Behavioral priming in response times

Overall error rate was 5% (range 2–10%). We performed an analysis of variance (ANOVA) on median correct RTs during the grammatical categorization task, with the same exclusion criteria as above, and factors of visibility (masked/unmasked), target category (noun/verb), and prime category (determiner/pronoun). This revealed a main effect of visibility (masked vs. unmasked; $F_{1,15} = 25.11$, $p < 0.001$): responses were 17 ms faster overall in the unmasked condition (572 ms versus 589 ms). There was no main effect of the category of the target ($F_{1,15} = 0.42$, $p = 0.53$) and of the prime ($F_{1,15} = 0.66$, $p = 0.43$). Crucially, a target category × prime category interaction revealed a syntactic priming effect (grammatical pairing: 572 ms; ungrammatical pairing: 588 ms, difference: 16 ms, $F_{1,15} = 37.13$, $p < 0.001$). A triple interaction with visibility ($F_{1,15} = 12.59$, $p = 0.003$) indicated greater priming in the unmasked compared to the masked condition. Strong syntactic priming was found in the unmasked condition (559 ms versus 585 ms, difference: 26 ms, $F_{1,15} = 36.05$, $p < 0.001$).

Under masked condition, the effect was reduced and did not reach classical two-tailed significance. However, the direction of the effect could be predicted, either from data from the unmasked trials in the present experiment, from data from previous experiments in the present paper, or from past research: primes that bias subjects towards a certain decision facilitate subsequent response times for that decision, and this phenomenon, which is highly replicable (as reviewed e.g. by Kouider & Dehaene, 2007), is predicted by models of decision-making as evidence accumulation (e.g. Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003).

Here, therefore, grammatical pairings were predicted to be processed faster than ungrammatical pairings. One-tailed tests supported this prediction: masked syntactic priming was significant in a one-tailed test (585 ms versus 592 ms; 7 ms in the predicted direction, $F_{1,15} = 3.99$, one-tailed $p = 0.032$) (see Fig. 5). The size of the syntactic priming effect was similar to the category priming in experiment 2, under both masked and unmasked conditions (unmasked: 26 ms vs. 18 ms, Welch $t_{32.3} = -1.24$, $p = 0.23$; masked:

7 ms vs. 7 ms; Welch $t_{31.3} = 0.038$, $p = 0.97$).

3.2.2. Prime visibility

Measures of d′ values for each participant confirmed that they failed to consciously perceive the category of the primes in the masked condition (52.1% correct, $d' = 0.12$, $t_{15} = 1.83$, $p = 0.087$), whereas they could do so in the unmasked condition (96.6% correct, $d' = 3.4$, $t_{15} = 31.95$, $p < 0.001$). There was no significant correlation between the size of the priming effect and prime visibility in the masked condition ($t_{14} = 1.27$, $p = 0.23$), but the intercept failed to reach significance (3.5 ms, $t_{14} = 0.83$, $p = 0.42$).

3.3. Discussion

Our third experiment explored syntactic priming, defined as the ability for a word to prime a target word belonging to the grammatical category that should normally follow it in a grammatical sentence. We obtained a significant syntactic priming under unmasked and masked conditions (respectively of 26 ms and 7 ms). Given the controls we imposed on the stimuli, these priming effects cannot be attributed to other factors such as orthographic, phonological, semantic, or morphological priming. Automatized stimulus-response mapping is also excluded, because neither the masked nor the unmasked primes were ever used as targets. Because few masked primes were used, a subliminal action-trigger hypothesis could be invoked (Kunde, Kiesel, & Hoffmann, 2003), but this possibility was excluded by our experimental design: masked primes were never used as targets, had never been consciously perceived nor categorized during the experiment, and did not even share the same grammatical category as the targets. Therefore, unlike in experiments 1 and 2, priming could no longer be caused by a repetition of the target categories. Finally, on masked trials, participants were unable to consciously perceive the primes and were at chance in discriminating their grammatical category.

We therefore conclude that an irrelevant word can prime the syntactic categorization of a subsequent noun or verb, when those two words form a grammatical constituent. This effect, which we term “syntactic priming”, was very strong for unmasked primes, and was marginal but significant in the predicted direction for masked primes. Furthermore, it was similar in size to the grammatical category priming observed in experiments 1 and 2, suggesting that categorical and syntactic priming are of comparable size.

Interestingly, a similar coexistence of categorical and predictive priming was also observed for movements: two photographs of movement were subsequently presented and yielded subliminal priming when they depicted two similar movements or when reflecting the natural movement order (Güldenpenning, Koester, Kunde, Weigelt, & Schack, 2011; Güldenpenning, Kunde, Weigelt, & Schack, 2012).

Regarding the framework we proposed, these results support the existence of a third influence on syntactic categorization: beyond word ending cues and syntactic category repetition, the syntactic context formed by the preceding words indeed exerted a strong influence on the retrieval of the syntactic features of the target word. Before discussing this finding further, we replicate and extend it.

4. Experiment 4

The syntactic priming observed in experiment 3 is compatible with the hypothesis that abstract syntactic rules such as “a determiner precedes a noun phrase” are applied unconsciously. However, an alternative explanation based on transition probabilities cannot be excluded. According to this interpretation, priming would result merely from the fact that grammatical combinations of words are more frequent than ungrammatical ones in natural language, and that adults and even infants are sensitive to such transition probabilities (Thompson, Colleges, & Newport, 2007). Thus, the difference in RTs between grammatical and ungrammatical pairs might only reflect a difference in transitional probability (do note, however, that this interpretation cannot explain the results of experiments 1 and 2, where all pairs were ungrammatical).

To address this problem, and to further expand our studies of syntactic priming, we designed another experiment in which two syntactic features were orthogonally contrasted: grammatical category and grammatical number (singular or plural). With this new design, we could investigate the distinct contributions of two forms of grammatical agreement: the syntactic relationship between prime category and target category (e.g. determiner noun) and their agreement in number (e.g. singular followed by singular). Because these factors were orthogonally manipulated, there were prime-target pairs that violated syntactic category relationships but agreed in grammatical number, such as “il reptile” (roughly translated as “he reptile”), and pairs that fitted in terms of categories but violated number agreement, such as “des reptile” (“some reptile”). This feature of the design allowed us to study the presence of two orthogonal priming effects (by syntactic category and by number), as well as their presence even in ungrammatical prime-target word pairs. If, as argued by many syntactic theories (as reviewed e.g. by Sportiche et al., 2013), grammatical number is a stand-alone feature shared by many word categories, then one might expect priming whenever this feature is shared between two words, even these words do not form a grammatical phrase. Crucially, such feature-based priming would not be explainable by transition probabilities, because such probabilities are very close to zero for ungrammatical word pairs.

4.1. Material and methods

4.1.1. Participants

Twenty-seven right-handed native French speakers (12 males; mean age 23.7 years old; range 19–31 years old) were tested. Three participants were excluded: one had an error rate exceeding 10%, one had a mean response time of over 800 ms, and one had a response time variance of 300 ms.

4.1.2. Stimuli

Prime words were either a determiner, singular “un” (“a”) or plural “des” (“some”), or a 3rd person personal pronoun, singular “on” (pronoun “one”) or plural “ils” (“they”). Target words were almost identical to experiment 3. Some stimuli were changed because we excluded words starting by the letter “d” to avoid orthographic priming by “des”, verbs that were homographs or near-homographs of other words in their plural forms (for instance the verb “persiste” was excluded because it is written “persistent” in the present plural, which looks like the adjective “persistant” in French); and nouns or singular verbs that ended in “ent” (for instance “sergent” or “provient“) because they could be confounded with plural verbs.

There were 120 targets in total: 30 French regular countable masculine nouns, either singular or plural, and 30 verbs conjugated in the 3rd person present, either singular or plural. Thus, these targets formed 30 quadruplets of 4 words, for instance “cortège” (“procession”), “cortèges” (“processions”), “coopère” (“cooperates”) and “coopèrent” (“cooperate”). These words were matched in orthography, ending, number of letters (mean 7.5; range 5–12), and frequency in French (mean 14.1 per million; range 1.31–252). We again excluded words homophones or homographs of words from other grammatical categories, words with a strong emotional valence, and nouns derived from verbs. Primes also formed couples (“on/un” and “ils/des”) that were similar in orthography, number of letters, and frequency (mean 7451.2 per million, range 3075–12088).

Participants all saw all combinations of the 120 target words (30 singular and 30 plural nouns and 30 singular and 30 plural verbs) and the 4 prime words. These combinations could be congruent for syntax and number (e.g. “un reptile”), congruent for syntax but not for number (“des reptile”), incongruent for syntax but congruent for number (“on reptile”) or incongruent for syntax and number (“ils reptile”). Note that all of these trial types were equally frequent and were, on average, composed of exactly the same prime words and target words. Only one of them was grammatical.

4.1.3. Procedure

Task, stimulus presentation and procedure were almost identical to experiment 3 (see Fig. 6). To avoid any contamination by stimulus-response automatization, participants first performed the noun-verb categorization task with masked trials only, then the visibility task, and finally the task with unmasked trials only.

Each participant first performed a training block of 60 masked trials, then 5 blocks of 96 masked trials, 2 blocks of forced-choice

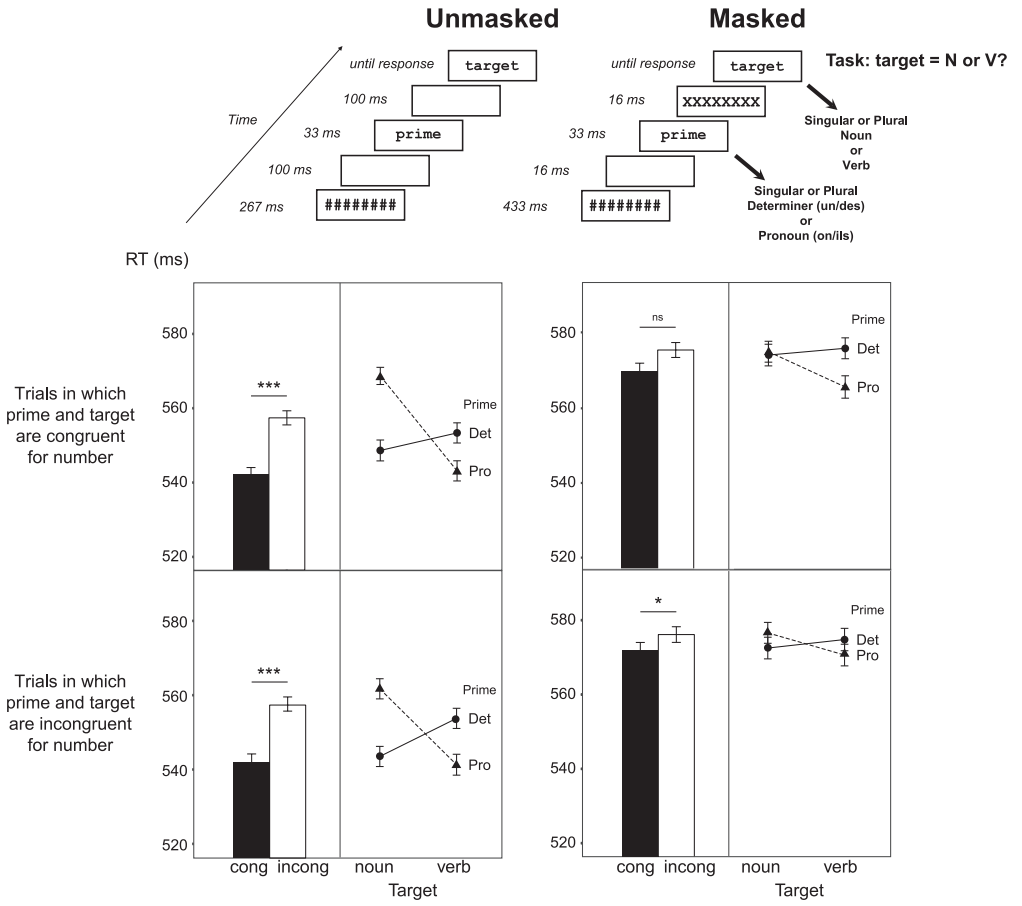

Fig. 6. Procedure and results of experiment 4. Participants classified target words as nouns or verbs, each of which was preceded by a masked or unmasked determiner or pronoun prime. Same format as Fig. 5. Error bars represent one *SEM*. *** = $p < 0.001$; * = $p < 0.05$.

task (64 trials each), and finally 5 blocks of 96 unmasked trials.

4.2. Results

4.2.1. Behavioral priming in response times

Overall error rate was 6% (range 3–10%). An analysis of variance (ANOVA) on median correct RTs, with usual exclusion criteria, with factors of visibility (masked/unmasked), target category (noun/verb), prime category (determiner/pronoun), target number (singular/plural), prime number (singular/plural), revealed a main effect of visibility (masked vs. unmasked; $F_{1,23} = 27.44$, $p < 0.001$): responses were 22 ms faster overall in the unmasked condition (551 ms versus 573 ms). There was no main effect of the category of the prime ($F_{1,23} = 0.71$, $p = 0.41$), the category of the target ($F_{1,23} = 1.14$, $p = 0.30$), the number of the prime ($F_{1,23} = 0.11$, $p = 0.74$), but there was a significant effect of the number of the target ($F_{1,23} = 174$, $p < 0.001$).

Crucially, we observed an interaction of prime category and target category, indicating a significant syntactic priming effect (grammatical pairings: 557 ms, ungrammatical pairings: 567 ms, difference: 10 ms, $F_{1,23} = 20.7$, $p < 0.001$). An interaction with visibility ($F_{1,23} = 11.57$, $p = 0.003$) indicating greater priming in the unmasked compared with the masked condition. Nevertheless, syntactic priming was found in the unmasked condition (544 ms versus 559 ms, difference: 15 ms, $F_{1,23} = 22.36$, $p < 0.001$) as well as in the masked condition (571 ms versus 576 ms, difference: 5 ms, $F_{1,23} = 5.94$, $p = 0.023$).

Interactions with number congruity were not significant, indicating that the size of the syntactic priming effect was not significantly modulated by congruity in grammatical number (all $F_{1,23} < 0.2$, all $p > 0.7$). Unmasked priming was present when number was congruent (545 ms versus 560 ms, difference: 15 ms, $F_{1,23} = 16.53$, $p < 0.001$) and when it was incongruent (542 ms versus 557 ms, difference: 15 ms, $F_{1,23} = 20.70$, $p < 0.001$). Masked priming was small but nevertheless present in the predicted direction when number was incongruent (572 ms versus 576 ms, difference: 4 ms, $F_{1,23} = 3.03$, one-tailed $p = 0.048$) but did not reach significance when number was congruent (570 ms versus 576 ms, difference: 6 ms, $F_{1,23} = 2.69$, $p = 0.11$) (see Fig. 6).

While we found a clear effect of the task-relevant variable (grammatical category), the task-irrelevant variable of number did not yield any significant effects. The main interaction of prime number × target number, indexing number congruity, was not significant ($F_{1,23} = 0.516$, $p = 0.48$) and the effect did not reach significance either under unmasked or under masked conditions (all $F_{1,23} < 3$, all $p > 0.1$, differences ≤ 3 ms). As mentioned above, the interaction with syntactic priming was not significant, and number priming failed to reach significance both when the grammatical categories were congruent (determiner-noun or pronoun-verb; $F_{1,23} = 0.121$, $p = 0.73$) and when they were incongruent (determiner-verb or pronoun-noun; $F_{1,23} = 0.510$, $p = 0.48$).

4.2.2. Prime visibility

Examination of d′ values suggested that participants were very slightly but significantly able to classify the four primes in the masked condition (54.0% correct, $d' = 0.215$, $t_{23} = 2.38$, $p = 0.025$), and performed at near-ceiling level in the unmasked condition (99.1% correct, $d' = 3.956$, $t_{23} = 115.94$, $p < 0.001$). Furthermore, the Greenwald (Greenwald et al., 1996) analysis revealed no significant correlation between the priming effect and the prime visibility in the masked condition ($t_{22} = 1.19$, $p = 0.25$), but also no significant intercept (1.45 ms, $t_{22} = 0.60$, $p = 0.56$). The fact that, in this part of the experiment, all prime words appeared under both masked and unmasked conditions could have enhanced visibility or induce automatized stimulus-response mapping relative to other experiments. However, only four participants had a d′ significantly larger than zero in the masked condition. Once these participants were excluded, performance in the visibility task dropped to chance level (51.25% correct, $d' = 0.068$, $t_{19} = 0.96$, $p = 0.35$), but a significant masked syntactic priming was still observed ($F_{1,19} = 5.15$, $p = 0.035$).

4.3. Discussion

In experiment 4, we confirmed that a determiner or pronoun can exert a significant syntactic priming on a subsequent noun or verb. The effect was clear under unmasked conditions (with an effect size of 15 ms), which is not trivial given that the prime was entirely irrelevant and presented for a short duration and SOA. The evidence for masked priming was much smaller (effect size of 5 ms) but still significant, including in the critical condition where the prime and target differed in number. Those results fully replicate those of experiment 3, with a similar size. Furthermore, they extend them in one crucial direction: priming effects remained significant when primes and targets failed to agree in number, again under both unmasked and masked condition (with effect sizes of 15 ms and 4 ms respectively). Examples of this critical condition include “on coopèrent” (“one cooperate”), “ils coopère” (“they cooperates”), “un cortèges” (“a processions”) and “des cortège” (“some procession”), all of which are strongly ungrammatical in French. The fact that syntactic priming remains unchanged in the presence of such grammatical violations indicates that the priming cannot be solely attributed to transitional probabilities, and must reflect genuine processing of grammatical categories.

Under masked condition, the syntactic priming effect failed to reach significance when number was congruent, but one may assume that this was due to a lack of power when analyzing half of the experiment, given that significant syntactic priming was observed on masked trials in experiment 3 (where number was congruent), and on unmasked trials in experiment 4. It is conceivable that the syntactic priming effect would be reduced on number-congruent trials, due to an interference between the two priming effects, but the fact that the interaction between the two priming effects was non-significant only allows us to conclude that the category priming was no different on number-congruent and number-incongruent trials.

More importantly, we did not find any priming effect based on the congruity in grammatical number between the prime and the target, neither under unmasked nor masked condition. It is remarkable that participants were no faster on grammatically correct trials, where the prime and target agreed in number, than on ungrammatical trials where such agreement was violated. Experiment 4

leaves open two alternative interpretations of this negative result. First, the feature of grammatical number may not be able to induce any detectable priming. This hypothesis is compatible with some previous studies of language production. Using picture-word interference, it was shown that number congruency between a picture and distractors words had no effect on naming (Schiller & Caramazza, 2002) while such an effect was previously demonstrated for semantic, phonology and gender congruency (Schiller & Caramazza, 2003; Schriefers, 1993; Schriefers, Meyer, & Levelt, 1990). Alternatively, its absence could be due to the fact that number was irrelevant to the task, which required classifying targets as nouns or verbs without paying any attention to their singular/plural status. Indeed, task-induced attention is known to massively affect neuronal tuning in sensory and cognitive areas (Çukur, Nishimoto, Huth, & Gallant, 2013), and masked priming is known to be influenced by top-down effects of task instructions (Ansorge et al., 2013; Dagenbach, Carr, & Wilhelmsen, 1989; Eckstein & Perrig, 2007; Nakamura, Dehaene, Jobert, Le Bihan, & Kouider, 2007) and attention (Naccache, Blandin, & Dehaene, 2002).

To separate those two alternatives, we performed an additional experiment (experiment 5) where we kept the stimuli unchanged but made the number dimension relevant to the task.

5. Experiment 5

Experiment 5 was strictly identical to experiment 4, except that participants were asked to perform a number categorization task, i.e. to determine whether the target words were singular or plural. If grammatical number cannot induce priming, then there should be no difference between trials according to prime-target number congruity. If, however, task-irrelevance was responsible for its absence in experiment 4, then by asking participants to focus on number, we should now observe a number-based priming effect in experiment 5. The latter explanation also predicts that syntactic category-based priming should be reduced or even disappears, since grammatical category (determiner versus pronoun, and noun versus verb) was now made irrelevant.

Because grammatical congruity and number congruity were orthogonally manipulated, we could also explore whether number would induce priming on trials in which syntax was incorrect. In agreement with considerable research in cognitive linguistics (Sportiche et al., 2013), the model presented in Fig. 1 hypothesizes that syntactic word processing culminates in a representation of words as a list of grammatical features. If grammatical number is such a free-floating syntactic feature, shared between all of the categories of words used here (determiners, pronouns, nouns and verbs), then we would predict that priming based on grammatical number should be observed in all conditions, irrespective of grammatical category or even of the grammaticality of the word pair.

5.1. Material and methods

5.1.1. Participants

Twenty-four right-handed native French speakers (10 males; mean age 23.6 years old; range 18–30 years old) were tested. No participant was excluded.

5.1.2. Stimuli and procedure

Stimuli and procedure were identical to experiment 4. Only the task was changed: participants were asked to determine as quickly as possible the grammatical number of the target word (singular or plural), with the usual bimanual response (see Fig. 7). Also, to better evaluate prime visibility and avoid automatized stimulus-response mapping, the visibility task was split in two blocks. The visibility task on masked stimuli was performed just after the masked block of the main task, and the visibility task on unmasked stimuli was performed at the end of the experiment, after the unmasked block of the main task. During this task, after the prime and target presentation, the words “PLURIEL (ils, des)” and “SINGULIER (un, on)” appeared randomly right and left of fixation, and participants selected one of these two responses.

5.2. Results

5.2.1. Behavioral priming in response times

Overall error rate was 6% (range 2–10%). An analysis of variance (ANOVA) median correct RTs, with usual exclusion criteria, during the number categorization task revealed a main effect of presentation type (masked vs. unmasked; $F_{1,23} = 7.11$, $p = 0.011$): responses were 10 ms faster overall in the unmasked condition (465 ms versus 475 ms). There was no main effect of the category of the prime ($F_{1,23} = 0.02$, $p = 0.88$), the category of the target ($F_{1,23} = 0.18$, $p = 0.67$), the number of the target ($F_{1,23} = 1.59$, $p = 0.22$), but there was a significant effect of the number of the prime ($F_{1,23} = 41.6$, $p < 0.001$).

A prime number × target number interaction revealed a main effect of number priming (congruent 460 ms versus incongruent 480 ms, difference: 20 ms, $F_{1,23} = 139.7$, $p < 0.001$). A triple interaction with visibility ($F_{1,23} = 6.56$, $p = 0.018$) indicated greater priming in the unmasked compared with the masked condition. Indeed, a strong number priming effect was found in the unmasked condition (452 ms versus 477 ms, difference: 25 ms, $F_{1,23} = 114.7$, $p < 0.001$). This effect was present whether the prime-target categories were grammatical (determiner-noun or pronoun-verb; 25 ms effect; $F_{1,23} = 120.2$, $p < 0.001$) or ungrammatical (determiner-verb or pronoun-noun; 24 ms effect; $F_{1,23} = 49.79$, $p < 0.001$).

Crucially, number priming was also found under masked condition (467 ms versus 484 ms, difference: 17 ms, $F_{1,23} = 45.30$, $p < 0.001$). This effect was present on grammatical (16 ms effect; $F_{1,23} = 19.78$, $p < 0.001$) and ungrammatical trials (16 ms effect; $F_{1,23} = 36.04$, $p < 0.001$) (see Fig. 7). There was no interaction, indicating that the size of the number priming effect was not significantly affected by the congruity in grammatical categories (unmasked trials: $F_{1,23} = 0.11$, $p = 0.75$; masked trials:

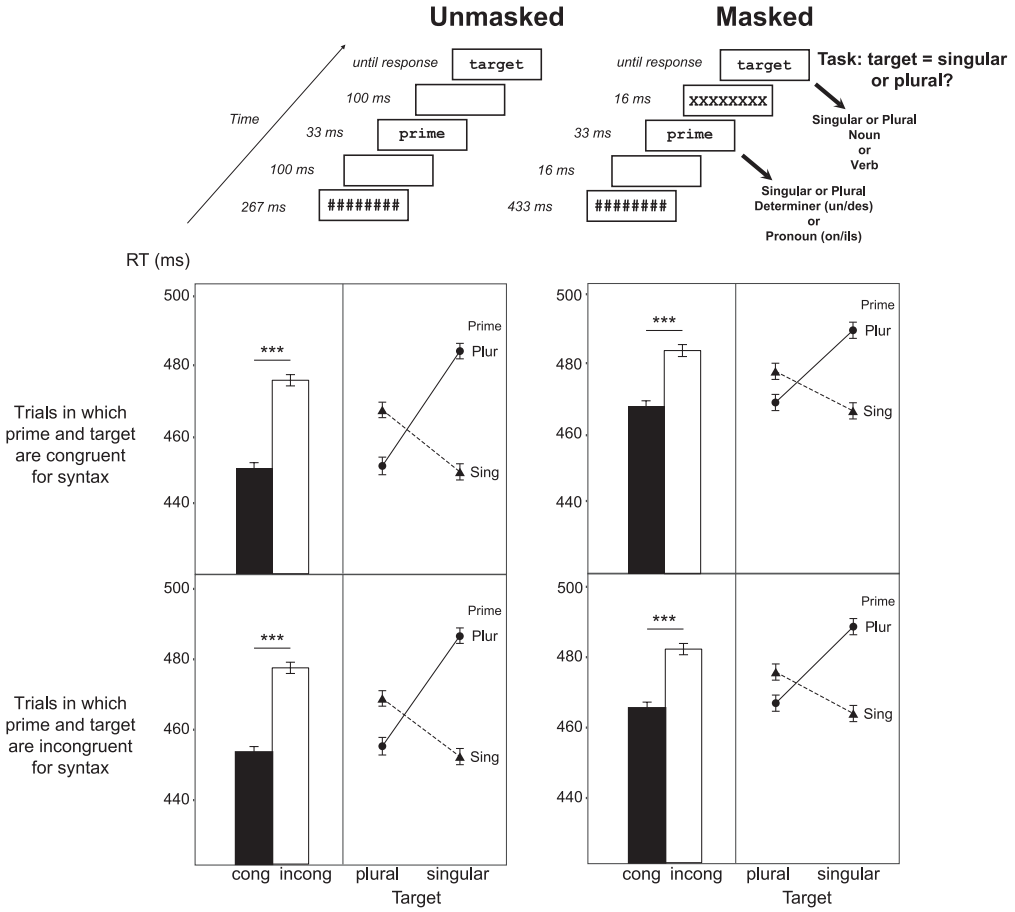

Fig. 7. Procedure and results of experiment 5. Participants classified target words as singular or plural, each of which was preceded by a masked or unmasked singular or plural prime. At the bottom, barplots show response times for congruent (black bars) and incongruent (white bars) trials, lineplots show response times as a function of prime number (Plur = plural, solid line; Sing = singular, dashed line) and target number. Error bars represent one *SEM*. *** = $p < 0.001$; * = $p < 0.05$.

$F_{1,23} = 0.05$, $p = 0.83$).

Importantly, although the stimuli were identical to experiment 4, we now failed to observe any syntactic priming based on grammatical category in any conditions of experiment 5: the prime category × target category interaction was not significant globally ($F_{1,23} = 0.13$, $p = 0.72$), neither on masked (−3 ms effect size; $F_{1,23} = 2.72$, $p = 0.11$) nor on unmasked trials (−2 ms effect size; $F_{1,23} = 2.02$, $p = 0.17$). A direction comparison indicated that the size of the number priming effect was significantly larger in experiment 5 compared to experiment 4 (unmasked: 25 vs. −3 ms, Welch $t_{45.19} = 9.08$, $p < 0.001$; masked: 17 vs. 1 ms; Welch $t_{41.49} = 5.14$, $p < 0.001$), while the reverse was true for the syntactic priming effect (unmasked: −3 vs. 15 ms, Welch $t_{31.06} = -3.80$, $p < 0.001$; masked: −3 vs. 5 ms; Welch $t_{44.77} = -2.93$, $p = 0.005$). Finally, number priming in experiment 5 was stronger than syntactic priming in experiment 4 in the unmasked condition (Welch $t_{41.62} = 2.38$, $p = 0.022$) and the masked condition (Welch $t_{44.39} = 3.64$, $p < 0.001$).

5.2.2. Orthographic contribution to number priming

In French, plural is marked by the morpheme "-s" for nouns, determiners, and pronouns. Only for verbs is a different morpheme used, i.e. "-ent" in the 3rd person plural present as used here. Thus, part of the number-priming effect could conceivably arise from the repetition of the terminal letter "s" from prime to target, i.e. an orthographic rather than a grammatical priming effect. However, if orthography was the main source of this effect, then priming should be reduced for verbs relative to nouns, since plural verbs do not end in "-s". Crucially, under masked condition, we did not find any difference in the size of the number priming effect for verb versus noun targets ($t_{23} = 1.13$, $p = 0.27$): the number priming effect was 18 ms for noun targets and 15 ms for verb targets, and both effects were significant (noun: $F_{1,23} = 36.98$, $p < 0.001$; verb: $F_{1,23} = 26.46$, $p < 0.001$). Therefore, the observed number priming effect could not be explained by orthographic priming.

5.2.3. Prime visibility

d′ values indicated that participants were unable to consciously categorize the primes in the masked condition (51.3% correct,

$d' = 0.07$, $t_{23} = 0.94$, $p = 0.36$), whereas they could do so in the unmasked condition (97.3% correct, $d' = 3.69$, $t_{23} = 38.53$, $p < 0.001$). There was no significant correlation between the priming effect and the prime visibility on masked trials ($t_{22} = 0.74$, $p = 0.47$), and the intercept of this regression was significant: 16.2 ms, $t_{22} = 6.12$, $p < 0.001$).

5.3. Discussion

Experiment 5 demonstrated that prime-target congruity in grammatical number could induce a strong priming effect under both unmasked and masked conditions (25 ms and 17 ms respectively), provided that the task required participants to focus on this grammatical dimension. For instance, the noun "reptile" was categorized faster as singular when preceded by the singular determiner "un", and even by the singular pronoun "on", than by the plural determiner "des" or the plural pronoun "ils".

The emergence of a strong effect of grammatical number was accompanied by the disappearance of any category-based syntactic priming effect, under both unmasked and masked condition. For instance, there was no longer any significant RT difference between the grammatically correct "des reptiles" ("some reptiles") and the grammatically incorrect "ils reptiles" ("they reptiles"). Thus, task demands radically altered the pattern of grammatical priming, as confirmed by direct statistical comparisons of experiments 4 and 5. This aspect of our findings agrees with previous findings by Ansorge et al. (2013) for grammatical gender (feminine/masculine) in German. Gender agreement triggered a behavioral priming effect between a determiner and a noun when the task required determining the gender of the target. However, such gender priming disappeared when participants performed a task unrelated to gender.

The absence of a behavioral priming effect need not indicate that lexico-syntactic representations were not activated, only that this activation did not propagate all the way to the decision system. Indeed, a study using electroencephalography recordings during a naming task showed that incongruency between the picture and a classifier (a syntactic feature comparable to grammatical gender) elicited a N400 component without affecting naming latencies (Wang, Chen, & Schiller, 2018). Indirect evidence of such an activation is provided by experiments using German or Dutch, where gender governs the selection of a determiner: in this case, gender congruency had a significant influence on behavior when the task was to choose the appropriate determiner (Schiller & Caramazza, 2003).

Another important aspect of our results is that grammatical number caused priming even between words that did not constitute a well-formed grammatical phrase (as also reported by Ansorge et al., 2013 for grammatical gender). Thus, a plural determiner primed a plural verb, and a plural pronoun primed a plural noun, even though these word combinations are ungrammatical in French. Those findings support the hypothesis that, during reading, syntactic features such as singular or plural are quickly extracted and encoded independently from each other. The presence of priming indicates that the feature of "plurality" is encoded in a format which is similar for the four categories of words tested here. This is remarkable given that this feature is realized orthographically in a very different manner, namely the addition of a terminal "s" on nouns and pronouns; a lexical change (e.g. "un" versus "des") for determiners; and the addition of a morpheme "-ent" for verbs. The observed priming must have occurred at a level of representation abstract enough to be shared by all these words, in spite of their superficial differences. Moreover, in French, the pronoun "on" is grammatically singular but it is mostly used in informal language in place of "we", and therefore semantically refers to plural. This argument suggests that number priming in this experiment could not be imputed to the semantic aspects of plural.

Overall, our results strongly argue in favor of a level of syntax processing in the brain that encodes abstract syntactic features such as "singular", "plural", and probably also "feminine", "masculine", etc. (Ansorge et al., 2013). Still, it was previously suggested that conceptual number (i.e. unique versus multiple) influences grammatical number processing (Nickels et al., 2015). As mentioned above, activations of such representations are not excluded by the absence of behavioral effects (Wang et al., 2018) and deserve further exploration.

6. General discussion

Across five experiments, we repeatedly observed that the repetition of a syntactic feature from a prime word to a target word could induce both conscious and subliminal priming; and we used this phenomenon to probe our hypothetical framework for the extraction of syntactic features from written words (Fig. 1). We studied four different types of priming: grammatical category priming, priming by pseudo-morphological ending, syntactic priming, and number priming. In experiments 1 and 2, we demonstrated that a prime belonging to a given grammatical category could accelerate the processing of a target belonging to the same grammatical category (grammatical category priming). Word ending was a strong cue to grammatical category and was also able to induce priming, at least for fast responses (for instance, after a prime with an ending typical of French verbs, responses were given faster to a verb target than to a noun target). In experiments 3 and 4, we then showed that a prime word belonging to a given grammatical category (e.g. determiner) could prime a target word belonging to a distinct but grammatically appropriate category (e.g. noun). We showed that this syntactic priming effect involves more than mere transitional probabilities (Thompson et al., 2007), because determiners prime nouns and pronouns primed conjugated verbs even when the words were incongruent for grammatical number, and therefore their transition probability was close to zero. Finally, in experiment 5, we observed that a word could prime another word simply by sharing the same grammatical number (singular or plural), even if the prime-target pair was ungrammatical. This number-priming effect was only observed, however, when the task was a number categorization task (experiment 5) but was absent when it was a grammatical categorization task (experiment 4). Conversely, syntactic priming was only present when the task was a grammatical categorization task (experiment 4) and vanished when it was a number categorization task (experiment 5).

Our study extends previous results which demonstrated that semantic, orthographic, phonological, and morphological features of

words can be subliminally processed (Dehaene et al., 1998; Gaillard et al., 2006; Giraudo & Grainger, 2001; Kouider et al., 2007; Naccache et al., 2005; Van den Bussche & Reynvoet, 2007; van Gaal et al., 2014; Yeh et al., 2012). It confirms that the repetition of syntactic features such as grammatical category and number can induce priming, as previously proposed for gender (Ansorge et al., 2013), verbal inflection patterns (Deutsch et al., 1998), and verb transitivity (Iijima & Sakai, 2014).

Crucially, our results prove that a single word may induce different types of priming: we observed syntactic category priming when participants classified the targets as nouns versus verbs, and number priming when they classified them as singular versus plural. This finding supports linguistic theories which postulate that each word is associated with a set of syntactic features (category, number, etc.) (Sportiche et al., 2013), each of which may be shared with other words. Linguists denote this level of representation using binary features (e.g. +singular; +noun; etc.). Our experiments can be construed as a demonstration of the psychological reality of this abstract linguistic construct. They suggest that this level exists and can quickly be accessed from a written word, with or even without consciousness.

Our experiments were designed, not only to probe the validity of the construct of syntactic features, but also to test a model of the cognitive architecture by which they are extracted from written words (Fig. 1). We proposed that this architecture is organized into two distinct pathways, each organized to exploit a distinct source of information about syntactic features. On the one hand, a fast pseudo-morphological route examines word endings for the presence of known grammatical morphemes that index syntactic features such singular vs plural, word categories, verb tense, etc. (e.g. French words ending with "-er" tend to be verbs; those ending in "s" are likely to be plural; etc.). On the other hand, a syntactic lexicon indexes the genuine syntactic status of each word (e.g; "boulanger" is actually a noun; "bus" is actually singular; etc.).

The results of experiments 1 and 2 confirmed the existence of those two pathways toward syntactic category, because we found two distinct and orthogonal priming effects arising respectively from pseudo-morphological information and from lexical information. Those effects occurred under both conscious and unconscious conditions. Our results therefore suggest that both routes can be activated unconsciously and in parallel. Furthermore, analyses of the impact of SOA and of the difference between short and long RTs suggested that the lexical route may operate at a slower pace, yet with a strength ultimately capable of overriding the initial hunch provided by the pseudo-morphological route.

As also suggested by previous experiments (Rastle et al., 2004), we thus propose that each incoming word is submitted to a rapid but shallow analysis which decomposes it into tentative morphemes (e.g. boulanger = boulang + er = "verb"), and which is later validated or rejected based on lexical information. Do note that we only tested this dual-route model in experiments 1 and 2, using syntactic category information (noun vs verb) for which word ending cues and genuine category could be orthogonally varied in a large set of words. Two competing routes likely exist for the retrieval of other syntactic features such as singular versus plural, but this is much more difficult to prove, in French at least, because plural is almost always conveyed by a morpheme (e.g. nouns ending with s or x) rather than by lexical information (irregular plural nouns such as *women* being exceedingly rare in French).

Once conflicts between the two routes are resolved, each word is thought to be encoded by the list of its syntactic features. The last key hypothesis of the model in Fig. 1 is that those features then drive syntactic parsing and lead to syntactic expectations about subsequent words. For instance, a determiner induces the expectation of a noun phrase. In experiments 3 and 4, we tested this hypothesis by evaluating whether a determiner primed a noun, and a pronoun a verb, even when those pairings were arbitrary and rendered the prime entirely irrelevant to the target-based task. We again observed a strong conscious priming effect as well as a smaller unconscious priming effect. Therefore, our study goes beyond previous experiments demonstrating that a subliminal word can be integrated into a conscious syntactic context (Batterink & Neville, 2013; Hung & Hsieh, 2015): in the present experiments, the converse occurs, i.e. a subliminal word induces a syntactic context that influences the processing of a subsequent conscious word. Rabagliati et al. (2018) recently contested that multiple words could be subliminally combined during continuous flash suppression (CFS; Axelrod et al., 2014; Sklar et al., 2012; van Gaal et al., 2014). Our claim, however, bears on visual masking rather than CFS, and is also much more modest: we merely provide replicable evidence for unconscious processing at the earliest stages of syntactic analysis, whereby the syntactic features of a single unconscious word are extracted and their compatibility with a single upcoming conscious word is evaluated.

Importantly, those effects were found to be task-dependent in experiment 5: once participants focused their attention on the singular/plural decision task, priming by syntactic category (i.e. determiner-noun and pronoun-verb) entirely vanished. The fact that short-latency priming, including subliminal priming, can vary with the participant's task is now a well-established fact (e.g. Naccache et al., 2002). This finding fits squarely within the evidence-accumulation framework for decision making and extends this hypothesis to decisions based on syntactic features: when participants prepare for a specific task, they set up two accumulators, one for each of the possible responses (e.g. singular vs. plural), and priming then reflects the initial accumulation of evidence arising from the prime word and its replacement by subsequent evidence about the target (Dehaene, 2011; Vlassova, Donkin, & Pearson, 2014; Vorberg et al., 2003). This framework readily explains why information which is orthogonal to the task-relevant dimension (e.g. whether the target is a noun or a verb) has no influence on response time: this information is simply never "read-out" by the decision-making process.

Importantly, the absence of any category-priming effect in RTs in experiment 5 does not imply that syntactic category information is not automatically activated. On the contrary, experiments 3 and 4 suggest that, even when participants focus entirely on whether the target is a noun or a verb, the syntactic category of the prime (determiner or pronoun) automatically interferes, even though it is irrelevant and subliminal. Thus, we tentatively surmise that the syntactic-category congruity of the prime and target words was probably automatically computed even in experiment 5, but that this computation did not have any detectable effect on RTs. One way to test this hypothesis could be to record event-related potentials: we would predict the automatic emission of a violation response

such as a left anterior negativity (LAN; see e.g. Batterink & Neville, 2013) when the prime and target do not form a grammatically valid pair.

In the future, brain imaging could also help objectify the two routes postulated in our model, by examining whether they relate to distinct cerebral areas and their connections. Hypothetically, the morphological analysis of written words could take place in the anterior sector of the visual word form area in the left occipito-temporal sulcus (Cohen et al., 2000; Dehaene et al., 2001) while grammatical category retrieval could involve the left superior temporal gyrus (Friederici, 2002, 2012) or the left posterior temporal gyrus (Snijders et al., 2009). Whether the "syntactic lexicon" can be localized to one or several cerebral areas, however, remains unknown. Some fMRI experiments that reported a broadly distributed set of regions for syntactic features have contrasted grammatically correct versus incorrect expressions (Carreiras, Quiñones, Mancini, Hernández-Cabrera, & Barber, 2015; Molinaro, Barber, Pérez, Parkkonen, & Carreiras, 2013), raising concerns of a potential confound between syntactic priming and grammatical violation detection. The fact that, in our study, priming emerges from the repetition of syntactic features even within ungrammatical expressions opens the possibility of disentangling these two effects in order to ultimately isolate the areas involved in the syntactic lexicon.

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