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Morphological operations in French verbal inflection: Automatic, atomic, and obligatory

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Abstract

In this article, we examined how complex words are recognized as being mediated by their morphological operations and structure. French verbal inflection is a system where the stems provide the lexical meaning and the inflectional suffixes activate the functional information by the morphosyntactic features. We investigated the morphological decomposition and inflectional suffixes processing through visual lexical decision tasks. Experiment 1 accessed general differences in the number of morphological operations regarding low and high frequencies, and regular and irregular verbal forms (e.g., *jou-ent/jou-ai-ent* 'they play/played', *prend-s/pren-ai-s* 'you$_{sg}$ take/took'). Experiment 2 tested specific differences in the tense and agreement inflectional suffixes (e.g., *jou-ons/jou-i-ons/jou-ez/jou-i-ez* 'we/you$_{pl}$ play/played'). Our hypothesis is that words are automatically decomposed early for morphological processing and that morphemes are later hierarchically recombined for word recognition. We found significant differences between the number of morphological operations in regular and irregular verbs in low and high frequencies; we also found significant differences in tense and agreement suffix processing with longer responses for the past tense and first plural agreement verbal forms, suggesting additive effects. Our results are supported by single-mechanism pre-lexical decompositional models; we propose a model where stems and inflectional suffixes are processed differently for lexical access and word recognition.

Keywords: Morphological operations; Verbal inflection; Decomposition; Word recognition; Psycholinguistics.

1. Introduction

Morphological processing has been largely studied in psycholinguistics since the first whole-word (Manelis and Tharp, 1977) and decompositional (Taft, 1979) models. Two main frameworks have survived: search models with symbolic

Abbreviations: v, root; AAM, Augmented Address Morphology; ACC, accuracy; Agr, agreement; ANOVA, analysis of variance; Asp, aspect; DP, determiner phrase; IRB, Institutional Review Board; LCD, liquid-crystal display; NP, noun phrase; OD, Obligatory Decomposition Model; OLD20, Orthographic Leveinshtein Distance between the 20 closest words; PDP, Parallel Distributed Processing; pl, plural; PLD20, Phonological Leveinshtein Distance between the 20 closest words; RT, reaction time; S−, one inflectional suffix; S+, two inflectional suffixes; SF−, low surface frequency; SF+, high surface frequency; sg, singular; Spec, specifier; SR, Single Route Model; T, tense; Th, theme vowel; TP, tense phrase; v, stem; V, vowel; W&R, Words and Rules; WW, Whole-Word Model.

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manipulation and rule-based computations (Halle and Marantz, 1994; Stockall and Marantz, 2006) and parallel-distributed-processing (PDP) models based on statistical associations (Baayen et al., 2011; McClelland and Rumelhart, 1981). The former assumes that word recognition is mediated by sub-lexical processing driven by morphological operations, whereas the latter assumes not a morphological level but rather a direct associative system between form and meaning that is based on phonological, orthographic, and semantic overlap. Alternatively, Taft (1994) proposed an interactive-activation model which attributes a strong role to the morphological level, where morphemes are activated through an interactive-association parser.

Research in morphological processing has accumulated results and knowledge mainly with respect to lexical morphemes, such as root and stem representations and processing (Amenta and Crepaldi, 2012; Estivalet and Meunier, 2015); in contrast, in the present study we propose to more deeply explore the processing of morphological operations and morphosyntactic features, considering the word hierarchical structure (Arregi, 2000; Embick and Halle, 2005). Inflectional suffixes are morphemes that have regular and paradigmatic behavior in verbal conjugation, such as tense (T) and agreement (Agr) morphemes, activating abstract morphosyntactic features, such as [past/future], and [1st/2nd/3rd person] and [singular/plural], respectively (Halle and Marantz, 1994; Penke et al., 2004). Interestingly, evidence from aphasic patients has shown that tense morphemes are more impaired than agreement ones, underlying the morphological nature of the tense deficit that affects the [past] morphosyntactic feature (Wenzlaff and Clahsen, 2004).

Most of morphological processing studies have been carried in English, which is an analytic language with poor inflectional morphology. English has only a nominal morpheme for plural [-s]$\sim$[-en] (e.g., ball/ball-s, ox/ox-en), and three verbal morphemes for regular past tense [-ed], progressive tense [-ing], and 3rd singular person agreement [-s], (e.g., play/play-ed/play-ing/play-s). These suffixes are exclusive, never being combined in complex words. In contrast, Romance languages are inflectional languages with rich inflectional morphology; morphemes are combined in complex word formations, such as the French nouns *étudiant* 'student$_{\text{male}}$', *étudiant-e* 'student$_{\text{female}}$', *étudiant-s* 'students$_{\text{male}}$', *étudiant-e-s* 'students$_{\text{female}}$' and the French verbs *jou-ons* 'we play', *jou-i-ons* 'we played', *jou-e-r-ons* 'we will play', *jou-e-r-i-ons* 'we would play'. Therefore, it is important to consider the number of morphological operations and the hierarchical morphological structures involved in word recognition (Marantz, 2013).

In this study, we investigated the processing of the number of morphological operations and morphosyntactic features activated by different morphemes for word recognition. From our knowledge, this is the first study to address the verbal inflectional morphological operations in Romance languages. We ran two experiments using visual lexical decision tasks. Experiment 1 tested reaction time (RT) differences in function of the number of morphological operations (i.e., one inflectional suffix vs. two inflectional suffixes), verb type (i.e., regular verbs from the 1st class vs. irregular verbs from the 3rd class), and surface frequency (i.e., low surface frequency vs. high surface frequencies) on French verbal forms, where surface frequency is the number of times that a word form appears in a corpus (Taft, 1979). Experiment 2 tested the morphological processing of specific tenses (i.e., indicative present vs. indicative imperfect past) and agreements (i.e., 1st plural vs. 2nd plural).

1.1. Morphological processing

From a theoretical perspective, decompositional models with symbolic manipulation are in line with the Item-and-Process architecture, where inflection is the realization of the morphosyntactic features through the inflectional suffixes merged with the stem (Halle and Marantz, 1994). In contrast, from an associative Word-and-Paradigm architecture, words are stored as whole-forms in the mental lexicon with their morphosyntactic representations (Anderson, 1992; Jackendoff, 1975). One crucial difference between these two architectures is if words are pre-lexically decomposed for morphological processing or if they are recognized as whole-forms and are post-lexically decomposed to have their morphosyntactic representations activated.

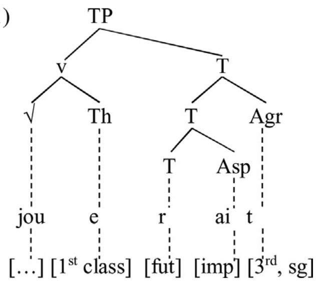
Concerning single-mechanism models, Taft (1979) proposed the Obligatory Decomposition (OD) model with three phases: words are decomposed in morphemes, have their morphemic representations activated in the mental lexicon, and morphemes are recombined for word verification; this model has recently received strong support from the full decompositional Single Route (SR) model (Stockall and Marantz, 2006). In contrast, Manelis and Tharp (1977) proposed a Whole-Word (WW) model where words are stored in the mental lexicon as full-entries (Jackendoff, 1975). Alternatively, PDP models can be seen as full-entry models in which linguistic representations are the overlap of phonological, orthographic, and semantic information in hidden units (McClelland and Rumelhart, 1981).

Dual-mechanism models solve this dichotomy by proposing two routes for lexical access: a procedural route based on rules and combinatorial processes, and a declarative whole-word route based on associative activation (Ullman, 2001). Different dual-mechanism models have been proposed, varying in the characteristics that influence the word recognition, such as frequency in the Augmented Addressed Morphology (AAM) model with high-frequency words being recognized by the whole-word route and unknown and low-frequency words by the morphological one (Caramazza et al., 1988), or regularity in the Words and Rules (W&R) model with irregulars being recognized by the whole-word route and regulars by the rule-based one (Pinker, 1999).

1.2. French inflectional morphology

Unlike Germanic languages, which have reduced inflectional morphology and free stems, Romance languages inherited their rich morphological system from Latin and are analyzed in terms of complex combinations: (a) they have no free stems, (b) even irregular verbs (mostly from 2nd and/or 3rd classes) with allomorphic stems are merged with inflectional suffixes, and (c) all inflected forms contain a minimal computation between lexical and functional morphemes (Embick and Halle, 2005). Thus, we assume the general French verbal morphological structure in (1) (e.g., *jou-e-r-ai-t* 'I would play' $[[[\text{jou}]_{\surd}[\text{e}]_{\text{Th}}]_{v}[[[\text{r}]_{\text{T}}[\text{ai}]_{\text{Asp}}]_{\text{T}}[\text{t}]_{\text{Agr}}]_{\text{T}}]_{\text{TP}}$, where √ for root, Th for theme vowel, v for stem, T for tense, Asp for aspect, and Agr for agreement), with the morphosyntactic features between squared brackets, adapted from (Arregi, 2000).

(1)



In Romance languages such as French, the indicative present and simple past are non-marked tenses, where the root is combined with the theme vowel (i.e., $[\text{-e}]_{\text{1st class}}{\sim}[\text{-a}]_{\text{past}}$, $[\text{-i}]_{\text{2nd class}}{\sim}[\text{-iss-}]_{\_V}$, others for 3rd class) for the stem/theme formation, and/or to the agreement morpheme (i.e., $[\text{-s}]_{\text{1st/2nd, singular}}$, $[\text{-t}]_{\text{3rd, singular}}$, $[\text{-ons}]_{\text{1st, plural}}{\sim}[\text{-mes}]_{\text{past}}$, $[\text{-ez}]_{\text{2nd, plural}}{\sim}[\text{-tes}]_{\text{past}}$, and $[\text{-ent}]_{\text{3rd, plural}}$), as for example *jou-e/jou-e-s/jou-ons/jou-a-s* 'I/he play(s)/you$_{\text{sg}}$ play/we play/you$_{\text{sg}}$ played'). Indicative imperfect past, simple future, and conditional present are marked tenses. The indicative imperfect past tense has the root directly merged to the tense node that contains the tense morpheme (i.e., $[\text{-ai-}]_{\text{past}}{\sim}[\text{-i-}]_{\text{1st/2nd, plural}}$) and the agreement morpheme (e.g., *jou-ai-s/jou-ai-t/jou-i-ons/jou-i-ez/jou-ai-ent* 'I/you$_{\text{sg}}$/he/we/you$_{\text{pl}}$/they played'). Further, the indicative simple future tense has the root combined with the theme vowel, if available, forming the stem/theme; then, the stem is merged with the tense node containing the tense morpheme (i.e., $[\text{-r-}]{\sim}[\text{-rr-}]_{\text{future}}$) and the agreement morpheme (i.e., $[\text{-ai}]_{\text{1st, singular}}$, $[\text{-as}]_{\text{2nd, singular}}$, $[\text{-a}]_{\text{3rd, singular}}$, and $[\text{-ont}]_{\text{3rd, plural}}$). Finally, the conditional present tense has the same inflectional nodes as the indicative simple future, with an additional aspect morpheme (i.e., indicative imperfect past tense morphemes) between the tense and agreement morphemes (Kilani-Schoch and Dressler, 2005).

It follows that the agreement morpheme is present in almost all inflected forms, except for bare stems formed by the root combined with the theme vowel. In sum, words that have only the agreement morpheme have one morphological operation, whereas words that have the tense and agreement morphemes have two morphological operations (Arregi, 2000; Marantz, 2013).

Although hierarchical morphological structures have been neglected in morphological processing studies, the grammatical computations during word recognition might be very important. Thus, "the morphological features of Tense and Agr have two functions: they check properties of the verb that raises to them, and they check properties of the NP (DP) that raises to their Spec position; [...] in French overt raising is a prerequisite for convergence; in English it is not" (Chomsky, 1993, pp. 29–30). In French, the stem raises to the tense node and the strong agreement forces overt raising for morphosyntactic feature checking before the spell-out. This allows us to hypothesize that hierarchical morphological structures in Romance languages yield informative results regarding the morphological operations in word recognition (Stockall and Marantz, 2006). It is important to note that while the agreement morpheme is required by syntax to subject-verb concordance, tense is required by the speaker's intentional situation (Anderson, 1992).

Our past results have shown that all French verbs might be decomposed for lexical access (Estivalet and Meunier, 2016). Meunier and Marslen-Wilson (2004) found similar cross-modal and masked priming results with regular and allomorphic stem primes for different French verb types (i.e., regular, morphophonological, irregular, and idiosyncratic) and suggested a single-mechanism to process all inflected forms. Manipulating surface and cumulative frequencies, Estivalet and Meunier (2015) found no differences for morphophonological verbs (e.g., *appeler/appElles* 'to call/you$_{\text{sg}}$

call', *adorer/adO*[2]*res* 'to adore/you$_{sg}$ adore'), suggesting an underlined phonological representation; most important, they found significant differences between allomorphs in irregular verbs from the 3rd class (e.g., *boire/buvons* 'to drink/we drink'), suggesting different, albeit linked, stem allomorphic representations or morphological operations in allomorphic stems for word recognition.

In Experiment 1, we explored the hierarchical processing of the inflectional suffixes in the verbal structures with one or two morphological operations. We investigated morphological processing differences as a function of the number of morphological operations in both regular verbs from the 1st class and irregular verbs from the 3rd class at both low and high surface frequencies. If words are fully decomposed for word recognition, verbs with two inflectional suffixes should present longer RTs than those with only one inflectional suffix. Indeed, a significant effect in the number of morphological operations assumes that each morphological operation has a specific cognitive cost, suggesting pre-lexical decomposition. We predict that there will be a significant difference between regular and irregular verbs, with longer RTs for the latter because of stem allomorphic processing, a significant difference between low and high surface frequencies, and a significant difference in the number of morphological operations in both verb types and both surface frequencies, but no interaction between any of these variables.

The questions that guided Experiment 1 were as follows: (a) Are there processing differences between the number of morphological operations (inflectional suffixes) in French verbs? (b) Are these differences consistent in regular and irregular French verbal forms? (c) Are morphological operations considered differently for low and high surface frequencies?

In Experiment 2, we constrained our investigation to specific tenses and agreements to better understand the hierarchical morphological structure processing of the inflectional suffixes in French verbs. We tracked differences in the processing of morphosyntactic features activated by the indicative imperfect past inflectional suffix. We contrasted two variables with two conditions each: (a) tense (i.e., indicative present [ø] vs. indicative imperfect past [-i-]) and (b) agreement (i.e., 1st plural [-ons] vs. 2nd plural [-ez]) (e.g., *jou-ons/jou-i-ons/jou-ez/jou-i-ez* 'we/you$_{pl}$ play/played'). If words are decomposed into atomic morphemes, verbs in the indicative imperfect past with tense and agreement inflectional suffixes should present longer RTs than verbs in the indicative present containing only the agreement suffix; there should also be no differences between verbs in the 1st and 2nd plural agreements in each verbal tense. However, if words are recognized by their whole-form, there should be no significant difference in the tense and agreement suffixes. Indeed, the [-i-]$_{past,\ 1st/2nd,\ plural}$ morpheme is a glide semi-vowel phonologically incorporated into the agreement suffix pronunciation and perhaps does not trigger decompositional processes; thus, it is possible that verbs are decomposed only in stem and one suffix (i.e., *jou-ions/jou-iez*), percolating the tense [past] morphosyntactic feature to the agreement morpheme and yielding no significant difference between both tenses.

The questions that drove Experiment 2 were as follows: (a) Are there differences in the processing of different tenses in French? (b) Are there differences in the processing of different agreements? (c) Which is the hierarchical processing of the tense and agreement suffixes? (d) Is there an interaction in the processing of tense and agreement suffixes?

Based on the nature of the morphological operations and verbal hierarchical structure, agreement is an overt operation required by syntax for subject-verb concordance, whereas tense is a covert operation required by the speaker's intentional situation. Thus, we predict that the agreement processing may not have a large cognitive cost, but that the processing of tense might impact the hierarchical morphological structure processing and, consequently, slow the RTs in word recognition. Finally, an interaction between tense and agreement would suggest a dependent processing of these suffixes.

2. Method

2.1. Experiment 1: verbal morphological operations

2.1.1. Participants

A total of 30 adult native speakers of French between the ages of 18 and 31 (mean age 21.4, 15 women) took part in Experiment 1. All participants were right-handed, had normal hearing, had normal vision or corrected by glasses or contact lenses, and had no history of cognitive or language disorders. All participants were students at the *Université Lumières Lyon 2*.

Participants did not know the purpose of the study and gave their written consent to participate in the experiment as volunteers. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the ethics committee *Comité de Protection des Personnes Sud-Est II* (IRB: 00009118).

[2] We used the characters /E, O/ for phonological notation, where /E/ means the front open-mid and /O/ means the back open-mid productions.

Table 1
Examples of stimuli in the different conditions of Experiment 1: verb type, surface frequency, and morphological operations. S− for one inflectional suffix, S+ for two inflectional suffixes, SF− for low surface frequency, and SF+ for high surface frequency.

Verb type	Frequency	One suffix (S−)	Two suffixes (S+)
Regular	SF−	travers-ons	travers-ai-s
	SF+	parl-ez	parl-i-ez
Irregular	SF−	joign-ent	joign-ai-t
	SF+	buv-ons	boi-r-ai

2.1.2. Material and design

Participants performed a lexical decision task in visual modality between words and pseudowords. We investigated two verb types: (a) regular verbs from the 1st class (e.g., *aimait* 'he loved') and (b) irregular verbs from the 3rd class (e.g., *buvait* 'he drank'). In both verb types, we investigated the number of morphological operations: (a) verbs with one inflectional suffix (S−) (e.g., *aim-ons* 'we love', *buv-ons* 'we drink'$_{\text{IND.PRES.-1P.PL}}$) and (b) verbs with two inflectional suffixes (S+) (e.g., *aim-ai-t* 'he loved', *buv-ai-t* 'he drunk'$_{\text{IND.IMPPAST-3P.SG}}$[3]). As presented in (1) above, French verbal inflection present a complex inflectional structure; the stem is followed by the Tense morpheme and the Tense morpheme is followed by the Agreement morpheme. Therefore, accordingly to the examples, we tested French inflected verbs with one or two inflectional suffixes, it means, one or two morphological operations. Furthermore, we investigated these effects in (a) low surface frequency (SF−) and (b) high surface frequency (SF+), as shown in Table 1. We remark that the surface frequency is the same than word frequency or lexeme frequency, it is, the number of times that a specific word form appears in a specific corpus (Taft, 1979).

We selected 160 verbal forms as experimental items: 80 regular forms from the 1st class and 80 irregular forms from the 3rd class. Within each verb type, 40 forms were of low surface frequency, and 40 forms were of high surface frequency. Then, in each verb type and surface frequency subgroup, there were 20 forms with one morphological operation and 20 forms with two morphological operations (Appendix A). All experimental items were matched in lemma frequency, surface frequency, number of letters, number of phonemes, number of syllables, and neighborhood calculated by the Orthographic and Phonological Leveinshtein Distance between the 20 closest words (OLD20 and PLD20) (Yarkoni et al., 2008), as shown in Appendix B.

Using a different set of 160 French verbal forms, we created French pseudowords changing one or two letters. All experimental items were selected and controlled using the French database *Lexique* (New et al., 2004), and the pseudowords were created using its pseudoword generator toolbox.

Four different lists were constructed using the Mix program (van Casteren and Davis, 2006) with pseudorandom orders to counterbalance the sequence of stimuli presentation between conditions and participants. The lists were subdivided in four blocks containing the same number of stimuli in all conditions. Then, these four blocks were rotated in a Latin-square design among the four lists, assuring that all stimuli were equally presented in different blocks along the experimental sections. The lists had the following criteria: (a) a stimulus was never preceded by another stimulus starting with the same letter, (b) there were at most three words or pseudowords in sequence, and (c) there were at least 10 stimuli between experimental stimuli from the same condition. In total, Experiment 1 included 320 stimuli and 10 practice stimuli; it lasted approximately 18 min.

2.1.3. Procedure

Experiment 1 was constructed and ran using E-Prime® 2.0 Professional (Psychology Software Tools, Inc., Sharpsburg, PA, USA) (Schneider et al., 2012). Participants were tested individually in a quiet room in the library of the *Université Lumières Lyon 2*. Each trial followed the sequence: first, a fixation point was displayed on the center of the screen for 500 ms; the target word was then presented on the center of the screen in lowercases for 2000 ms or until the participant's response; then, a blank screen was presented as inter-stimuli for 500 ms, and a new trial started with the fixation point. The stimuli were presented on the center of a 15″ LCD computer screen, in letter size 18-point Courier New font, in white letters against black background. RT measure began in the onset of the target screen and finished when the participants performed their responses via a keyboard button. Participants were asked to perform a lexical decision task as quickly and accurately as possible using a computer keyboard with both hands, where the right hand on the 'green' button corresponded to words and the left hand on the 'red' button corresponded to pseudowords.

[3] IND.PRES.-1P.PL for indicative mood, present tense, and first person plural agreement; IND.IMPPAST-3P.SG for indicative mood, imperfect past tense, and third person singular agreement.

Table 2
Overall RT means, SDs between parenthesis, and error rates by the different conditions of Experiment 1. S− for one suffix, S+ for two suffixes, SF− for low surface frequency, and SF+ for high surface frequency.

Verb type	Frequency	One suffix (S−)		Two suffixes (S+)	
		RT(ms)	Error(%)	RT(ms)	Error(%)
Regular	SF−	669(171)	.95	692(178)	1.03
	SF+	644(159)	.34	664(182)	.72
Irregular	SF−	704(187)	.93	721(221)	1.44
	SF+	669(167)	.42	696(202)	1.10

2.1.4. Results

Only experimental items were analyzed. RTs faster than 300 ms and slower than 1600 ms were considered out of task and discarded (.71%); one experimental stimulus (i.e., *vaille* 'I/it worth') was removed because it had an error rate higher than 50% (.61%); and incorrect responses were removed for the RT analysis (6.92%). In total, 8.15% of the data were discarded. Overall RT means, standard deviations (SD), and error rates are shown in Table 2.

Reversed RTs presented a more Gaussian-like distribution when compared to normal RTs and logarithmic function of RTs through the Kolmogorov-Smirnov test (i.e., RT: $D = .128$, $p < 2.2e{-}16$; log(RT): $D = .075$, $p < 2.2e{-}16$; 1/RT: $D = .028$, $p < .002$), thus making them more suitable for the application of parametric tests. The data were analyzed using two mixed-effects models (Baayen et al., 2008), one with the inverted RTs as the dependent variable, participants and targets as random variables, and verb type (i.e., regular vs. irregular), number of morphological operations (S− vs. S+, where S− for one inflectional suffix and S+ for two inflectional suffixes), and surface frequency (SF− vs. SF+, where SF− for low surface frequency and SF+ for high surface frequency) as fixed-effect variables; and another model with the logit accuracy (ACC) as the dependent variable and binomial family specified in the model. Mixed-effects model has as the main characteristics the use of crossed random effects for participants and items simultaneously and the use of the whole dataset of trials for analysis (Baayen et al., 2008).

The main RT effects through an analysis of variance (ANOVA) in the mixed-effects model (Type III with Satterthwaite approximation for degrees of freedom) revealed a significant effect of verb type ($F(1,151) = 11.412$, $p < .001$), with longer RTs for irregular than regular verbs; a significant effect of surface frequency ($F(1,151) = 17.059$, $p < .001$), with longer RTs for low- than high-frequency words; and a significant effect of the number of morphological operations ($F(1,151) = 6.241$, $p < .01$), with longer RTs for verbs with two morphological operations than verbs with one morphological operation. None of the interactions were significant (*F*s < 1, *p*s > .1).

In the error rate analysis, the ANOVA in the mixed-effects model (Type II Wald χ^2 test) showed a significant effect of verb type ($\chi^2(1, N = 30) = 4.041$, $p < .05$), with more errors in irregular than regular verbs; a significant effect of surface frequency ($\chi^2(1, N = 30) = 7.423$, $p < .01$), with more errors for low- than high-frequency words; and a significant effect in the number of morphological operations ($\chi^2(1, N = 30) = 4.017$, $p < .05$), with more errors in verbs with two morphological operations than one morphological operation. None of the interactions were significant (*p*s > .1).

2.1.5. Discussion

The results presented above show three significant main effects and no interaction between them: a main effect of verb type, a main effect of surface frequency, and a main effect of the number of morphological operations.

Of principal interest in this article, verbs with two morphological operations yield longer RTs than verbs with one morphological operation in the processing of inflectional suffixes on French verbs. These results were consistent in both regular and irregular verbs and for both low and high surface frequencies, with no interactions between these variables. We therefore consider that the processing of each inflectional suffix has an additive cognitive cost reflected in the RTs and that the lack of interaction between morphological operations and surface frequency indicates no processing difference for low and high surface frequency words. Additionally, the error rate results confirmed the same pattern of results with higher errors for forms with two morphological operations.

We also found an effect of verb type, with irregular verbs associated with longer RTs and more errors than regular ones. The lack of interactions with the other variables suggests that they are independent effects and that regular and irregular verbs are equally processed regarding the inflectional suffixes (de Diego Balaguer et al., 2006; Orsolini and Marslen-Wilson, 1997). Our interpretation is that stem competition or allomorphic operations on irregular verbs slow their RTs (Estivalet and Meunier, 2016).

The surface frequency effect observed is widely known in the psycholinguistic literature, but its interpretation varies (Amenta and Crepaldi, 2012); nevertheless, this variable did not interact with any other variable in our data, holding the effect of the number of morphological operations for both low and high surface frequency verbs. Thus, our interpretation is that the surface frequency reflects consistent and productive combinations of morphemes in word formation (Stockall and Marantz, 2006; Taft, 1979).

We remark that the phonological/orthographic differences between inflected verbs with one or two morphological operations occur mainly in the tense morpheme, given that the agreement morpheme is present in almost all inflected forms. Therefore, the presence of the tense morpheme adds phonological/orthographic material to be processed. Considering that the tense node is processed by covered movement, activating intentional situational features and that the agreement node is processed by overt movement for subject-verb concordance, we propose that these two morphological nodes are hierarchically processed by different cognitive processes. Thus, these results prompted new questions about the nature of specific verbal inflectional suffixes: (a) Is there a difference between the processing of the indicative present tense and indicative imperfect past tense (i.e., indicative present $[\text{ø}]_{present}$ vs. indicative imperfect past $[\text{-i-}]_{past}$)? (b) Is there a difference between the processing of agreement morphemes with different morphosyntactic features (i.e., *nous* ‘we’ ↔ $[\text{-ons}]_{1st,\ plural}$ vs. *vous* ‘you’ ↔ $[\text{-ez}]_{2nd,\ plural}$)? To answer these questions, Experiment 2 focused on the processing of specific inflectional suffixes on French verbs.

2.2. Experiment 2: tense and agreement suffix processing

2.2.1. Participants

Twenty-two adult native speakers of French between the ages of 18 and 33 (mean age 23.1, 11 women) with the same characteristics as Experiment 1 took part in Experiment 2; no participant performed both experiments.

Participants did not know the purpose of the study and gave their written consent to participate in the experiment as volunteers. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the ethics committee *Comité de Protection des Personnes Sud-Est II* (IRB: 00009118).

2.2.2. Material and design

Participants performed a lexical decision task in visual modality on words and pseudowords. We investigated tense and agreement suffix processing in regular verbs from the 1st class. We handled four different experimental conditions as a function of two variables with two levels each: (a) tense (i.e., indicative present [ø] vs. indicative imperfect past [-i-]) and (b) agreement (1st plural [-ons] vs. 2nd plural [-ez]), as shown in Table 3.

We selected 320 French regular verbs from the 1st class falling in the four different experimental conditions: 160 verbs in the indicative present tense and 160 verbs in the indicative imperfect past tense. Within each tense, 80 verbs were inflected in the 1st plural agreement, and 80 verbs were inflected in the 2nd plural agreement (Appendix C). We selected this large set of experimental stimuli for further multivariate analyses. All experimental stimuli and conditions were controlled and matched in lemma frequency between 5 and 300, surface frequency between .07 and 5, number of letters between 5 and 10, number of phonemes between 3 and 10, number of syllables between 2 and 4, 0 homographs, OLD20 and PLD20 (Yarkoni et al., 2008), as shown in Appendix D.

We also added a set of 40 infinitive verbs as fillers; then, we added a set of 360 pseudowords to counterbalance the responses. All experimental items were selected, controlled, and matched using the French database *Lexique* (New et al., 2004); the pseudowords were also created by using its pseudoword generator toolbox. Four lists were constructed with the same criteria and procedure as Experiment 1 using the Mix program (van Casteren and Davis, 2006) with pseudorandom order to counterbalance the sequence of stimuli presentation between conditions and participants. The lists were subdivided in four blocks with the same number of stimuli in all conditions. These blocks were rotated in a Latin-square design among the lists, assuring that all stimuli were equally presented along the experimental sections. In total,

Table 3
Examples of stimuli in the different conditions of Experiment 2: tense (indicative present vs. indicative imperfect past) and agreement (1st plural vs. 2nd plural).

Tense	Present		Imperfect past	
Agreement	1st plural	2nd plural	1st plural	2nd plural
Structure	$[[\text{jou}]_{V}[\text{ons}]_{Agr}]_{TP}$	$[[\text{jou}]_{V}[\text{ez}]_{Agr}]_{TP}$	$[[\text{jou}]_{V}[[\text{i}]_{T}[\text{ons}]_{Agr}]_{T}]_{TP}$	$[[\text{jou}]_{V}[[\text{i}]_{T}[\text{ez}]_{Agr}]_{T}]_{TP}$
Orthography	jouons	jouez	jouions	jouiez
Phonology	/ʒu’õ/	/ʒu’e/	/ʒu’jõ/	/ʒu’je/
Gloss	‘we play’	‘you$_{pl}$ play’	‘we played’	‘you$_{pl}$ played’

Experiment 2 had 720 stimuli and 12 practice stimuli; it was held in approximately 32 min, with two pauses during the experiment.

2.2.3. Procedure

The procedure for Experiment 2 was the same as for Experiment 1.

2.2.4. Results

Only experimental items were analyzed. RTs faster than 300 ms and slower than 1600 ms were considered out of task and discarded (1.04%), and incorrect responses were removed for the RT analysis (3.47%). In total, 4.47% of the data were discarded. The overall RT means, SDs, and error rates are shown in Table 4.

As in Experiment 1, reversed RTs presented the more Gaussian-like distribution (Kolmogorov–Smirnov test, RT: $D = .126$, $p < 2.2e{-}16$; log(RT): $D = .073$, $p < 2.2e{-}16$; and 1/RT: $D = .022$, $p < .006$). The data were analyzed using two mixed-effects models (Baayen et al., 2008), one with inverted RTs as the dependent variable, participants and targets as random variables, and tense (indicative present vs. indicative imperfect past) and agreement (1st plural vs. 2nd plural) as fixed-effect variables; and another model with logit ACC as the dependent variable and binomial family specified in the model.

The ANOVA in the RT mixed-effects model showed a significant effect of tense ($F(1,306) = 29.291$, $p < .001$), with longer RTs for verbs in the indicative imperfect past tense than present one; a significant effect of agreement ($F(1,306) = 28.456$, $p < .001$), with longer RTs for the 1st plural agreement than 2nd plural one; and a significant interaction between these two variables ($F(1,306) = 7.583$, $p < .01$), indicating that both effects are dependent on each other. The planned comparisons showed that the tense effect is bigger for the 1st plural ($t(309) = 5.762$, $p < .001$) than for the 2nd plural ($t(304) = 2.884$, $p < .05$) agreement suffix.

The ANOVA in the error rate analysis showed a significant effect in tense ($\chi^2(1, N = 22) = 5.630$, $p < .05$), with more errors for verbs in the indicative imperfect past tense than present one; a significant effect in agreement ($\chi^2(1, N = 22) = 12.197$, $p < .001$), with more errors for 1st plural agreement than 2nd plural one; and a significant interaction between these two variables ($\chi^2(1, N = 22) = 6.536$, $p < .05$). The planned comparisons showed a significant difference between present and imperfect past tenses in the 1st plural agreement ($z = -3.117$, $p < .001$), but not in the 2nd plural agreement ($z = .676$, $p = .499$).

To better comprehend our data, we scrutinized more complex mixed-effect models with multivariate analyses, including numerical surface frequency, lemma frequency, number of letters, number of phonemes, number of syllables, and OLD20 and PLD20 as fixed-effect variables. We started analyzing more complex models with many general additive effects and interactive effects between tense and agreement against other variables; we then proceeded to simplify the

Table 4
Overall RT means, SDs between parenthesis, and error rates by the different conditions of Experiment 2.

Tense	Present		Imperfect past		Total	
Agreement	RT(ms)	Error(%)	RT(ms)	Error(%)	RT(ms)	Error(%)
1st plural	653(194)	.66	693(211)	1.62	677(204)	2.28
2nd plural	636(183)	.63	660(184)	.56	643(183)	1.19
Total	645(189)	1.29	676(199)	2.18	660(195)	3.47

Table 5
ANOVA results from the multivariate mixed-effect model, including factorial tense and agreement; and numerical lemma frequency, number of letters, and number of syllables as fixed-effect variables (i.e., lmerH < - lmer(-1000 * 1/RT ~ Tense * Agreement + LemmaFreq + Letters + Syllables + (1|Participant) + (1|Target), data)).

Variables	MSE	NumDF	DenDF	F.value	Pr(>F)
Tense	2.7049	1	306.34	33.156	2.067e−08***
Agreement	1.5420	1	306.40	18.902	1.875e−05***
LemmaFreq	8.5876	1	312.98	105.264	<2.2e−16***
Letters	0.8028	1	304.87	9.841	0.001874**
Syllables	0.6609	1	307.00	8.101	0.004723**
Tense:Agreement	0.5163	1	306.28	6.328	0.012394*

* $p < .05$.
** $p < .01$.
*** $p < .001$.

model by eliminating non-significant variables and interactions. We analyzed nine different models and compared them by using an ANOVA between the models (Baayen et al., 2008); the ANOVA of the most significant mixed-effect multivariate model (i.e., lmerH: $\chi^2(9, N = 22) = 99.625$, $p < .001$) is shown in Table 5. The other mixed-effects multivariate models that were analyzed, as well as the ANOVA of the most complex model analyzed, are shown in Appendix E.

2.2.5. Discussion

Experiment 2 confirmed our prediction of a significant effect in the morphological processing of the tense suffix, yielding a consistent difference between indicative present and imperfect past in French verbs; unexpectedly, we also found a significant effect of agreement with longer RTs for the 1st plural agreement than the 2nd plural one. There was also a significant interaction between tense and agreement, showing a stronger effect of tense in the 1st plural agreement than in the 2nd plural one. It seems that the processing of the tense morpheme as an infix between the stem and the agreement morpheme has consequences on word recognition RTs and error rates. Our results speak to differences in the processing of the tense and agreement morphemes.

The tense effect observed shows that verbs inflected in the indicative imperfect past with two morphological operations yield longer RTs than verbs inflected in the indicative present with one morphological operation. Still, it appears that this effect is modulated by the agreement morpheme. In the indicative imperfect past tense, when the tense and agreement morphemes are merged, their respective morphosyntactic features percolate to the tense intermediary node (i.e., <-ions> ↔ /'jõ/ ↔ [past, 1st, plural]; <-iez> ↔ /'je/ ↔ [past, 2nd, plural]). Therefore, in contrast to the underspecified standard indicative present tense, which has neither the tense morpheme nor tense morphosyntactic features to be processed, the indicative imperfect past tense has additionally the [past] morphosyntactic feature to be processed, slowing the RTs (Penke et al., 2004).

In contrast to what was expected, we found a significant difference between the 1st and 2nd plural agreements; we suggest that this difference could be because the 2nd plural agreement (i.e., *vous* 'you$_{pl}$' ↔ [-ez]$_{2nd,\ plural}$) is the standard formal pronoun of treatment in French, very frequent, very productive, and highly disseminated in written and oral language, whereas the 1st plural agreement (i.e., *nous* 'we' ↔ [-ons]$_{1st,\ plural}$) has been largely substituted by the standard impersonal 3rd singular form (i.e., *on* 'we/one') (Kilani-Schoch and Dressler, 2005). Consequently, it is possible that the 2nd plural agreement [-ez] simply has the [2nd] morphosyntactic feature underspecified because it is the standard [plural] agreement morpheme; thus, it would have one morphosyntactic feature less to be processed (i.e., [-ez]$_{plural}$), accelerating RTs (Halle and Marantz, 1994; Penke et al., 2004). Indeed, the 2nd plural agreement morpheme [-ez] (i.e., token: 5828, type: 9240.9) is much more frequent than the 1st plural [-ons] (i.e., token: 2757, type: 2799.9), measured as bigram/trigram frequencies (New et al., 2004), and considering moreover the word length control and matching, it is a fact that the 1st plural agreement suffix [-ons] is one letter larger than the 2nd plural one [-ez].

It also appears that tense effect between indicative present and imperfect past in RTs and error rates is larger in the 1st plural agreement than in the 2nd plural. Nevertheless, the mixed-effects multivariate model scrutinized in Appendix E suggests that the interaction between tense and agreement is not robust. In this model, tense and agreement do not interact with any other variable, and the interaction between tense and agreement disappears when the other lexical variables are included in the analyses (Baayen et al., 2008). As expected, in the models analyzed, there were neither surface frequency, nor phonological length, nor neighborhood (i.e., OLD20 and PLD20) effects; in contrast, in Table 5 and Appendix E, analyses yielded letter and syllable length significant results, which is largely known as reflecting sensory stimuli length perception and processing (Caramazza, 1997; McClelland and Rumelhart, 1981; Taft, 1991). Most importantly, as predicted by the OB model there was an expected significant effect of lemma frequency, which supports early obligatory decomposition of verbs between stem and inflectional suffixes and morphemic search for word recognition (Amenta and Crepaldi, 2012; Estivalet and Meunier, 2015; Stockall and Marantz, 2006; Taft, 1979). Therefore, in line with large orthographic decomposition evidence (Rastle and Davis, 2008), our results suggest that lemma frequency and morphological operations are additive effects in the visual recognition of inflected words. Whereas the lemma frequency effect reflects the search of morphemic representations for activation in the mental lexicon, the morphological operation effect would reflect the morphosyntactic features checking in the combination of morphemes for word verification and recognition.

3. General discussion

In the present study, we investigated the processing of inflectional suffixes in French verbs, obtaining significant effects in the processing of a different number of morphological operations in tense and agreement morphemes. Our results suggest that words are not the atoms of languages, but that words are processed in terms of hierarchical morphological structures, activating morphemes as minimal meaningful units in word recognition (Halle and Marantz, 1994). These results are in line with studies that present evidence of pre-lexical decomposition for word recognition (de Diego Balaguer et al., 2006; Rastle and Davis, 2008; Stockall and Marantz, 2006; Taft, 1979), as well as our recent findings and other studies in French verbal morphology (Estivalet and Meunier, 2015, 2016; Meunier and Marslen-Wilson, 2004; Royle et al., 2012). The main novelty in our results is that we investigated the morphological processing of inflectional suffixes in French verbs independently of the root and stem processing, addressing the abstract morphosyntactic features activated by the tense and agreement suffixes in the hierarchical morphological structure (Arregi, 2000; Halle and Marantz, 1994).

3.1. Hierarchical morphological structure

We found significant differences between French verbal forms with one or two morphological operations in high surface frequency and irregular verbs, as the irregular verbs were also significantly slower than regular ones. These findings seem to rule out whole-word representation models (Baayen et al., 2011; Devlin et al., 2004; Manelis and Tharp, 1977; McClelland and Rumelhart, 1981) and dual-mechanism models that posit a whole-word route for high-frequency words, such as the AAM (Caramazza et al., 1988), or irregular words, such as the W&R (Pinker, 1999) and the declarative/procedural model (Ullman, 2001), but not the Parallel Dual-Route model (Baayen et al., 1997), where the decompositional route would always win the race for word recognition in French. Alternatively, the Minimalist Morphology model (Wunderlich, 1996) predicts a semi-structured mechanism for irregular words, with post-lexical decomposition and allomorphic representations in a Word-and-Paradigm architecture. However, our results speak in favor of pre-lexical decomposition and rule-based morphological processing, which is more in line with an Item-and-Process architecture (Halle and Marantz, 1994). Therefore, it seems that single-mechanism models can better fit our results, especially regarding single visual word recognition and morphological processing triggered by orthographic activation in early stages (Amenta and Crepaldi, 2012; Rastle and Davis, 2008; Taft, 1991).

If envisaging dual-mechanism models, it appears that they should be considered not in terms of exclusive different routes but in terms of different levels of word processing (Allen and Badecker, 2002; Caramazza, 1997; Crepaldi et al., 2010; Jackendoff, 1975). de Diego Balaguer et al. (2006) showed functional magnetic resonance (fMRI) results indicating that both regular and irregular Spanish inflected verbs activate areas related to grammatical processing (the left inferior frontal gyrus). While irregulars also activate areas of the prefrontal cortex, reflecting lexical retrieval, regular verbs show an increased activation of areas related to the phonological loop in the reutilization of the stem shared across regular forms (anterior superior temporal gyrus and hippocampus).

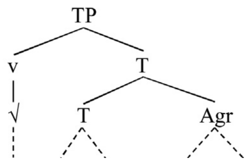
It should be noted that Romance languages almost always present these different levels of word processing as they almost always have inflectional suffixes independently of stem regularity (e.g., French: *je joue/je jouai, je prends/je pris*; Italian: *io giocai/io giocavo, io prendo/io presi*; Spanish: *yo juego/yo jugué, yo cojo/yo cogí*; Gloss: 'I play/I played, I take/I took'); therefore, word recognition in Romance languages is always mediated by the access of the lexical morpheme with semantic features and the functional morpheme with morphosyntactic features. In contrast, Germanic languages, for example, present regular forms with few suffixes and irregular allomorphic forms as free stems (e.g., English: 'I play/I played, I take/I took'; German: *Ich spiele/Ich spielte*, *Ich nehme/Ich nahm*; Dutch: *Ik speel/Ik speelde*, *Ik neem/Ik nam*); hence, word recognition of irregular verbs is the only access of the allomorphic lexical morpheme providing semantic features (and probably a [past] feature) (Wunderlich, 1996).

Our results showing differences in the processing of tense and agreement inflectional suffixes are also in line with those of aphasic patients, which show that tense is more impaired than agreement morpheme processing. Thus, our results support the interpretable feature hypothesis, where competence in morphological hierarchical structure processing and word recognition is directly dependent on morphosyntactic interpretable features (Wenzlaff and Clahsen, 2004). Therefore, the decompositional combinatorial route is the general mechanism for morphological processing; in particular, languages with rich inflectional morphology largely explore this mechanism (Orsolini and Marslen-Wilson, 1997).

3.2. Frameworking inflectional processing

We suggest that the processing differences and interaction between tense and agreement nodes take place during the activation and recombination phases based in the hierarchical morphological structure processing. In the activation phase, lexical morphemes activate semantic features and functional morphemes activate morphosyntactic features (de Diego Balaguer et al., 2006; Halle and Marantz, 1994). It follows that in the morphologically marked tenses, such as the indicative imperfect past, there is more phonological/orthographic material to be processed, as well as there are morphosyntactic features activated by the tense suffix to be processed for word recognition. According to schema (1) and the Experiment 2 critical stimuli shown in Table 3, French verbs inflected in the indicative present and imperfect past tenses in the 1st and 2nd plural agreements have neither the theme vowel nor the aspect morpheme, which is represented as (2):

(2)



In sum, the tense node is decomposed for morphosyntactic feature processing; the agreement morpheme is an overt operation required by syntax, which is quickly and easily feature checked in the subject-verb concordance, and the tense morpheme is a covered operation that conveys the speaker's intentional situation in the word formation (Chomsky, 1993). It seems that agreement processing is easy and does not require large cognitive resources; in contrast, the tense processing is deeper and demands greater cognitive resources, slowing the RTs. We speculated that the small differences between the 1st and 2nd plural agreements could be explained by the underspecified morphosyntactic features processing. If the 2nd person is the standard [plural] agreement morpheme, it is underspecified in the person morphosyntactic feature (i.e., [-ez]$_{plural}$); thus, there is one morphosyntactic feature less than the 1st plural agreement (i.e., [-ons]$_{2nd,\ plural}$) to be processed, accelerating the RTs (Penke et al., 2004).

We suggest that the different verbal inflectional nodes are processed hierarchically, separately, and interactively for word recognition. Our proposition is in line with morphological verbal inflectional studies presenting EEG evidence in French (Royle et al., 2012) and Catalan (Rodriguez-Fornells et al., 2001), magnetoencephalographic evidence in English (Stockall and Marantz, 2006), fMRI evidence in Spanish (de Diego Balaguer et al., 2006), aphasic evidence in German (Wenzlaff and Clahsen, 2004), and theoretical linguistics evidence in Spanish (Arregi, 2000) and Latin (Embick and Halle, 2005).

We would like to remark that while theoretical linguistics clearly separates the conceptual-intentional internal language machinery and the sensorial-motor interface for language externalization (Anderson, 1992; Chomsky, 1993; Halle and Marantz, 1994; Jackendoff, 1975), psycholinguistic models sometimes confound the sensorial interface with the language conceptual system (Baayen et al., 2011; Crepaldi et al., 2010; Devlin et al., 2004; McClelland and Rumelhart, 1981; Rastle and Davis, 2008; Taft, 1994), with the latter yielding results that can be generally fitted by PDP modeling, but which hardly correspond to the psycholinguistic computational reality. In what follows, we delineate the main framework of our single-mechanism model for morphology processing with pre-lexical and automatic decomposition, and symbolic-manipulation in an Item-and-Process architecture.

We propose that first, orthographic features information is processed by the visual sensory system based on n-gram frequency and constituency in an interactive-activation parser (Taft, 1991, 1994), thereby delivering enough evidence for triggering word decomposition (Rastle and Davis, 2008). Second, specific n-grams are encoded as morphemes; then, morphemic representations are searched and activated in the lexeme level, and subsequently their abstract representations are activated in the lemma level in the mental lexicon (Allen and Badecker, 2002), yielding the lemma frequency effect. Whereas lexical morphemes are numerous and present complex semantic features for meaning activation and phonological form in stem processing, functional morphemes are limited and present specific relevant morphosyntactic features and phonological form (Marantz, 2013). Thus, suffixes are the best candidates to be represented and quickly processed in this phase; they are small units from one to three letters that are regular and systematic, presenting high phonological/orthographic consistency and grammatical function. Third, morphemes are hierarchically recombined in the word structure for the word verification and recognition (Stockall and Marantz, 2006; Taft, 1979). Baayen et al. (1997) describes these phases in segmentation, licensing, and composition, respectively; however, the licensing phase in our model would be within the recombination phase, when forms are verified and licensed as real and meaningful words.

4. Conclusions

In the present study, we presented evidence from two visual lexical decision experiments on French verbal inflectional suffixes that words are decomposed for lexical access and recognition. We showed that the number of morphological operations in inflected words is crucial in morphological decomposition and processing. Tense and agreement inflectional suffixes presented different behaviors. Tense marking is largely exploited in Romance languages and appears to influence the processing of other morphemes in the morphological structure in word recognition (de Diego Balaguer et al., 2006). These results can be interpreted by a single-mechanism model with automatic pre-lexical decomposition where regular and irregular, low and high surface frequency, simple and complex words are processed by the same mechanism in different levels of word processing.

Statement on ethics approval and consent

Participants gave their written consent to participate in the experiment as volunteers. The study was conducted in accordance with the Declaration of Helsinki and the protocol was approved by the ethics committee *Comité de Protection des Personnes Sud-Est II* (IRB: 00009118).

Availability of data and materials

We made all data and materials completely available. Experimental stimuli and lexical matching information are available in the Appendices in the body of the article. In the Supporting Files of the article, we made available the List of Abbreviations, the complete datasets and R scripts from Experiments 1 and 2.

Author's contributions

All authors equally contributed for the development of this study, from the theoretical conception, experimental protocol, empirical research, data analysis, and article writing.

Declaration of interests

None declared.

Appendix A

Experiment 1

Lemma	SF+/S+	SF+/S−	SF−/S+	SF−/S−
Regular				
adresser	adressais	adressent	adressera	adressons
ajouter	ajoutais	ajoutent	ajoutera	ajoutes
changer	changera	changent	changions	changeons
coucher	couchais	couchent	couchiez	couchons
décider	décidera	décident	décidiez	décidez
dépêcher	dépêchait	dépêchons	dépêchais	dépêchent
dîner	dînait	dînons	dîniez	dînent
estimer	estimais	estiment	estimiez	estimons
expliquer	expliquera	expliquent	expliquiez	expliquons
fatiguer	fatiguait	fatiguent	fatiguera	fatiguons
montrer	montrais	montrez	montriez	montrons
poser	posais	posent	posiez	posons
presser	pressais	pressons	pressera	pressent
raconter	racontais	racontez	racontiez	racontons
risquer	risquais	risquent	risquiez	risquons
sauver	sauvera	sauvent	sauvais	sauvons
supposer	supposais	supposons	supposiez	supposent
tourner	tournais	tournons	tournera	tournes
traverser	traversais	traversons	traversera	traversez
tromper	trompais	trompent	trompiez	trompons
Irregular				
apercevoir	apercevait	aperçoit	apercevrai	aperçoives
apprendre	apprendra	apprends	apprendrez	apprenons
boire	boirai	buvions	boiras	buvez
connaître	connaissiez	connaît	connaîtrez	connaisses
craindre	craignait	crains	craindra	craignes
devenir	devenais	deviens	deveniez	devient
envoyer	envoyaient	envoie	envoyions	envoies

mourir	mourait	meurent	mouriez	meures
obtenir	obtenait	obtient	obtiendra	obtenons
parvenir	parvenais	parviens	parveniez	parvient
prévenir	prévenait	prévient	prévenais	préviens
recevoir	recevaient	reçoivent	recevions	reçoives
rejoindre	rejoignaient	rejoins	rejoignais	rejointes
reprendre	reprenaient	reprends	reprendras	reprenons
retenir	retenait	retient	retenions	retiens
revoir	revoyais	revoit	reverront	revoyons
souvenir	souvenaient	souvienne	souvenions	souviennes
surprendre	surprenait	surprend	surprendra	surprenons
tenir	tenions	tient	teniez	tiens
valoir	valaient	vaille	valais	vaillent

Appendix B

VT	Suffix	Lemma	Surface	Letter	Phoneme	Syllable	OLD20	PLD20
Regular								
SF−	S−	194.86	0.52	8.05	5.60	2.20	1.95	1.40
SF−	S+	194.86	0.41	8.25	6.65	2.85	2.10	1.40
SF+	S−	194.86	3.78	8.10	4.80	2.15	1.94	1.45
SF+	S+	194.86	3.75	8.20	5.80	2.70	1.93	1.17
Irregular								
SF−	S−	198.84	0.43	8.75	6.10	2.40	2.04	1.71
SF−	S+	198.84	0.49	8.60	6.60	2.80	2.19	1.67
SF+	S−	198.84	3.77	8.35	5.45	2.15	1.99	1.65
SF+	S+	198.84	4.04	8.55	6.15	2.75	1.96	1.37

Appendix B – Lexical characteristics from Experiment 1. All experimental conditions were matched in lemma frequency, surface frequency, number of letters, number of phonemes, number of syllables, OLD20, and PLD20.

Appendix C

Experiment 2

Present/1st/plural							
acceptons	approchons	décidons	espérons	gaspillons	luttons	prêtons	renouons
acheminons	aspirons	désirons	évitons	glissons	manquons	promenons	respectons
achetons	attirons	dévorons	évoquons	grimpons	mêlons	proposons	retournons
achevons	avouons	échappons	exagérons	habillons	montrons	racontons	soupirons
activons	calmons	éclatons	existons	ignorons	occupons	ramenons	supportons
adressons	comptons	embarquons	expliquons	imitons	opposons	rassurons	toussons
affrontons	contentons	emportons	félicitons	insistons	penchons	réclamons	traitons
aidons	continuons	empruntons	fermons	invitons	possédons	refusons	trinquons
ajoutons	créons	enjambons	fumons	libérons	préférons	relevons	versons
apportons	creusons	enterrons	gagnons	livrons	préparons	remontons	voguons
Present/2nd/plural							
abandonnez	bousculez	dessinez	espérez	manquez	précipitez	reniflez	souhaitez
abîmez	brûlez	doutez	évacuez	marquez	profitez	renoncez	supposez
accusez	caressez	dressez	évitez	marrez	promenez	rentrez	témoignez
adorez	cessez	échappez	fatiguez	mélangez	prononcez	repassez	tourmentez
annoncez	commandez	éloignez	flanquez	montrez	propagez	reprochez	tracez
approuvez	considérez	emmenez	foncez	nommez	proposez	respirez	travaillez
assimilez	contribuez	emportez	glissez	occupez	rappliquez	retournez	traversez

attaquez	crevez	enfermez	hésitez	partagez	rapprochez	séchez	troublez
attardez	décidez	engagez	ignorez	plongez	refusez	séparez	utilisez
bougez	déshonorez	épousez	insultez	poussez	remontez	sifflez	veillez

Imp.Past/1st/plural

abîmions	cachions	devinions	évitions	hochions	nommions	priions	répétions
achevions	chantions	dînions	explorions	hurlions	obstinions	profitions	réservions
affichions	collions	disputions	extasions	ignorions	opposions	projetions	roulions
allumions	couchions	écartions	figurions	imaginions	osions	promenions	sautions
apportions	crions	éloignions	formions	invitions	oubliions	racontions	scrutions
apprêtions	déchirions	emportions	frôlions	livrions	oublions	regagnions	secouions
arpentions	décidions	enfilions	gardions	manquions	plantions	rejetions	serrions
arrosions	déjeunions	entourions	grimpions	mariions	pleurions	remontions	supplions
assurions	dérobions	éprouvions	habitions	montrions	possédions	rentrions	traitions
brisions	désirions	éveillions	hésitions	moquions	préparions	repassions	trompions

Imp.Past/2nd/plural

acceptiez	cessiez	désiriez	étudiez	ignoriez	mêliez	racontiez	retourniez
achetiez	changiez	détestiez	évitiez	imaginiez	méritiez	raisonniez	rêviez
aidiez	charriez	doutiez	existiez	imposiez	montriez	rappeliez	risquiez
ajoutiez	comptiez	éclairiez	expliquiez	indiquiez	moquiez	réclamiez	sacrifiez
amusiez	condamniez	emmeniez	fermiez	invitiez	multipliez	rectifiez	signiez
approuviez	confiez	emportiez	filiez	jugiez	pleuriez	refusiez	souhaitiez
assistiez	couchiez	enleviez	fumiez	justifiez	pratiquiez	regrettiez	tâtiez
attachiez	débarquiez	enviez	gardiez	mangiez	préfériez	remarquiez	tentiez
attiriez	décidiez	épousiez	habitiez	manquiez	présentiez	rentriez	utilisiez
cédiez	demeuriez	espériez	humiliez	méfiez	promeniez	répétiez	vérifiez

Appendix D

Tense	Agr.	LemFreq	Surface	Letter	Phoneme	Syllable	OLD20	PLD20
Present	1pl	102.88	0.57	8.35	5.60	2.74	2.11	1.46
	2pl	107.28	0.82	8.03	5.81	2.81	2.05	1.53
Imp.Past	1pl	105.61	0.58	8.96	6.16	2.69	2.33	1.83
	2pl	110.88	0.78	8.13	6.23	2.70	2.18	1.80

Appendix D – Lexical characteristics from Experiment 2. All experimental conditions were matched in lemma frequency, surface frequency, number of letters, number of phonemes, number of syllables, OLD20, and PLD20.

Appendix E

In what follows, it is shown the nine mixed-effects models analyzed, where: lmerA is the simplest model presented in the general analysis in the article, lmerH is the best multivariate fitted model presented in the article, and lmerE is more complex multivariate model presented below. Tense (indicative present vs. indicative imperfect past) and Agreement (1st plural vs. 2nd plural) are factorial variables; and LemmaFreq, SurfFreq, Letters, Phonemes, Syllables, OLD20, and PLD20 are numerical variables drawn from the French corpus *Lexique 3* (New et al., 2004):

Mixed-effects models:

A. lmerA < - lmer(-1000 * 1/RT ∼ Tense + Agreement + (1|Participant) + (1|Target), data)
B. lmerB < - lmer(-1000 * 1/RT ∼ Tense * Agreement + (1|Participant) + (1|Target), data)
C. lmerC < - lmer(-1000 * 1/RT ∼ Tense + Agreement + LemmaFreq + SurfFreq + Letters + Phonemes + Syllables + OLD20 + PLD20 + (1|Participant) + (1|Target), data)
D. lmerD < - lmer(-1000 * 1/RT ∼ Tense * Agreement + LemmaFreq + SurfFreq + Letters + Phonemes + Syllables + OLD20 + PLD20 + (1|Participant) + (1|Target), data)
E. lmerE < - lmer(-1000 * 1/RT ∼ Tense * Agreement * (LemmaFreq + SurfFreq + Letters + Phonemes + Syllables + OLD20 + PLD20) + (1|Participant) + (1|Target), data)

F. lmerF < - lmer(-1000 * 1/RT ~ Tense + Agreement + LemmaFreq + SurfFreq + Letters + Phonemes + Syllables + (1|Participant) + (1|Target), data)
G. lmerG < - lmer(-1000 * 1/RT ~ Tense + Agreement + LemmaFreq + Letters + Syllables + (1|Participant) + (1|Target), data)
H. lmerH < - lmer(-1000 * 1/RT ~ Tense * Agreement + LemmaFreq + Letters + Syllables + (1|Participant) + (1|Target), data)
I. lmerI < - lmer(-1000 * 1/RT ~ Tense * Agreement * (LemmaFreq + Letters + Syllables) + (1|Participant) + (1|Target), data)

ANOVA between the different mixed-effects models analyzed:

Model	Df	AIC	BIC	logLik	Chisq	Chi Df	Pr(>Chisq)
A	6	2808.3	2849.2	−1398.1			
B	7	2802.7	2850.4	−1394.3	7.5717	1	0.005929**
C	13	2712.0	2800.6	−1343.0	0.1516	2	0.926979
D	14	2705.2	2800.6	−1338.6	8.7757	1	0.003053**
E	35	2722.7	2961.2	−1326.4	17.5248	16	0.352449
F	11	2708.1	2783.1	−1343.1	0.0000	1	1.000000
G	10	2702.7	2770.8	−1341.3	6.3866	1	0.011499*
H	9	2707.1	2768.4	−1344.5	99.6255	2	<2.2e−16***
I	19	2708.2	2837.7	−1335.1	6.9462	5	0.224671

*$p < .05$.
**$p < .01$.
***$p < .001$.

ANOVA results from the multivariate mixed-effect model including tense, agreement; and numerical lemma frequency, surface frequency, number of letters, number of phonemes, number of syllables, OLD20, and PLD20 as fixed-effect variables (i.e., lmerE < − lmer(−1000 * 1/RT ~ Tense * Agreement * (LemmaFreq + SurfFreq + Letters + Phonemes + Syllables + OLD20 + PLD20) + (1|Participant) + (1|Target), data)).

Variables	MSE	NumDF	DenDF	F.value	Pr(>F)
Tense	1.2612	1	284.79	9.750	0.00384**
Agreement	0.3212	1	284.79	3.938	0.04818*
LemmaFreq	4.1569	1	285.48	50.959	7.829e−12***
SurfFreq	0.1713	1	281.43	2.100	0.14837
Letters	0.3795	1	283.05	4.652	0.03186*
Phonemes	0.1347	1	282.53	1.652	0.19980
Syllables	0.3804	1	282.83	4.663	0.03166*
OLD20	0.1424	1	282.16	1.746	0.18743
PLD20	0.0036	1	283.57	0.044	0.83360
Tense:Agreement	0.0038	1	284.78	0.046	0.83021
Tense:LemmaFreq	0.0658	1	285.50	0.807	0.36981
Tense:SurfFreq	0.1604	1	281.45	1.967	0.16189
Tense:Letters	0.0999	1	283.04	1.225	0.26929
Tense:Phonemes	0.0098	1	282.52	0.120	0.72959
Tense:Syllables	0.0037	1	282.80	0.045	0.83127
Tense:OLD20	0.0423	1	282.18	0.519	0.47206
Tense:PLD20	0.0268	1	283.56	0.329	0.56690
Agreement:LemmaFreq	0.0182	1	285.49	0.223	0.63738
Agreement:SurfFreq	0.0938	1	281.43	1.150	0.28438
Agreement:Letters	0.0008	1	283.04	0.010	0.91989
Agreement:Phonemes	0.1837	1	282.54	2.252	0.13453
Agreement:Syllables	0.0000	1	282.80	0.000	0.98225
Agreement:OLD20	0.0127	1	282.15	0.156	0.69359
Agreement:PLD20	0.0001	1	283.56	0.001	0.97961

Tense:Agreement:LemmaFreq	0.0271	1	285.47	0.333	0.56461
Tense:Agreement:SurfFreq	0.0000	1	281.43	0.000	0.98374
Tense:Agreement:Letters	0.0984	1	283.03	1.207	0.27292
Tense:Agreement:Phonemes	0.0432	1	282.53	0.530	0.46730
Tense:Agreement:Syllables	0.1691	1	282.80	2.073	0.15105
Tense:Agreement:OLD20	0.0110	1	282.15	0.135	0.71360
Tense:Agreement:PLD20	0.0625	1	283.57	0.766	0.38224

*$p < .05$.
**$p < .01$.
***$p < .001$.

Appendix F. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:10.1016/j.lingua.2020.102839.

References

Allen, M., Badecker, W., 2002. Inflectional regularity: probing the nature of lexical representation in a cross-modal priming task. J. Memory Lang. 46 (4), 705–722. http://dx.doi.org/10.1006/jmla.2001.2831
Amenta, S., Crepaldi, D., 2012. Morphological processing as we know it: An analytical review of morphological effects in visual word identification. Front. Psychol. 3 (232). http://dx.doi.org/10.3389/fpsyg.2012.00232
Anderson, S., 1992. A-Morphous Morphology. Cambridge University Press.
Arregi, K., 2000. How the Spanish verb works.. In: LSRL, vol. 30. University of Florida, Gainesville, pp. 1–52.
Baayen, R.H., Davidson, D., Bates, D., 2008. Mixed-effects modeling with crossed random effects for subjects and items. J. Memory Lang. 59 (4), 390–412. http://dx.doi.org/10.1016/j.jml.2007.12.005
Baayen, R.H., Dijkstra, T., Schreuder, R., 1997. Singulars and plurals in Dutch: Evidence for a parallel dual-route model. J. Memory Lang. 37 (1), 94–117. http://dx.doi.org/10.1006/jmla.1997.2509
Baayen, R.H., Milin, P., Đurđević, D.F., Hendrix, P., Marelli, M., 2011. An amorphous model for morphological processing in visual comprehension based on naive discriminative learning. Psychol. Rev. 118 (3), 438–481. http://dx.doi.org/10.1037/a0023851
Caramazza, A., 1997. How many levels of processing are there in lexical access? Cognit. Neuropsychol. 14 (1), 177–208. http://dx.doi.org/10.1080/026432997381664
Caramazza, A., Laudanna, A., Romani, C., 1988. Lexical access and inflectional morphology. Cognition 28 (3), 297–332. http://dx.doi.org/10.1016/0010-0277(88)90017-0
Chomsky, N., 1993. A minimalist program for linguistic theory. In: Hale, K., Keyser, S.J. (Eds.), The View From Building 20: Essays in Linguistics in Honor of Sylvain Bromberger. The MIT Press, Cambridge, Massachusetts, pp. 1–52.
Crepaldi, D., Rastle, K., Coltheart, M., Nickels, L., 2010. ''Fell'' primes ''fall'', but does ''bell'' prime ''ball''? Masked priming with irregularly-inflected primes. J. Memory Lang. 63 (1), 83–99. http://dx.doi.org/10.1016/j.jml.2010.03.002
de Diego Balaguer, R., Rodríguez-Fornells, A., Rotte, M., Bahlmann, J., Heinze, H.-J., Münte, T.F., 2006. Neural circuits subserving the retrieval of stems and grammatical features in regular and irregular verbs. Hum. Brain Mapp. 27 (11), 874–888. http://dx.doi.org/10.1002/hbm.20228
Devlin, J.T., Jamison, H.L., Matthews, P.M., Gonnerman, L.M., 2004. From the cover: morphology and the internal structure of words. Proc. Natl. Acad. Sci. 101 (41), 14984–14988. http://dx.doi.org/10.1073/pnas.0403766101
Embick, D., Halle, M., 2005. On the status of stems in morphological theory. In: Geerts, T., Jacobs, H. (Eds.), Procedings of Going Romance 2003. John Benjamins, Amsterdam, pp. 59–88.
Estivalet, G.L., Meunier, F., 2015. Decomposability and mental representation of French verbs. Front. Hum. Neurosci. 9 (4). http://dx.doi.org/10.3389/fnhum.2015.00004
Estivalet, G.L., Meunier, F., 2016. Stem formation in French verbs: Structure, rules, and allomorphy. Languages 1 (2), 13. http://dx.doi.org/10.3390/languages1020013
Halle, M., Marantz, A., 1994. Some key features of distributed morphology. MIT Working Papers Linguist. 21 (Papers on Phonology and Morphology), 275–288.
Jackendoff, R., 1975. Morphological and semantic regularities in the lexicon. Language 51 (3), 639. http://dx.doi.org/10.2307/412891
Kilani-Schoch, M., Dressler, W.U., 2005. Morphologie naturelle et flexion du verbe français, vol. 488. Gunter Narr Verlag Tübingen, Tübingen.
Manelis, L., Tharp, D.A., 1977. The processing of affixed words. Memory Cognit. 5 (6), 690–695. http://dx.doi.org/10.3758/BF03197417
Marantz, A., 2013. No escape from morphemes in morphological processing. Lang. Cognit. Process. 28 (7), 905–916. http://dx.doi.org/10.1080/01690965.2013.779385
McClelland, J.L., Rumelhart, D.E., 1981. An interactive activation model of context effects in letter perception: I. An account of basic findings. Psychol. Rev. 88 (5), 375–407. http://dx.doi.org/10.1037/0033-295X.88.5.375
Meunier, F., Marslen-Wilson, W., 2004. Regularity and irregularity in French verbal inflection. Lang. Cogn. Process. 19 (4), 561–580. http://dx.doi.org/10.1080/01690960344000279
New, B., Pallier, C., Brysbaert, M., Ferrand, L., 2004. Lexique 2: A new french lexical database. Behav. Res. Methods Instrum. Comput. 36 (3), 516–524. http://dx.doi.org/10.3758/BF03195598

Orsolini, M., Marslen-Wilson, W., 1997. Universals in morphological representation: evidence from Italian. Lang. Cognit. Process. 12 (1), 1–47. http://dx.doi.org/10.1080/016909697386899

Penke, M., Janssen, U., Eisenbeiss, S., 2004. Psycholinguistic evidence for the underspecification of morphosyntactic features. Brain Lang. 90 (1–3), 423–433. http://dx.doi.org/10.1016/S0093-934X(03)00453-X

Pinker, S., 1999. Words and Rules: The Ingredients of Language. Weidenfeld and Nicolson, London/UK.

Rastle, K., Davis, M.H., 2008. Morphological decomposition based on the analysis of orthography. Lang. Cognit. Process. 23 (7–8), 942–971. http://dx.doi.org/10.1080/01690960802069730

Rodriguez-Fornells, A., Clahsen, H., Lleó, C., Zaake, W., Münte, T.F., 2001. Event-related brain responses to morphological violations in Catalan. Cognit. Brain Res. 11 (1), 47–58. http://dx.doi.org/10.1016/S0926-6410(00)00063-X

Royle, P., Drury, J.E., Bourguignon, N., Steinhauer, K., 2012. The temporal dynamics of inflected word recognition: a masked ERP priming study of French verbs. Neuropsychologia 50 (14), 3542–3553. http://dx.doi.org/10.1016/j.neuropsychologia.2012.09.007

Schneider, W., Eschman, A., Zuccolotto, A., 2012. E-Prime 2.0. Psychology Software Tools, Inc.. Learning Research and Development Center, University of Pittsburgh.

Stockall, L., Marantz, A., 2006. A single route, full decomposition model of morphological complexity: MEG evidence. Mental Lexicon 1 (1), 85–123. http://dx.doi.org/10.1075/ml.1.1.07sto

Taft, M., 1979. Recognition of affixed words and the word frequency effect. Memory Cognit. 7 (4), 263–272. http://dx.doi.org/10.3758/BF03197599

Taft, M., 1991. Reading and the Mental Lexicon. Lawrence Erlbaum Associates Ltd., East Sussex/UK.

Taft, M., 1994. Interactive-activation as a framework for understanding morphological processing. Lang. Cognit. Process. 9 (3), 271–294. http://dx.doi.org/10.1080/01690969408402120

Ullman, M.T., 2001. A neurocognitive perspective on language: the declarative/procedural model. Nat. Rev. Neurosci. 2 (10), 717–726. http://dx.doi.org/10.1038/35094573

van Casteren, M., Davis, M.H., 2006. Mix, a program for pseudorandomization. Behav. Res. Methods 38 (4), 584–589. http://dx.doi.org/10.3758/BF03193889

Wenzlaff, M., Clahsen, H., 2004. Tense and agreement in German agrammatism. Brain Lang. 89 (1), 57–68. http://dx.doi.org/10.1016/S0093-934X(03)00298-0

Wunderlich, D., 1996. Minimalist morphology: the role of paradigms. In: Booij, G., van Marle, J. (Eds.), Yearbook of Morphology 1995. Springer, Netherlands, pp. 93–114. http://dx.doi.org/10.1007/978-94-017-3716-6_6

Yarkoni, T., Balota, D., Yap, M., 2008. Moving beyond Coltheart's N: a new measure of orthographic similarity. Psychon. Bull. Rev. 15 (5), 971–979. http://dx.doi.org/10.3758/PBR.15.5.971