



# A Processing-Oriented Investigation of Inflectional Complexity

Claudia Marzi\*, Marcello Ferro\* and Vito Pirrelli

*Institute for Computational Linguistics, National Research Council, Pisa, Italy*

Due to the typological diversity of their inflectional processes, some languages are intuitively more difficult than other languages. Yet, finding a single measure to quantitatively assess the comparative complexity of an inflectional system proves an exceedingly difficult endeavor. In this paper we propose to investigate the issue from a processing-oriented standpoint, using data processed by a type of recurrent neural network to quantitatively model the dynamic of word processing and learning in different input conditions. We evaluate the relative complexity of a set of typologically different inflectional systems (Greek, Italian, Spanish, German, English and Standard Modern Arabic) by training a Temporal Self-Organizing Map (TSOM), a recurrent variant of Kohonen's Self-Organizing Maps, on a fixed set of verb forms from top-frequency verb paradigms, with no information about the morphosemantic and morphosyntactic content conveyed by the forms. After training, the behavior of each language-specific TSOM is assessed on different tasks, looking at self-organizing patterns of temporal connectivity and functional responses. Our simulations show that word processing is facilitated by maximally contrastive inflectional systems, where verb forms exhibit the earliest possible point of lexical discrimination. Conversely, word learning is favored by a maximally generalizable system, where forms are inferred from the smallest possible number of their paradigm companions. Based on evidence from the literature and our own data, we conjecture that the resulting balance is the outcome of the interaction between form frequency and morphological regularity. Big families of stem-sharing, regularly inflected forms are the productive core of an inflectional system. Such a core is easier to learn but slower to discriminate. In contrast, less predictable verb forms, based on alternating and possibly suppletive stems, are easier to process but are learned by rote. Inflection systems thus strike a balance between these conflicting processing and communicative requirements, while staying within tight learnability bounds, in line with Ackermann and Malouf's Low Conditional Entropy Conjecture. Our quantitative investigation supports a discriminative view of morphological inflection as a collective, emergent system, whose global self-organization rests on a surprisingly small handful of language-independent principles of word coactivation and competition.

**Keywords:** morphological complexity, discriminative learning, recurrent neural networks, self-organization, emergence, processing uncertainty, stem-family size

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### \*Correspondence:

Claudia Marzi  
claudia.marzi@ilc.cnr.it  
Marcello Ferro  
marcello.ferro@ilc.cnr.it

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## 1. INTRODUCTION

Assessment of the complexity of the inflection system of a language and its comparison with a functionally-equivalent system of another language are hot topics in contemporary linguistic inquiry (Bearman et al., 2015). Their goals may vary from a typological interest in classifying different morphologies, to a search for the most compact formal description of an inflection system, to an investigation of the nature of word knowledge and its connection with processing and learning issues (Juola, 1998; Goldsmith, 2001; Moscoso del Prado Martín et al., 2004; Bane, 2008; Ackerman and Malouf, 2013).

From a cross-linguistic perspective, the way morphosyntactic features are contextually realized through processes of word inflection probably represents the widest dimension of grammatical variation across languages, in a somewhat striking contrast with universal invariances along other dimensions (Evans and Levinson, 2009). This has encouraged linguists to focus on differences in morphological marking. Inflectional complexity is thus approached as a problem of feature counting, through comprehensive catalogs of the morphological markers and patterns in a given language or language type. In contrast with such “enumerative” approaches (Ackerman and Malouf, 2013), information-theoretic models have addressed the issue in terms of either algorithmic complexity (Kolmogorov, 1968), measuring the length of the most compact formal description of an inflection system, or in terms of information entropy (Shannon, 1948), which measures the amount of uncertainty in inferring a particular inflected form from another form, or, alternatively, from a set of paradigmatically related forms.

An altogether different approach, more conducive to addressing fundamental psycholinguistic and cognitive issues, is to conceive of complexity as related to the problem of *learning how to process* an inflection system. This step has far reaching consequences for the way we look at word knowledge, shifting our focus from what speakers know when they know inflection (mainly representations), to how speakers develop knowledge of inflection by processing input data (learning). According to this perspective, redundant patterns are predominantly statistical, and even irregularities appear to be motivated by their frequency distribution in the system and by the speaker’s processing bias. All these issues are very different in character from the formal constraints on units, representations or rule systems proposed within theoretical and computational models, and make room for an empirical validation grounded in learning theory.

In this paper, we show the potential of such a learning-based, processing-oriented view of inflection complexity through a quantitative analysis of the behavior of Temporal Self-Organizing Maps (or *TSOMs*, Ferro et al., 2011; Marzi et al., 2012; Pirrelli et al., 2015), a recurrent variant of classical Self-Organizing Maps (Kohonen, 2002), independently trained on the inflectional systems of Standard Modern Arabic, English, German, Greek, Italian and Spanish.

The choice of *TSOMs* as neuro-biologically inspired computational learning models is motivated here by practical and theoretical reasons. First, their role is instrumental, as we use them to illustrate the dynamic approach to complexity

we intend to advocate. Hence, some of the points made here will also hold, with some qualifications, for other existing computational models (Althaus and Mareschal, 2013; Baayen et al., 2019; Li et al., 2007; Mayor and Plunkett, 2010, among others). Secondly, *TSOMs* are based on discriminative principles of selective synchronization of processing nodes, supporting a *Word-and-Paradigm* view of the mental lexicon<sup>1</sup>. Accordingly, words are dynamically represented as emergent, superpositional patterns of short-term node activation, reflecting gradient levels of lexical specificity: from holistic to decompositional lexical representations. Thirdly, for each input word, *TSOMs* make it possible to inspect levels of node activation during online processing with a fixed sampling rate. This allows us to monitor patterns of node activation changing non-linearly with time as more symbols of the input word are presented, and check how levels of uncertainty in processing correlate with structural transitions in the input word (e.g., from a stem to its inflectional ending). Finally, we can correlate the *TSOM* temporal patterns with multiple defining features of typologically different inflectional systems, including: (i) the number of realization patterns of formal contrast (ranging from suppletion to extensive syncretism, through a whole range of intermediate cases); (ii) the type of such formal patterns (continuous, discontinuous or mixed); (iii) the amount of formal transparency they exhibit (ranging from a more fusional to a more agglutinative pattern); (iv) the frequency distribution of inflectionally marked forms within the same paradigm, and their relative dominance; (v) the frequency distribution of markers in their inflectional classes, and (vi) the amount of interpredictability among patterns (e.g., how easy it is for a speaker to predict an unknown inflected form from an already known inflected form of the same paradigm) as a function of their transparency and systematic nature.

As we shall see, data from our simulations makes room for an insightful analysis of time-bound patterns of structural organization of the network and its processing responses, accounting for the correlation between the complexity of inflectional data and processing aspects like speed of recognition, learnability and ease of production. Variation in complexity may have multiple, and in some cases opposite effects on all these issues, depending on the factors involved. For example, while regularly inflected forms are easier to learn because they take part of larger paradigm families, irregularly inflected forms are easier to discriminate because they are more isolated and ultimately less confusable. Based on non-linear analyses of simulation data

<sup>1</sup>*Word-and-Paradigm* Morphology (Matthews, 1991; Blevins, 2016) explicitly avoids the central problem of segmenting an inflected form like *walked* into meaningful sublexical parts (or “morphemes,” e.g., *walk-ed*), and expressing the morpho-lexical content of the whole as a function of the morpho-lexical content of its parts. Rather, inflected words are themselves parts of two parallel networks of formal and semantic relations between members of the same paradigm. Crucially, *Word and Paradigm Morphology* says nothing about the ways the two networks are mutually related, thus avoiding problems of morphemes with no meanings (empty morphemes), meanings with no morphemes (zero morphemes), bracketing paradoxes etc. This strikes us as the most typologically-neutral approach to an assessment of inflectional complexity, as it eschews any attempt to put a morphemic straitjacket to non agglutinative languages. As *TSOMs* are trained on inflected forms with no morphosemantic and morphosyntactic content, only redundant formal relations are learned.

reported in this paper and other linear analyses from our previous work (Marzi et al., 2018), we suggest that inflection is better understood as a dynamic, potentially unstable system, whose complexity results from a balancing act between competing processing and communicative requirements, finely tuned during language acquisition.

## 2. INFLECTIONAL COMPLEXITY

Inflection lies at the intersection of two independent but interacting issues: (i) what syntactic contexts require morphosyntactic and/or morphosemantic word marking, and for what lexical and grammatical units; (ii) how morphosyntactic and morphosemantic information is overtly realized on lexical and grammatical units. In this paper, our attention will be devoted to the second issue, by simulating and evaluating the learning dynamics of differently graded morphological (ir-)regularities. To investigate the issue of how degrees of inflectional complexity affect word processing strategies, we selected 6 languages that are differently positioned in a typological continuum ranging from a more isolating type to a more fusional inflecting one:<sup>2</sup> namely English, German, Spanish, Italian, Greek, and, to broaden our typological coverage, Standard Modern Arabic.

We will focus on systemic aspects of lexical organization that are common to most (if not all) inflection systems, and in particular we will examine the possibility of discovering morphological organization in the implicative network of relations between words, in order to understand the impact of this organization on word processing and learning issues. All inflection systems share the property that they have families of related word forms exhibiting collective properties that cannot be deduced from any one of these forms individually. This is the hallmark of inflectional paradigms, i.e., clusters of fully inflected forms which are associated with an individual lexical exponent (e.g., English *walk*, *walks*, *walking* and *walked*) and mutually related through inflectional classes (i.e., classes of inflectional markers in complementary distribution).

### 2.1. Paradigm Complexity

Over the last decades, investigation of the formal properties of inflectional paradigms has played a prominent role in changing the research agenda in inflectional morphology, marking a tendency to move away from part-whole relations within complex words, toward descriptive relations between inflected forms (Matthews, 1991; Blevins, 2016). Accordingly, the complexity of a paradigm resides in two basic dimensions. The first dimension defines the amount of full formal contrast realized within the paradigm, i.e., how many different markers are uniquely associated with distinct combinations

of morphosyntactic features (or paradigm cells, e.g., present indicative 1st singular), and how structurally different these markers are. The second dimension describes the number of interpredictability patterns between words in the same paradigm, i.e., how easy it is for a speaker to infer an unknown paradigmatic form from other familiar forms within the same paradigm.

Both dimensions of complexity are functionally relevant. Patterns of formal contrast serve to distinguish paradigmatically-related forms, and associate them with specific cells to communicate meaning or function within an inflectional system. We refer to this dimension as the level of “discriminative complexity” of the system. At the same time, variation in patterns of formal contrast is not scattered randomly across paradigm cells. Formal patterns tend to be interdependent, to the extent that knowing the inflection in one paradigm cell allows speakers to predict the inflection in another cell. This type of interdependency defines the “inferential complexity” of an inflectional system: paradigms where many forms are predicted upon exposure to one or few forms only, are *less* complex than paradigms where fewer forms are predicted from other forms.

From a cross-linguistic perspective, the discriminative complexity of an inflectional system is typically measured by enumerating the number of category values instantiated in the system (e.g., person, number or tense features) and the range of available markers for their realization. Accordingly, the larger the number of paradigm cells and their markers, the more difficult the resulting system (McWorther, 2001; Bickel and Nichols, 2005; Shosted, 2006). This notion of “Enumerative Complexity,” however, has been criticized on several grounds (Bane, 2008; Sagot and Walther, 2011; Ackerman and Malouf, 2013; Sagot, 2018). It soon gets difficult, if not impossible, to compare inflectional systems whose feature-value inventories differ dramatically. For instance, according to the World Atlas of Language Structures (Haspelmath et al., 2005), there are more than 10 different cases in Hungarian and none in Swahili, and more than 5 gender values in Swahili as opposed to none in Hungarian. In cases like this, we have no principled basis for arguing that either system is more or less complex than the other. In addition, even in the most favorable case of two hypothetical systems whose feature-value inventories match perfectly, simple counting can be misleading. Suppose we are comparing two systems, each with only two categories (say, singular and plural) and three different endings for each category: A, B, C for singular, and D, E, and F for plural. In the first system, paradigms are found to present three possible pairs of endings only: <A, D>, <B, E>, <C, F>, which can be described as corresponding to three different inflection classes. In the second system, any combination is attested. Clearly, the latter system would be more difficult to learn than the former, as it makes it harder to infer the plural form of a word from its singular form (or the singular from the plural for that matter). Nonetheless, both systems present the same degree of Enumerative complexity.

Recently, information theoretic approaches have been proposed as a way to circumvent the limitations of pure feature counting methods. Following Kolmogorov (Kolmogorov, 1968), the complexity of a dataset of inflected forms can be measured

<sup>2</sup>According to Dressler and colleagues (Bittner et al., 2003), European languages can be arranged along an inflectional complexity continuum, ranging from a more inflecting/fusional type (left) to a more isolating type (right):

Lithuanian → Greek → Russian → Croatian → Italian →  
Spanish → German → Dutch → French → English.

by the shortest possible grammar needed to describe them, or their *algorithmic complexity*, in line with the Minimum Description Length (MDL) principle (Rissanen, 2007). For example, following Goldsmith (2001), we can model the task of morphological induction as a data compression problem: find the collection of markers forming the shortest grammar that fits the empirical evidence best. To illustrate, English conjugation can be modeled as consisting of sets of endings in complementary distribution (somewhat reminiscent of “inflectional classes,” referred to by Goldsmith as “signatures”), and a set of stems. For example, the list  $\langle \text{NULL}, -er, -ing, -s \rangle$  is a signature for the verb stems *count*, *walk* and *mail*, but not for *love* or *notice*, which require the stems *lov-* and *notic-*, and the signature  $\langle e, -ed, -ing, -es \rangle$ . Licensing an irregular verb like *drink* in this grammar formalism is even more verbose, as it requires three stems, *drink*, *drank* and *drunk*, and two signatures:  $\langle \text{NULL}, -ing, -s \rangle$  for *drink*, and  $\langle \text{NULL} \rangle$  for both *drank* and *drunk*. Goldsmith’s algorithm, however, models paradigm learning as a top-down optimization problem, boiling down to a grammar evaluation procedure. The segmentation of forms into sublexical constituents is based on heuristic criteria and makes no contact with the problem of finding the minimally redundant set of paradigms. Ultimately, we are left with no clues about how word processing (segmentation) interacts with the paradigmatic organization of the morphological lexicon.

An alternative information-theoretic approach to complexity is based on Shannon’s entropy (Shannon, 1948), or *informational complexity* of a set of paradigms. Information complexity rests on the intuition that a more complex system of inflected forms presents fewer interpredictability patterns between existing forms than a less complex system does. Ackerman et al. (2009) and Ackerman and Malouf (2013) use Shannon’s information entropy to quantify prediction of an inflected form as a paradigm-based change in the speaker’s uncertainty. They conjecture that inflectional systems tend to minimize the average conditional entropy of predicting each form in a paradigm on the basis of any other form of the same paradigm (the Low Conditional Entropy Conjecture, or LCEC). This is measured by looking at the distribution of inflectional markers across inflection classes in the morphological system of a language. More recently, Bonami and Beniamine (2016) propose to generalize affix-to-affix inference to inference of intraparadigmatic form-to-form alternation patterns (Pirrelli and Yvon, 1999; Albright, 2002). This approach offers several advantages. It avoids the need for the theoretically-loaded segmentation of inflected forms into stems and affixes in the first place. Secondly, it models implicative relations between stem allomorphs (or stem-stem predictability), thereby providing a principled way to discover so-called “principal parts,” i.e., a minimal set of selected forms in a paradigm from which all other paradigm members can be deduced with certainty (Finkel and Stump, 2007). Finally, it emphasizes the role of joint prediction, i.e., the use of sets of forms to predict one missing form of the same paradigm, as a convenient strategy to reduce the speaker’s uncertainty in addressing the cell filling problem.

In spite of their differences, however, both Kolmogorov’s and Shannon’s approaches are biased by a few *a priori* assumptions. Results obtained from the use of algorithmic complexity strongly

depend on the formalism adopted for grammatical description (Sagot, 2018): for example, surface representations of verbs are typically segmented into stem-ending patterns. Information entropy dispenses with segmentation, but it rests crucially on the types of formal relations used to identify predictability patterns in inflectionally related forms. In either case, the algorithm does not adapt itself to the specific structural requirements of the systems it analyzes. Instead, it presupposes considerable knowledge of the morphology of the target language, in order to assess how effectively that knowledge can describe the language.

A more principled approach to measuring morphological complexity is to investigate the impact of incremental learning and online processing principles on paradigm organization, based on observation of the behavior of an unsupervised algorithm acquiring an inflection system from fully-inflected forms. The approach is central to establishing a connection between human language behavior, word distributions in input data, learning mechanisms and the taxonomy of units and combinatorial principles of linguistic theories. Careful quantitative analysis of the way a computational learning system can bootstrap structural information from typologically different training sets is not too far from what is done in experimental psycholinguistics, where the role of multiple factors on human processing is investigated by controlling factor interaction in the execution of a specific processing task. In the end, this allows us to frame the problem of inflectional (and paradigm) complexity into the larger context of word processing complexity, to which we turn in the following section.

## 2.2. Processing-Oriented Complexity

The discriminative and inferential dimensions of paradigm complexity illustrated in section 2.1 meet potentially competing communicative requirements. A maximally contrastive inflection system is one where inflected forms, both within and across paradigms, present the *earliest possible point of recognition*<sup>3</sup>, i.e., the position where they are uniquely distinguished from their paradigm companions. From this perspective, extensive suppletion (e.g., with English *be/am/are/is/was/were*) reflects a recognition-driven tendency for a maximally efficient contrast.

A maximally contrastive system, however, may require extensive storage of its forms, insofar as relatively few items can be *inferred* from its paradigm companions. Hence, any such system is not only slow to learn, but also fairly demanding and inefficient to use. Due to the Zipfian distribution of the forms in use within a speech community, almost half of the word forms of a language occur only once in a corpus, irrespective of corpus size (Blevins et al., 2017). This means that even high-frequency paradigms will tend to be partially attested, and speakers must be able to generalize available knowledge to rare events if they want to interpret or produce novel forms.

Issues of morphological regularity also have a bearing on the relationship between morphological complexity and word processing. We already noted that intra-paradigmatic suppletion,

<sup>3</sup>Starting from Marslen-Wilson’s classical definition of “uniqueness point” (Marslen-Wilson, 1984), we will make use of more recent refinements of this notion (Balling and Baayen, 2008, 2012).

arguably the most radical break with systematic and predictable inflection, is functional in maximizing contrast, but may represent a hurdle for word learning. Conversely, syncretic realization of many paradigm cells with identical forms (as in the English present indicative sub-paradigm) and, more generally, paradigm ambiguity, can slow down acquisition of overtly marked forms (e.g., the third singular present indicative *s*-forms in English). Researchers from diverse theoretical perspectives observe that rich inflection in fact facilitates early morphological production. In competition-based (Bates and MacWhinney, 1987), as well as functional (Slobin, 1982, 1985) and cue-response discriminative perspectives (Baayen et al., 2011), non-syncretic morphological paradigms such as those of Italian conjugation are argued to provide better syntactic cues to sentence interpretation, as compared, for example, to the impoverished inflectional system of English verb agreement. Biunique form-meaning relationships make inflectional markers more transparent, more compositional and in the end more easily acquired than the one-to-many mappings of morphological forms to syntactic features that are found in English, Swedish and Dutch (Phillips, 1996, 2010). Some researchers (Crago and Allen, 2001; Blom, 2007; Legate and Yang, 2007; Xanthos et al., 2011) have focused on the amount of finite verbs that children receive from the adult input, to observe that the high percentage of overtly inflected forms correlates with the early production of finite forms by children. In the framework of Natural Morphology, Dressler and colleagues (Bittner et al., 2003) claimed that a richer inflectional system makes children more aware of morphological structure, so that they begin to develop intra-paradigmatic relations sooner than children who are confronted by simpler systems do (Xanthos et al., 2011).

The literature reports a number of effects that family size and the frequency of family members have on a variety of processing tasks. A large family size supports visual word recognition, with printed words with many neighbors being recognized more quickly than words with fewer neighbors (Andrews, 1997). However, when neighbors are considerably more frequent than the target word, recognition of the target is inhibited. A similar reversal from facilitation to inhibition is reported in spoken word recognition and related tasks (Luce and Pisoni, 1998; Magnuson et al., 2007), where many neighbors are found to delay recognition of the target word. The effect has recently been interpreted as due to serial (as opposed to parallel) processing (Chen and Mirman, 2012): a word supported by a dense neighborhood is produced and read faster. But when the same word is presented serially (e.g., in spoken word recognition), high-frequency neighbors engage in competition and inhibit processing. Such a modality-driven subdivision of processing strategies is however not clear cut.

Balling and Baayen (2012) provide evidence for the combined processing effects of two uniqueness points in both auditory and visual processing. The first is the word's initial Uniqueness Point (*UPI*), where an input word is distinguished from its morphologically-unrelated competitors (e.g., *carrier* and *carpenter*). The second is the later Complex Uniqueness Point (*CUP*), where an input word is distinguished from its morphologically-related competitors (e.g., *writes* and *writing*).

They report that late *UPI* and *CUP* are inhibitory in auditory and visual lexical decision, both independently and in interaction. In line with this evidence, more regular paradigms are predicted to favor entrenchment of shared stems and quicker acquisition of full forms, but they may cause larger effects of processing uncertainty at the stem-ending boundary than more irregular paradigms do, due to the larger range of possible following inflectional endings in regulars, as compared to irregulars.

The human exquisite sensitivity to word frequency distributions appears to be at the root of entropy-based processing effects. Milin et al. (2009a,b) report that speakers engaged in a lexical decision task are sensitive to the divergence between the word frequency distribution within a single paradigm, and the cumulative word frequency distribution in the inflection class to which the paradigm belongs. In particular, if an inflected form occurs in its paradigm less frequently than one would expect from the frequency of its ending, the visual recognition of that form gets more difficult. This finding has been confirmed in follow-up studies (Kuperman et al., 2010; Baayen et al., 2011; Milin et al., 2017).

Ferro et al. (2018) replicate these effects with *TSOMs* trained on inflectional paradigms with frequency distributions of varying entropy. The quantitative analysis of computer simulations is amenable to an interesting interpretation of entropic effects in terms of competition between family members. On average, word recognition is facilitated when words belonging to the same paradigm compete on a par, i.e., when their distribution is highly correlated with the distribution of their inflectional endings. When this is not the case, the entropy of the family decreases, increasing the risk that a low-frequency form is inhibited by a high-frequency member of the same family.

Marzi et al. (2018) add a cross-linguistic perspective on this evidence, by measuring the processing costs incurred by *TSOMs* trained on the inflectional systems of 6 languages. They observe that the averaged word processing costs for each language oscillate linearly within a small range (in keeping with Ackermann and Malouf's *LCEC*), whose upper and lower bounds are marked by Modern Greek conjugation (harder) and English conjugation (easier) respectively. All other inflectional systems present no statistically significant differences in the processing "overheads" they require, in spite of their typological diversity and their varying levels of morphological transparency. The analysis supports an interpretation of the *LCEC* as resulting from a balancing act between word processing and word learning. Word processing puts a premium on a system where word forms are maximally distinct and accessed early. Word learning, however, somewhat counteracts such a processing bias. Acquiring new forms is in fact necessary for speakers to communicate and discriminate in an ever changing social environment. The need to keep the system open thus increases processing uncertainty, as it inevitably increases the number of elements in the system.

Our present investigation is intended to go beyond these preliminary results. In the following sections, we investigate the competitive dynamic between word processing and word learning in more detail, focusing on the role that paradigm contrast plays in a variety of training conditions. Based on the

data of Marzi et al. (2018), we model non-linear patterns of node activation in the online processing of inflected forms, in order to check how levels of processing uncertainty correlate with structural transitions in regularly and irregularly inflected forms within a single inflectional system, and across different inflectional systems. In addition, we model the impact of these effects on word learning, and we investigate the role that developing patterns of morphomic redundancy play during learning. As non-linear modeling can fit observed data patterns without *a priori* assumptions on the shape of the regression lines, this analysis is intended to lend further support to the dynamic view of inflectional complexity advocated here. In particular, we gain a better understanding of the basic language-invariant principles accounting for the discriminative and inferential dimensions of paradigm organization.

### 3. MATERIALS AND METHODS

In this section and in section 4, we provide data-driven evidence of the interaction between morphological complexity and word processing in six languages. The evidence is gathered through repeated computer simulations of the acquisition of the verb inflection system in each of the input languages. For this purpose, we use Temporal Self-Organizing Maps (*TSOMs*), a recurrent variant of Kohonen's Self-Organizing Maps (Kohonen, 2002) that offers a neurally-inspired computational model of *discriminative* learning of time-series of symbolic units (Ferro et al., 2011; Marzi et al., 2014; Pirrelli et al., 2015)<sup>4</sup>. *TSOMs* can learn all training sets accurately (Table 1), while showing, at the same time, differential effects in paradigm self-organization, learning pace, and word processing. We start this section with a short description of their architecture and learning principles. A more technical, detailed description is found in the **Appendix** to this paper.

#### 3.1. Recurrent Topological Networks for Word Learning

In *TSOMs*, word learning proceeds by developing maximally discriminative Markov-like chains of topologically arranged memory nodes, derived from exposure to fully inflected input forms with no morphological annotation. Nonetheless, node chains can mirror effects of gradient morphological structure and emergent paradigm organization. By developing specialized patterns of map nodes through recurrent connections, *TSOMs* encode input symbols auto-associatively, exploiting the formal redundancy of symbolic temporal series. Node specialization is modeled through discriminative learning equations (Ramscar and Yarlett, 2007; Baayen et al., 2011), which offer a powerful strategy for scaffolding the input stream into internalized structured representations that are efficient for word recognition and production. We provide here an informal, functional description of *TSOMs*. The interested reader is again referred to the **Appendix** for all mathematical and algorithmic details.

A lexical *TSOM* consists of a bank of input nodes encoding input letters, and a bank of processing nodes making up the lexical map proper (Figure 1). Each processing node is connected to the input layer through one-way input connections, and to other processing nodes (including itself) through one-time delay re-entrant temporal connections. At each time tick  $t$ , activation flows from the input layer to the map nodes through input connections. Re-entrant temporal connections update each map node with the state of activation of all nodes at the previous time tick (see the unfolded view of Figure 1). As with classical Recurrent Neural Networks (Elman, 1990), a word is input to a *TSOM* one symbol  $S$  at a time. Activation spreads through both input and temporal connections to yield an overall activation state, or Map Activation Pattern for  $S$  at time  $t$ :  $MAP_t(S)$ . The node with the highest activation level in  $MAP_t(S)$  is called the Best Matching Unit for  $S$  at time  $t$ , or  $BMU_t(S)$ . A time series of sequentially activated *BMUs* will be referred to as a *BMU* chain below. It represents the map's cumulative memory trace for an input time series.

Weights on temporal connections encode how strongly the current  $BMU_t$  is predicted by  $BMU_{t-1}$ , over a continuous range from 0 to 1. Temporal connection weights are trained on input data according to the following principles of discriminative learning, strongly reminiscent of Rescorla and Wagner (1972) equations (see **Appendix**). When the bigram 'AX' is input, a *TSOM* goes through two learning steps:

1. the temporal connection between  $BMU_{t-1}(A)$  and  $BMU_t(X)$  is strengthened (*entrenchment*);
2. all other temporal connections to  $BMU_t(X)$  are weakened (*competition*).

Step 1. and 2. incrementally enforce node specialization. Over the course of training, the map tends to allocate maximally distinct processing nodes, as a function of the form overlap and form frequency of input strings in the training set.

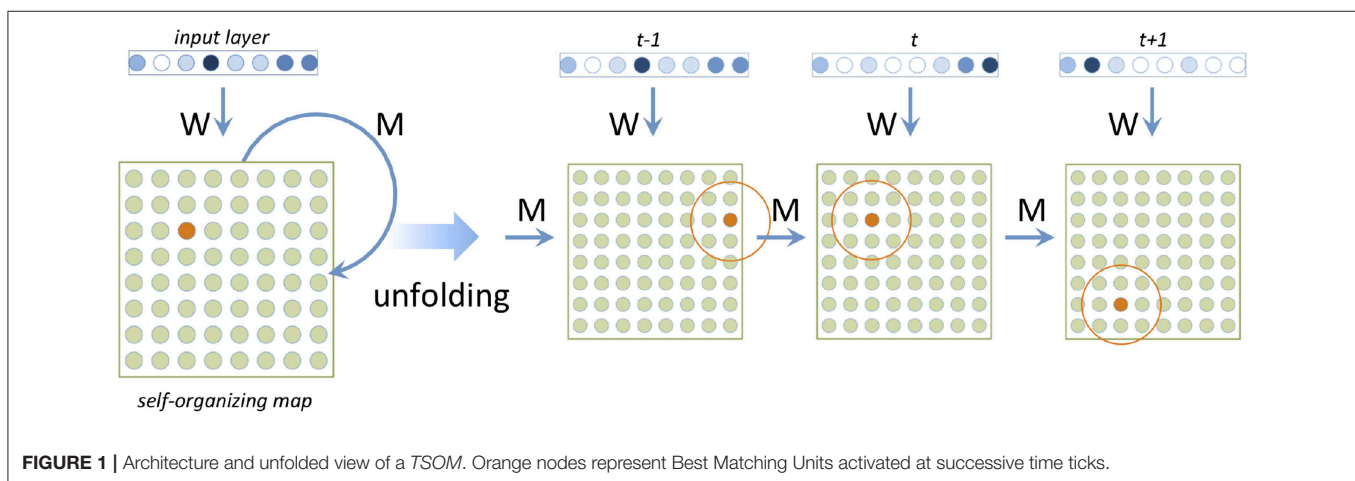
To illustrate the effects of node specialization, Figure 2A sketches two possible end-states in the allocation of *BMU* chains responding to 9 form types of German *geben* 'give': *geben* (infinitive, 1p and 3p, present indicative), *gibst* (2s, present indicative), *gibt* (3s, present indicative), *gebe* (1s, present indicative), *gab* (1s, 2s and 3s, preterite), *gaben* (1p and 3p, preterite), *gab* (2p, preterite) and *gebend* (present participle). In the left panel, *BMUs* are arranged in a word tree. Any node  $N$  keeps track of all nodes that were activated in order to arrive at  $N$ . The right panel of Figure 2A, on the other hand, offers a compressed representation for the 9 form types, with shared letters activating identical *BMUs*. As a result, when the shared node 'b' is activated, one loses information encoding which node was activated at the previous time tick. Let us briefly consider the implications of the two structures for word processing. In the word-tree (left), *gibt*, *gabt*, and *gebt* are mapped onto distinct node chains, bifurcating at the earliest branching point in the hierarchy (after the "g" node). From that point onward, the three forms activate distinct node paths. Clearly, when a node has only one outgoing connection, the *TSOM* has no uncertainty about what step to take next, and can anticipate the upcoming input symbol with certainty. In the word-graph on the

<sup>4</sup>A running version of the *TSOM* package can be downloaded at <http://www.comphyslab.it/redirect/?id=frontiers2019>.

**TABLE 1** | Statistics for the 6 datasets.

Language	Min/max form length	Regular/irregular Paradigms	Form types/ Training size	Recoding %	Recall %	sd %
Arabic	4/11	18/28	560/601	100	99.93	0.16
English	2/11	20/30	208/750	100	99.62	0.86
German	3/11	16/34	504/750	100	99.76	0.18
Greek	2/13	37/13	744/750	100	99.84	0.06
Italian	2/12	23/27	748/750	100	99.79	0.15
Spanish	2/15	23/27	715/750	100	99.94	0.13

Form length is given by number of input symbols (with the exclusion of # and \$), with orthographically marked stress being encoded as a distinct symbol. Differences between cardinality of form types and cardinality of the training set are due to syncretism. Percentage values of correctly recoded and recalled word types (and for the latter standard deviations) are given for each language, averaged over 5 map instances.



right, on the other hand, branching paths converge to the same node as soon as input forms share an identical symbol. Having more branches that converge to a common node increases processing uncertainty. The node encapsulates information of many preceding contexts, and its possible continuation paths are multiplied accordingly.

In **Figure 2B**, a word tree of the German verb *glauben* (“believe”) is given for the 9 form types filling the same 14 paradigm cells selected for *geben* (**Figure 1A**). It is instructive to compare these structures. Of particular interest is the base stem *glaub-*, which is systematically shared by all its verb forms, and followed by a longer stretch of inflectional markers (conveying features of tense, person and number) than the base stems of *geben* (namely, *geb-*, *gib-* and *gab-*) are. Accordingly, the left-to-right processing of regularly inflected forms of *glauben* requires the traversal of more branching structures (and thus more indecision points). This marks an important structural difference between regular and irregular paradigms in all languages considered here, with a significant impact on the processing behavior of TSOMs, as we shall see later in more detail (section 5.1.1).

### 3.2. The Data

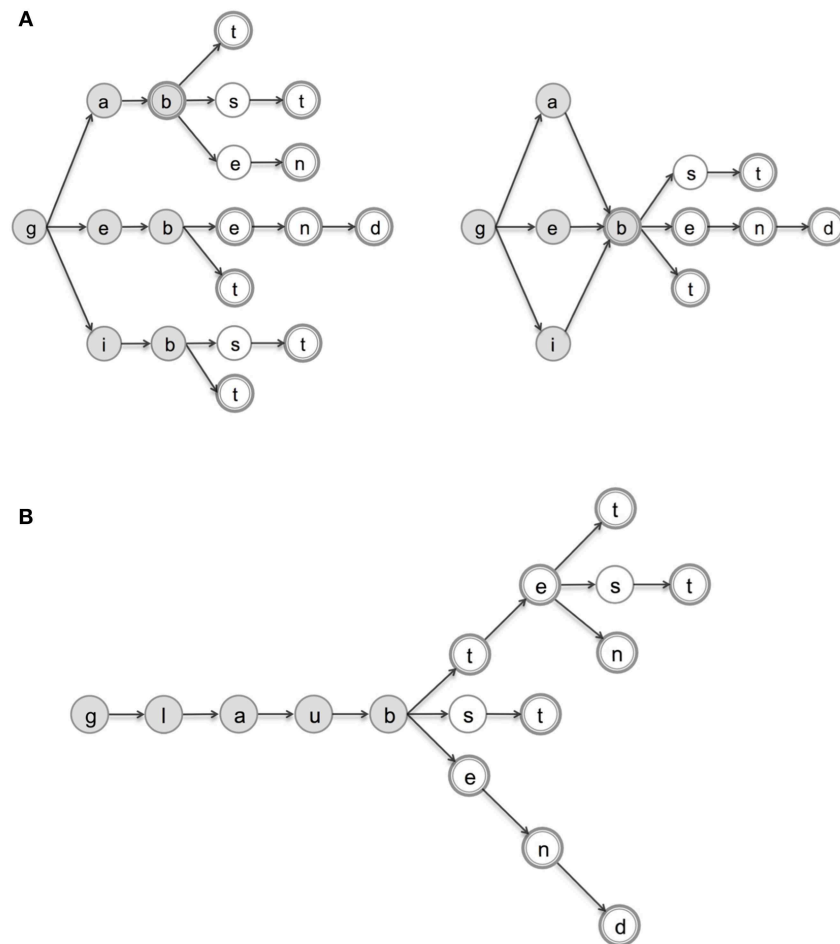
The TSOM architecture of **Figure 1** was used to simulate the acquisition of the verb inflection system of six languages:

Standard Modern Arabic, English, German, Modern Greek, Italian and Spanish. For all languages, we selected 15 forms (14 forms for Arabic) for each of the 50 top frequency paradigms sampled from a reference corpus<sup>5</sup>. For each language, forms were chosen from a fixed set of paradigm cells. To the greatest extent possible, the set of cells was kept comparable across languages<sup>6</sup>. Each input form was transliterated into an ASCII-based sequence of possibly complex symbols preceded by the start-of-word symbol (“#”), and followed by the end-of-word symbol (“\$”). For Modern Standard Arabic forms we used the Buckwalter transliteration rules<sup>7</sup>.

<sup>5</sup>Our data sources are: CELEX (Baayen et al., 1995), for German and English; the Italian Paisà Corpus (Lyding et al., 2014); the European Spanish Subcorpus of the Spanish *TenTen* Corpus ([www.sketchengine.co.uk](http://www.sketchengine.co.uk)); the SUBTLEX-GR corpus (Dimitropoulou et al., 2010) for Modern Greek, and the Penn Arabic Treebank (Maamouri et al., 2004). The full set of word forms, for each language, is available at [http://www.comphyslab.it/redirect/?id=lrec2018\\_data](http://www.comphyslab.it/redirect/?id=lrec2018_data).

<sup>6</sup>For English, German, Modern Greek, Italian and Spanish, the list includes all present and past indicative cells. English, German, Italian and Spanish also include the infinitive, past participle and gerund/present participle cells, which are replaced by the three singular cells of the simple future in Modern Greek. For Standard Modern Arabic, we selected the first, second and third masculine singular and plural cells, and the third feminine singular cell for both the imperfective and perfective.

<sup>7</sup>[www.qamus.org/transliteration.htm](http://www.qamus.org/transliteration.htm).



**FIGURE 2** | Graph-based representations for a few German verb forms of *geben* “give” (A) and *glauben* “believe” (B). Double-circled nodes represent word-final states, i.e., letters ending a word form; shaded nodes represent (possibly allomorphic) stems, according to the segmentation criteria of section 3.2. In (A), we provide a word-tree (left) and a word-graph (right) for the same set of 9 form types of *geben*.

Although forms are input to the map with no information about their internal structure, the dataset was annotated manually, to allow us to correlate variation in the map response after training with variation in the (morphological) structure of training forms. First, for each form, we marked up two uniqueness points: *UPI* and *CUP*. *UPI* was marked at the position in the verb form where the stem is uniquely identified, both relative to *paradigmatically-unrelated* onset-aligned forms in the dataset, and with respect to other possible stem allomorphs *within the same paradigm*. For example, the stem *drunk* is distinguished from the unrelated *doubt* at “r” in second position, but it is distinguished from *drink* or *drank* only when “u” is reached in third position<sup>8</sup>. The marking of *CUP* followed Balling

<sup>8</sup>In fact, Balling and Baayen’s definition of *UPI* is intended to index competition from morphologically unrelated words only (Balling and Baayen, 2008, 2012). However, this is justified by the fact that their database only includes regularly inflected forms, i.e., inflected forms showing no stem allomorphy: in this case, identification of the stem automatically entails identification of the entire

and Baayen in marking the point at which the whole verb form is distinguished from other forms of the same paradigm.

In addition, we based morphological segmentation on a uniform (PREFIX) + STEM + (SUFFIX) template, where the notion of verb stem has the Aronovian, morphomic status of an unpredictable allomorph of the base stem, conveying systematic, but possibly non homogeneous clusters of morpho-lexical features (Aronoff, 1994). Accordingly, formally predictable stems derived from their base stem through a systematic process of stem formation (e.g., English past(*walk*) → *walk-ed*) are segmented into a base and a suffix (*walk-ed*). Inflected forms containing unpredictable stems (e.g., English past\_part(*drink*) → *drunk*, German past\_1S(*geben*) → *gab*, German pres\_2S(*geben*) → *gibst*) are segmented into a stem and a suffix (whenever overtly realized) (e.g., *drunk-*, *gab-*, *gib-st*).

paradigm. Our operational definition of *UPI* represents a natural extension of Balling and Baayen’s criteria to a dataset containing irregularly inflected forms.



Paradigms that undergo unpredictable stem formation processes are classified as *irregular*. Paradigms whose stems are formed transparently and systematically<sup>9</sup> are annotated as *regular*. In Standard Modern Arabic, where verbs appear to cluster into different inflectional classes depending on the vocalic patterns intercalated with the roots, irregular (or weak) verb paradigms have stems that undergo a reduction in the number of root consonants (traditionally referred to as first, second, third weak and doubled roots, depending on the position and number of the radical consonants being dropped) (Marzi et al., 2017). Our segmentation template thus cuts across the traditional regular vs. irregular classification, yielding *ya-ktub-u* “he writes” and *katab-a* “he wrote” (as an example of a regular paradigm), together with *ya-qūl-u* “he says” and *qāl-a* “he said” (as an example of an irregular paradigm). Finally, for those languages (like Modern Greek and Italian) where regular paradigms exhibit unpredictable stem vowel selection (Ralli, 2005, 2006), stem identity/regularity was based on the form obtained by dropping the thematic vowel from the stem (Pirrelli, 2000; Pirrelli and Battista, 2000; Bompolas et al., 2017).

To annotate graded regularity in our data, we define, for each paradigm, the stem-family of a target form as the set of its formally distinct stem-sharing members. For instance, in our English training set, the forms *drink*, *drinks* and *drinking* are each associated with a stem-family of size 2, whereas *drank* and *drunk* have each an empty family. Likewise, the Italian verb forms *vengo* “I come” and *veng-ono* “they come” have each a stem-family of size 1, as do *vien-i* “you come” (2s) and *vien-e* “(s)he comes.” In contrast, *ven-ire* “to come,” *ven-iamo* “we come,” *ven-ite* “you come” (2p), *ven-isti* “you came” (2s), *ven-immo* “we came,” and *ven-iste* “you came” (2p) have a stem-family of size 5. Finally, for each paradigm, we calculate its average stem-family size, and then normalize it by dividing it by the maximum number of possible stem-sharing members in the paradigm. Accordingly, the paradigm regularity for *drink* is  $\frac{2+2+2+0+0}{5} \cdot \frac{1}{4} = \frac{3}{10}$ . The score, which we will refer to in section 4 as *gradient paradigm regularity*, ranges between 0 (minimum value obtained when each paradigm member is formed on a distinct stem) and 1 (maximum value, obtained when a paradigm is fully regular, i.e., when the stem-family of each paradigm member includes all other members of the same paradigm).

We used the same setting of free learning parameters for training TSOMs on all languages. However, to minimize the impact on the map topology of cross-linguistic differences in the training data (for instance, in terms of form length and number of form types: see Table 1)<sup>10</sup>, the number of nodes for each

<sup>9</sup>In stem formation, transparency and systematicity do not necessarily correlate with predictability. Modern Greek provides a good example of transparent and systematic stem formation processes which however are not predictable, as they require a thematic vowel whose selection is based on lexical information (Ralli, 2014; Bompolas et al., 2017).

<sup>10</sup>Table 1 shows that English and (to a lesser extent) German conjugations exhibit identical verb forms (morphological syncretism) in a sizable subset of the 15 paradigm cells we selected. It can be objected that we are imposing the paradigm structure of inflectionally richer languages on inflectionally more impoverished ones, with the effect of spuriously inflating the token distribution of our dataset in languages such as English, where the base form is presented to the TSOM five times as many as *-s* forms are. However, we contend that our training sets

language-specific map was made to vary so as to keep constant the ratio between the map size and the number of nodes required to represent its training set with a word tree. Accordingly, a language-specific map size ranges between  $35 \times 35$  nodes (English) and  $42 \times 42$  nodes (Greek). Due to the combined effect of keeping this ratio constant across languages and preventing the temporal neighborhood radius (see Appendix) from decreasing to zero, maps tend to develop overlapping node chains for word forms sharing the same ending. Ultimately, these constraints on the topological organization of the map avoid data overfitting, as the map cannot possibly build up a dedicated memory traces for each form in the training set, i.e., it cannot memorize the original input data in its entirety (Marzi et al., 2014). For all languages, we stopped training at epoch 100, when all learning parameters reach minimum plasticity (see Appendix). To control for random variability in the map response, for each language we trained and tested the map 5 times on the same data, and averaged the results across all iterations.

## 4. RESULTS

To analyze the results of our simulations, we focused on the way TSOMs process input words, and adjust their processing strategies while learning different inflectional systems.

*Word processing* describes the map’s short-term response to an input word. The response consists in a distributed pattern of node activation and includes three sub-processes: *input recoding*, when a specific winning node (a BMU) is activated by an individual stimulus (a letter); *prediction*, i.e., the map’s on-line expectation for an upcoming input letter, after a time series of input letters is presented on the input layer; and *recall*, which consists in retrieving a series of letters from the map’s response to the series (the corresponding activation pattern). In turn, *word learning* consists in associating systematic, long-term patterns of node activation with input sequences of letters, so that each sequence can be discriminated from other sequences (i.e., it elicits a distinct response from the map), and letters can be retrieved from the pattern in their appropriate order for word recall. Accordingly, we can define the time of acquisition of a word as

are indeed comparable cross-linguistically, and can mirror realistic developmental conditions. The paradigmatic space of a language is not defined by the amount of morphological contrast conveyed by its inflected forms, but by the set of morphosyntactic relations (e.g., subject-verb agreement) holding between word forms in context. Children acquire inflected forms by binding them to larger contexts (e.g., *she’s walking*, *it rains*, etc., Wilson, 2003; Pine et al., 2008), and by abstracting away from recurrent combinations of number, person, gender, case, tense and aspect features in context. If a specific inflected form is seen in different such combinations (e.g., *I walk*, *you walk*, *we walk*, *they walk*), the child is repeatedly exposed to an invariant form, whose token frequency will correspondingly increase relative to other paradigmatically-related forms (e.g., *walks* and *walking*). This is confirmed by developmental evidence showing that extensive syncretism has perceivable effects on the child’s intake of the amount and distribution of morphological contrast exhibited by a language inflection (Legate and Yang, 2007; Pine et al., 2008; Xanthos et al., 2011; Krajewski et al., 2012). Thus, although we are deliberately partialing out token frequency effects (which appear to show complex interaction with word category, lexico-semantic class, modality and age of acquisition: see Bornstein et al., 2004; Goodman et al., 2008), our data enable us to focus on non trivial type-driven aspects of dynamic paradigm self-organization.

the learning epoch when the map is able to consistently recall the word correctly from its activation pattern, while making no mistakes at later epochs. It should be emphasized that, from this perspective, learning simply consists in developing long-term processing patterns from repeated, short-term successful processing responses. We will return to this mutual implication between short-term processing and long-term learning in the concluding section of this paper.

Accuracy of *recoding* measures the ability of a *TSOM* to correctly map an input word form onto a chain of *BMUs*. When presenting a *TSOM* with a time-series of symbols making up an input word, the word form is recoded correctly if all *BMUs* are associated with the correct input symbols in the appropriate order (see Equation 1 in **Appendix**). Accuracy of *recall* measures the ability of a *TSOM* to correctly retrieve a word form from its memory trace (or Integrated Activation Pattern, see **Appendix**). This is done by iteratively spreading node activation from the start-of-word node (“#”) through the nodes making up the temporal chain of an input word. At each time step, the *TSOM* outputs the symbol associated with the currently most highly-activated node. The step is repeated until the node associated with the end-of-word symbol (“\$”) is output (see Equations 19–21 in **Appendix**).

By measuring the map’s *prediction* rate, we assess the ability of a trained map to predict an incrementally presented input word. Prediction scores across input words are calculated by symbol position. The prediction score of a correctly predicted symbol is obtained by increasing the prediction score of its immediately preceding symbol by 1-point. Wrongly predicted symbols are given a 0-point score (see Equation 18 in **Appendix**). For each input word, the more symbols are predicted, the higher the prediction score assigned to the word. High prediction scores thus reflect strong expectations over upcoming input symbols, and measure the relation between successful serial word processing and accurate positional encoding of symbols in a time series.

Accuracy scores for recoding and recall are given in **Table 1**. The performance of each language-specific map is evaluated by averaging scores across five iterations of the learning experiment for each inflection system. Performance is consistently good for all the languages in our experiments, especially when we focus on the accuracy of recall, considering the difficulty of the task. This shows that the algorithm is adaptive enough to be able to fine tune its time-sensitive representations to the orthotactic and morphotactic redundancies of each system, irrespective of the specific position a system takes along the isolating-inflecting continuum.

Some interesting differences are observed when we consider the learning pace of the maps for the different languages. **Figure 3A** shows the boxplot distribution of per-word learning epochs for the 6 languages. In particular, Arabic per-word learning epochs are significantly later than those of all other languages ( $p < 0.001$ ), with English per-word learning epochs being significantly earlier ( $p < 0.01$ ). In **Figure 3B** we plotted, for each language, its paradigm *learning span*. The span measures the number of epochs taken by a map to learn an entire paradigm after the first member of the paradigm is learned.

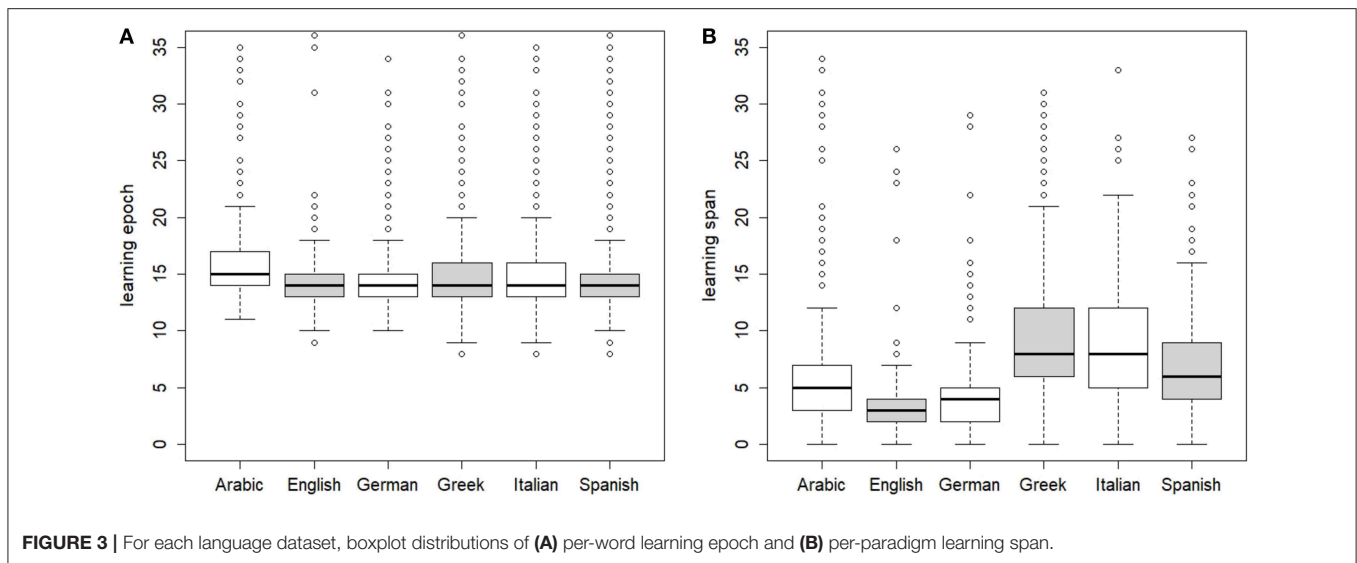
The span thus quantifies the average inferential ability of a map learning an inflection system, and, indirectly, the learnability of the system. The ranking order of the learning span for the languages of our experiments nicely mirrors the relative complexity of the inflectional processes in the six languages, according to Bittner et al. (2003). On the one hand, the learning span for the English verb set is significantly smaller than the learning span of all other languages ( $p < 0.01$  compared with German, and  $p < 0.001$  compared with all other languages). On the other hand, the learning span for the Greek verb set is comparatively larger than the span of the remaining languages ( $p < 0.001$ ), followed by the Italian set (which is not significantly different from the Greek one), and the Spanish one. In fact, Greek, Italian and Spanish present, unlike English and German, a verb system with more conjugation classes. The inferential process of filling empty cells from one attested form of the same paradigm thus requires preliminary identification of the appropriate conjugation class, with its set of inflectional endings<sup>11</sup>. Nonetheless, the comparatively small range of variation (between 3 and 8 for median values) that these languages exhibit in their learning span lends support to Ackerman and Malouf’s conjecture (Ackerman and Malouf, 2013) that the inferential complexity of inflectional system must oscillate within tight entropic bounds.

Based on the results reported in this section, it appears that *TSOMs* are capable of learning the underlying syntagmatic structure of inflection (consisting of serialized sublexical units like prefixes, stems and suffixes), and the inferential patterns necessary for generalizing this structure. Nonetheless, this is only partially satisfactory for our present concerns. We would like to know not only that a particular inflection system can be learned, but also how it can be learned, what is actually being learned, and how hard it is for a *TSOM* to learn the inflection system of a language compared with that of another language. To reach this level of understanding, in the following sections we report statistical analyses of the performance of *TSOMs* in the prediction task and investigate their learning dynamic by using the R software (R Core Team, 2014). Our statistical models will provide a careful, quantitative interpretation of what the map does, and will enable us to suggest a non impressionistic categorization of the time-bound representations hidden in the map’s topological self-organization, and match up these categories with familiar linguistic notions.

## 5. DATA ANALYSIS AND INTERPRETATION

The internal structure of a *TSOM* is not easy to examine, but there are ways to correlate the structure and distribution of the training data with the functional behavior of the map (e.g., its ability to predict what is coming next at a certain point in time in the input based on what was input until that point). In this section, we first consider categorical features of the training data: namely the language being input and its inflectional syntagmatics, by

<sup>11</sup>This is not needed in Standard Modern Arabic, whose learning span is smaller than in Greek, Italian and Spanish (but larger than in English and German), as Arabic class information is, in most cases, already conveyed by the verb stem.



looking at the way sublexical constituents are annotated, and inflected forms are classified as regular or irregular (section 5.1). The idea is to explore the language-specific sensitivity that the map develops while being trained on a given language and its set of inflectional processes. Secondly, we move on to take a *Word-and-Paradigm* perspective on the same material, with a view to matching up the behavior of the map with a more graded classification of morphological regularity, and with more fundamental, cognitive effects of family size on the map's behavior (section 5.2.1). From both perspectives, we examine processing effects as well as learning effects.

## 5.1. Cross-Linguistic and Regularity Effects

### 5.1.1. Processing Effects

The leftmost panel of **Figure 4** plots the linear rate of letter-by-letter *prediction* when a trained *TSOM* is processing regularly (cyan line) or irregularly inflected forms (red line), as a function of letter position (distance) to the Morpheme Boundary (*MB*) between stem and suffix, where  $MB = 0$  corresponds to the first element of the suffix. The prediction rate counts how many consecutive letters are predicted by the map during word processing. The plot is a linear regression model of the letter prediction rate, using as predictors the letter position and the dichotomous regular vs. irregular classification (see section 3.2). Verb forms from the 6 languages are considered cumulatively in the model.

Positive slopes indicate, unsurprisingly, that the map gets more and more accurate in anticipating an upcoming symbol as more of the word input is consumed. As has already been shown (see Marzi et al., 2018 for preliminary results on the same set of the 6 languages), *TSOMs* appear to be significantly more accurate in predicting forms belonging to regular paradigms than to irregular ones, but no apparent interaction is observed between regularity and distance to the stem-suffix boundary. To a first approximation, the evidence seems to show that inflectional regularity consistently facilitates word processing, independently

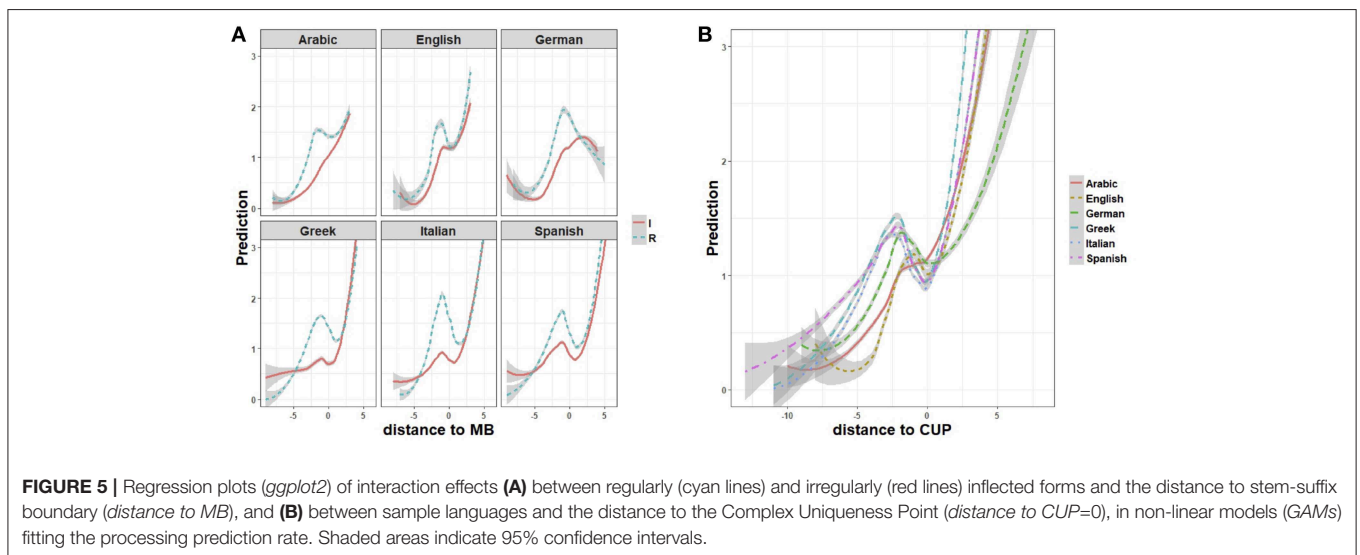
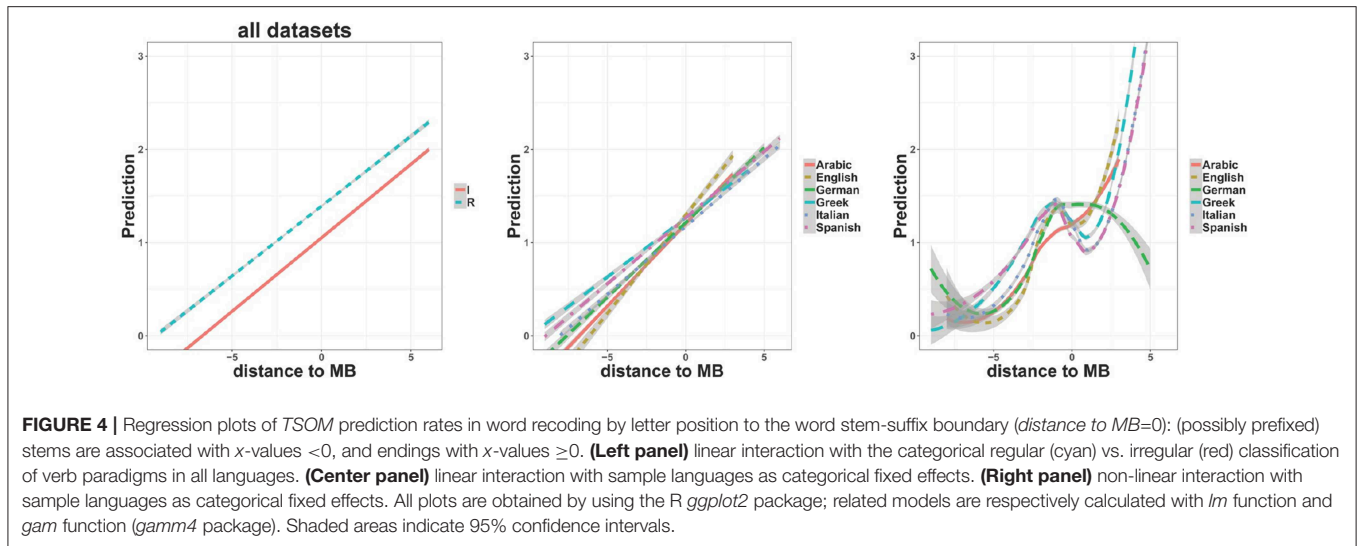
of how inflection is marked cross-linguistically. In fact, the center panel of **Figure 4** shows that the 6 languages of our sample present slightly different prediction slopes. Arabic and English exhibit a steeper prediction slope compared with the slope of German, Greek, Italian, and Spanish.

A more interesting picture<sup>12</sup> emerges when we move from a linear regression model to a non-linear regression model of the same data. The rightmost panel of **Figure 4** shows how prediction rates vary across languages when the time course of word prediction is modeled by a Generalized Additive Model (*GAM*). *GAMs*, and related plots (obtained with the *ggplot* function), eliminate spurious linear leveling, and allow changes over serial processing to be modeled in a fine-grained way<sup>13</sup>. The ascending path for increasing values of *distance to MB* basically confirms the linear trend observed in the center panel of **Figure 4**. But the non-linear interpolation highlights an important discontinuity at the stem-suffix boundary (for  $distance\ to\ MB=0$ ). In English, Greek, Italian and Spanish, the stem-suffix boundary marks a sharp drop in prediction rate, supporting the intuition that when the final letter of a stem is recognized, the map has to revise its expectations for an upcoming symbol. We interpret this as an effect of structural discontinuity between the stem and the following suffix, which is deeper in regularly inflected forms than it is in irregularly inflected forms for all languages in our sample (**Figure 5A**).

The same mechanism accounts for the fact that Greek, Italian and Spanish show a deeper prediction drop at the stem-suffix boundary than English does (**Figure 5A**). Greek, Italian and Spanish inflection markers are, in fact, more numerous and formally more contrastive than inflection markers are in English.

<sup>12</sup>The non-linear model is statistically more robust, as confirmed by an ANOVA Chi-squared test:  $p$ -value < 0.001.

<sup>13</sup>It should be noted that all word forms are centered on the 0-value, i.e., at the stem-suffix boundary. This makes the interval representing the onset of words less confident, due to the possible presence of an inflectional prefix and to differences in length between the stems.



The steeper ascending trend in the prediction of English forms has to do with the comparative simplicity of the English system, and the narrower range of possible continuations of the verb stem in regularly as well as irregularly inflected forms. The ascending prediction trend of the Arabic verb is more linear, particularly in irregular inflection (**Figure 5A**). In fact, the Arabic plot shows a less prominent drop at the stem-suffix boundary (for  $distance\ to\ MB=0$ ), which disappears altogether in irregulars, suggesting a greater structural continuity between the stem and the suffix. This is the combined effect of two factors: stem allomorphy in the perfective forms of irregular verbs, and prefixation of person and number features in the imperfective forms, both concur to reduce processing uncertainty at the stem-suffix boundary<sup>14</sup>.

<sup>14</sup>In Arabic imperfective forms (both regular and irregular), second and third person values are conveyed by the prefixes *ta-* and *ya-* respectively, and number is marked by the suffixes *-u* for the singular, and *-uwna* for the plural. In the first person, person and number are syncretically realized by two different prefixes followed by an identical suffix (*-u*). Hence, the amount of residual processing

Conversely, German exhibits only descending slopes after the stem-suffix boundary (for  $distance\ to\ MB=0$ ). This is an effect of the full formal nesting of shorter endings within longer, onset aligned endings (for instance *e-*, *-en*, *-end*: see **Figure 2** above), which makes it hard to predict upcoming symbols when contextual and frequency information is missing. As a result, prediction increases only at the point where the form is fully discriminated from all other forms (i.e., for  $distance\ to\ CUP=0$ ), as shown by the ascending slope for  $CUP>0$  in **Figure 5B**.

All in all, closer inspection of prediction curves for each language confirms that regular stems are structurally easier

uncertainty at the stem-suffix boundary is drastically reduced to a binary choice between *-u* and *-uwna* for the second person and the third person only. In perfective forms, regular verbs select one stem followed by different endings for different combinations of number, person and gender features, and irregular verbs select a specific stem allomorph for different combinations of gender and number values with the 3rd person. This further reduces processing uncertainty in the perfective forms of irregular verbs.

to process than irregular stems. Nonetheless, the processing advantage accumulated across regular stems is offset by suffix selection, which requires more effort in adjusting probabilistic expectations for regular forms than for irregular ones. This general, cross-linguistic effect can be interpreted in terms of “surprisal” as a source of processing difficulty (Levy, 2008), caused by the incremental reallocation of the map’s expectation for upcoming symbols. In irregular paradigms, the initial processing disadvantage is counterbalanced by a smaller effort (i.e., a smaller decrease in certainty) in processing the transition from a stem to the following suffix. As we will see in more detail in section 5.2.1, this processing facilitation is a consequence of the fact that irregular stems exhibit a formal contrast that regularly inflected forms typically realize with suffixal material. Ultimately, this early contrast provides an early point of lexical discrimination.

### 5.1.2. Learning Effects

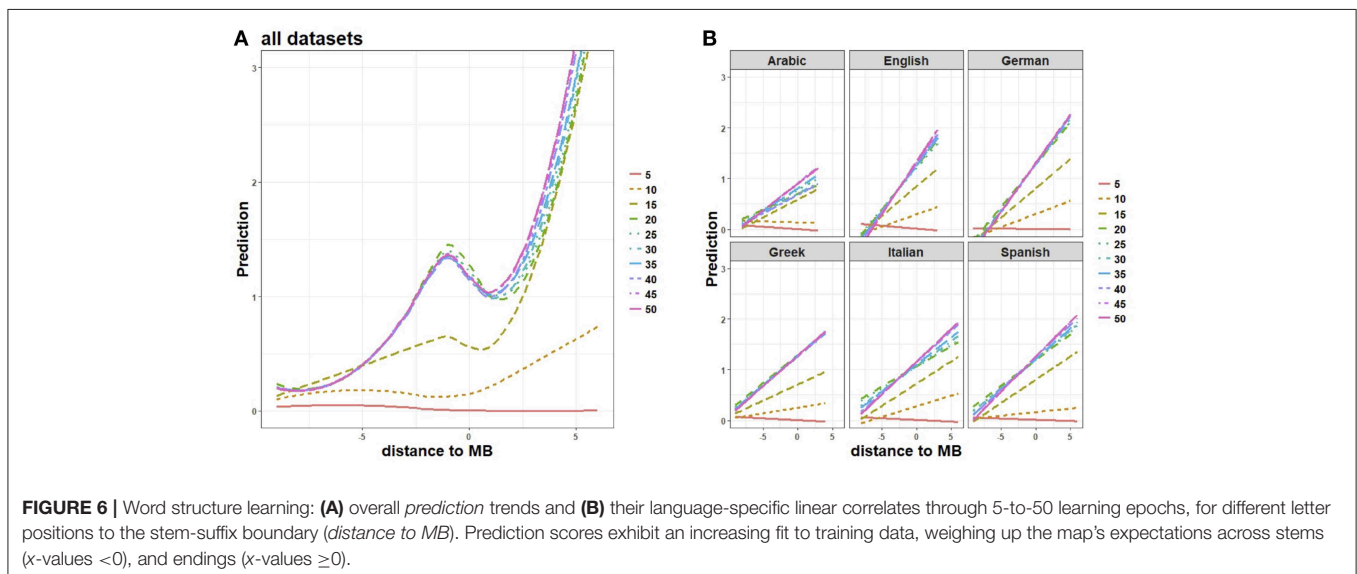
The *TSOM* learning algorithm has a bias to developing specialized chains of processing nodes (*BMUs*), which get more and more sensitive to structural discontinuity in the input data. We can monitor chain specialization by observing how prediction accuracy of online word processing evolves through learning. As training progresses, we expect prediction trends to increasingly reflect the underlying morphological structure of inflected forms. Due to chain specialization, a *TSOM* becomes more and more familiar with recurrent stems and endings. Its ability to predict upcoming symbols increases accordingly, and prediction rates become higher across input words as the map learns to assign maximally entrenched node chains to shared input sub-strings.

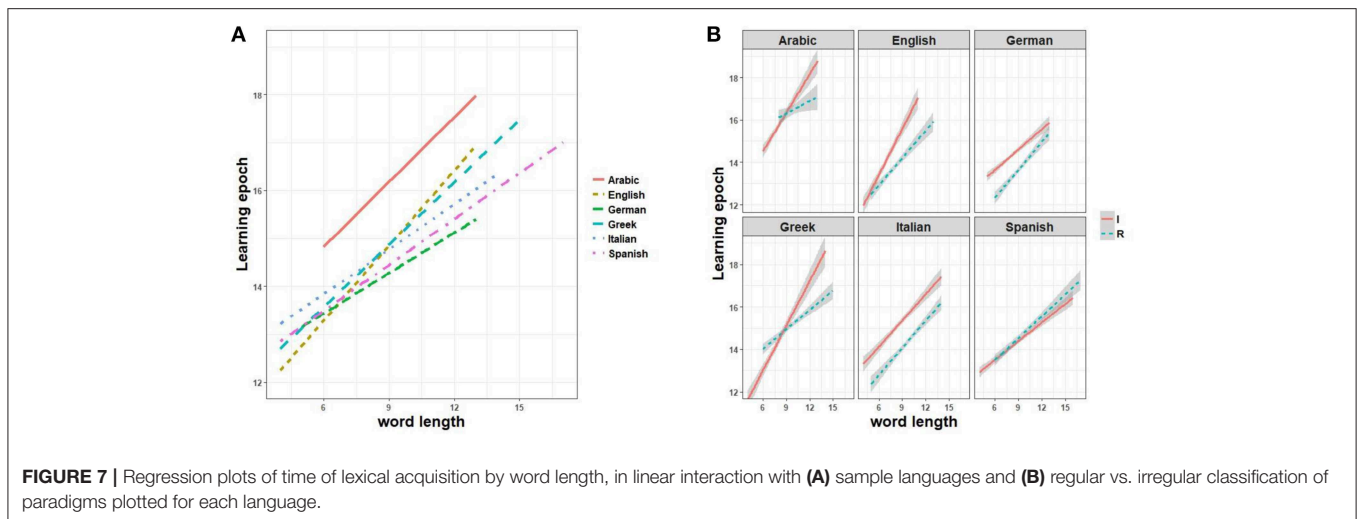
**Figure 6A** plots variation of word prediction rates at different learning epochs (going from epoch 5 to epoch 50 with a 5-epoch step), averaged across all languages in our sample. The prediction rate of inflectional endings starts increasing at epoch 10 (growing slope for  $x$ -values  $\geq 0$ ), when the *TSOM* is not yet able to accurately predict stems ( $x$ -values  $< 0$ ). This is the combined effect

that input frequency and length have on memory. Endings are, on average, more frequent and shorter than stems, and are thus learned more quickly. Processing sensitivity to stems becomes more discriminative only at later epochs, as shown by the local maximum at *distance to MB* =  $-1$  at epoch 15. Finally, when stems are predicted accurately (starting from learning epoch 20), the *TSOM* learns that some specific endings follow only some stems, and can adjust its prediction bias accordingly. This makes prediction values for endings (i.e., for  $x$ -values  $\geq 0$ ) increasingly higher at later epochs.

**Figure 6B** shows the linear growth of processing prediction for each language at different epochs (from epoch 5 to epoch 50). The trend shown by our sample of languages is consistent with the intuition that processing prediction and processing ease increase with learning as a function of memory entrenchment of word representations: the more entrenched word representations are, the more easily they are predicted during processing. This is illustrated by the word-graph in **Figure 2A** (right), which represents the node chains activated by a few forms of German *geben* “give” at an early learning epoch. At this stage, partially overlapping stem allomorphs (*gib-*, *geb-*, and *gab-*) activate superpositional node chains. This indicates that the Markovian order of the map cannot discriminate between *b* preceded by the letter *a*, and the same *b* preceded by the letter *i* or the letter *e*. During training, discriminative specialization results in the word graph being transformed into the tree-like structure of nodes on the left hand side of **Figure 2A**. Note that a word tree has fewer branching points than the corresponding word graph. This means that when the map arrives at a node with fewer branching points, uncertainty about the upcoming symbol decreases, and processing prediction increases.

Learning, like prediction, is dependent on word length. However, whereas short words are comparatively more difficult to predict, they are learned more easily. Epochs of word learning as a function of word length are compared for each language in **Figure 7A**. Unsurprisingly, short words are learned at early epochs and longer words are learned at later epochs irrespective





of language. Nonetheless, the time lag can vary depending on the specific inflection system. For example, English is shown to exhibit a steeper learning slope, i.e., a greater difficulty in learning inflected forms of increasing length, and Arabic shows both a steeper slope and a higher intercept.

When we look at each language in more detail, we observe an interesting interaction between the impact of word length on learning epochs and inflectional regularity. **Figure 7B** plots word learning epochs as a function of word length and the regular vs. irregular dichotomous classification for each language. With the only exception of Spanish (where differences do not reach statistical significance,  $p > 0.1$ ), all languages exhibit different learning paces for regulars vs. irregulars, with the former enjoying advantages over the latter. The pace of learning interacts with word length in Arabic, Greek and English, where long regulars tend to be learned progressively earlier than long irregulars. This contrasts with German, where the trend is reversed, and Italian, which shows no significantly different interaction with increasing length. Note, finally, that when Arabic and Greek irregular forms happen to be significantly shorter than regular forms, the former are learned a few epochs earlier than the latter, reversing the advantage enjoyed by regulars when length is controlled.

## 5.2. Stem-Family Effects

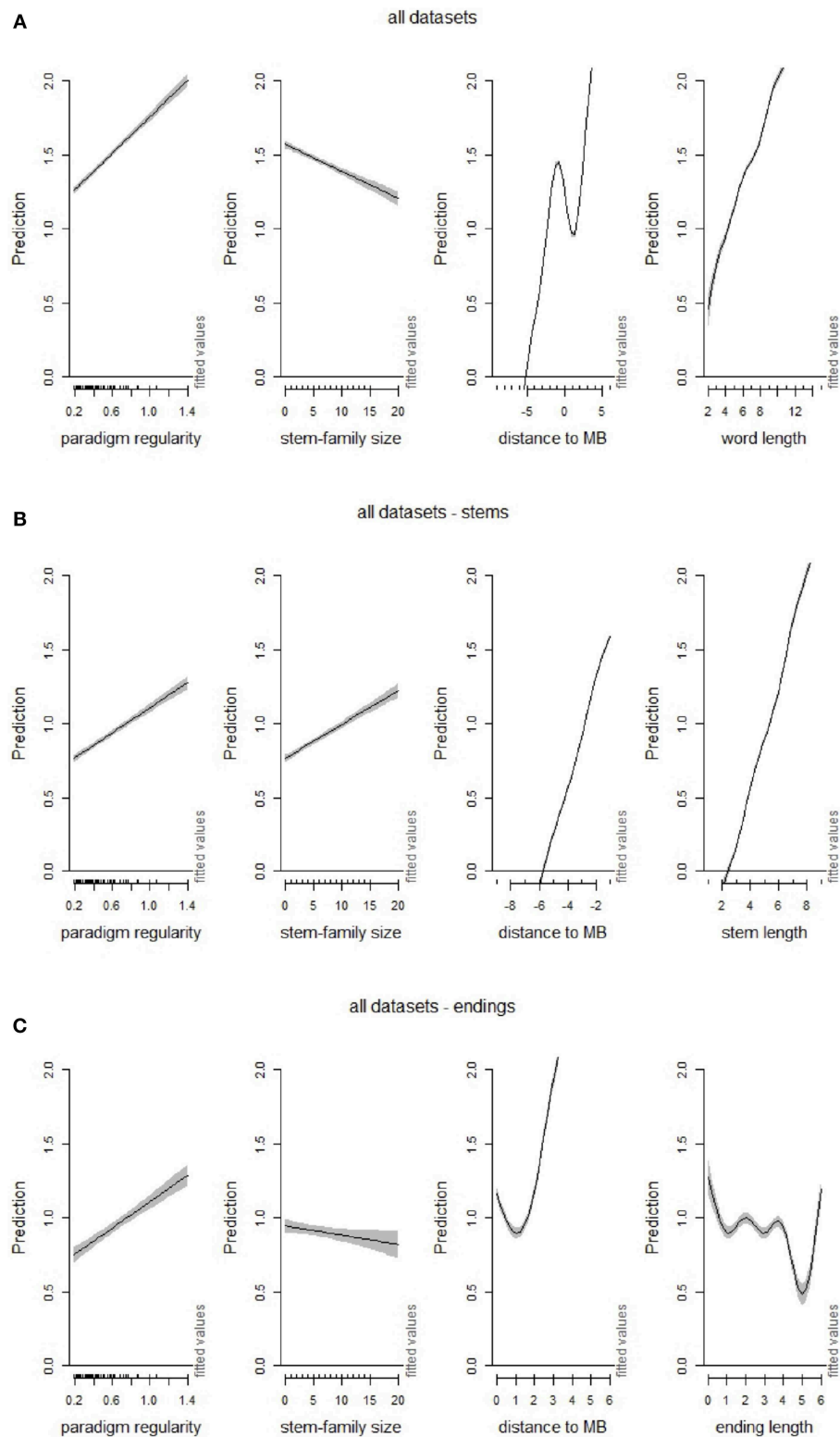
### 5.2.1. Processing Effects

The evidence reported in section 5.1 throws into sharp relief a theoretically interesting connection between the structural notions of morphological regularity and transparency, on the one hand, and word processing (un)certainly, on the other hand. *Word-and-Paradigm* approaches to inflection have questioned the primacy of sublexical constituent structure as a key to understanding speaker's word knowledge. In contrast, they support a view of inflectional competence grounded in a complex network of fully-inflected forms organized in word families of lexically-related members (paradigms) and inflectionally-related members (conjugation classes). Accordingly, morphological regularity is the expression of the formal and lexical support that each inflected form receives from its family members: regularly

inflected forms tend to get the largest possible amount of formal support from their paradigmatic companions in terms of redundant stem forms (e.g., *walk-s*, *walk-ed*, *walk-ing*), and from their conjugation members in terms of redundant inflectional markers (e.g., *walk-ing*, *see-ing*, *speak-ing*). In this section, we move away from a dichotomous notion of paradigm regularity to a graded one, based on statistical patterns of lexical co-activation and competition. These patterns are better understood, in line with psycholinguistic evidence of human processing behavior, as word family effects.

In section 3.2, we introduced two ways of assessing paradigm regularity as a gradient: one is based on forms, and the other is based on paradigms. Given a target form, we can calculate the number of stem-sharing members of the form's paradigm, or *stem-family size*. For each verb paradigm, the (normalized) average stem-family size of the paradigm gives a graded score of *paradigm regularity*. The two notions are clearly correlated (in our data,  $r = 0.79$ ,  $p < 0.001$ ). In a fully regular paradigm, all forms have the same stem-family size. Conversely, suppletive forms in irregular paradigms tend to be isolated. Nonetheless, the two measures account for different effects on word processing. Intuitively, our paradigm regularity score is the same for all members of a paradigm, irrespective of how stem-families are distributed within the paradigm. However, a form supported by a larger stem-family has a different processing cost from a form with an empty stem-family in the same paradigm. Thus, while paradigm regularity can account for different processing costs between different paradigms, the stem-family size explains the variation, in processing costs, between paradigmatically-related forms.

In our simulations, paradigm regularity has a facilitative effect on stem processing. An identical stem, transparently shared by all paradigmatically-related forms, represents a perceptually salient, deeply entrenched formal core of the paradigm. This core is highly familiar, and is accordingly processed more easily. Conversely, degrees of alternation in stem formation for irregular paradigms tend to slow down the processing of the corresponding stems. The more stem allomorphs a paradigm presents, the larger the effort taken to process them, as more



**FIGURE 8** | Effects of (graded) paradigm regularity interacting with stem-family size, distance to stem-suffix boundary (*MB*) and (word, stem and suffix) length in GAMs modeling *TSOM* prediction rates in: **(A)** word processing, **(B)** stem processing, and **(C)** suffix processing. The specified predictors are taken in interaction with paradigm regularity as summed effects (*itsadug* package, *plot\_smooth* function).

points of processing uncertainty are encountered along the way. This is again shown pictorially in **Figure 2A**, where the shaded nodes of the irregular verb *geben*, corresponding to its stem allomorphs, are arranged through branching paths, in contrast with the non-branching path associated with the regular base stem of *glauben* (**Figure 2B**).

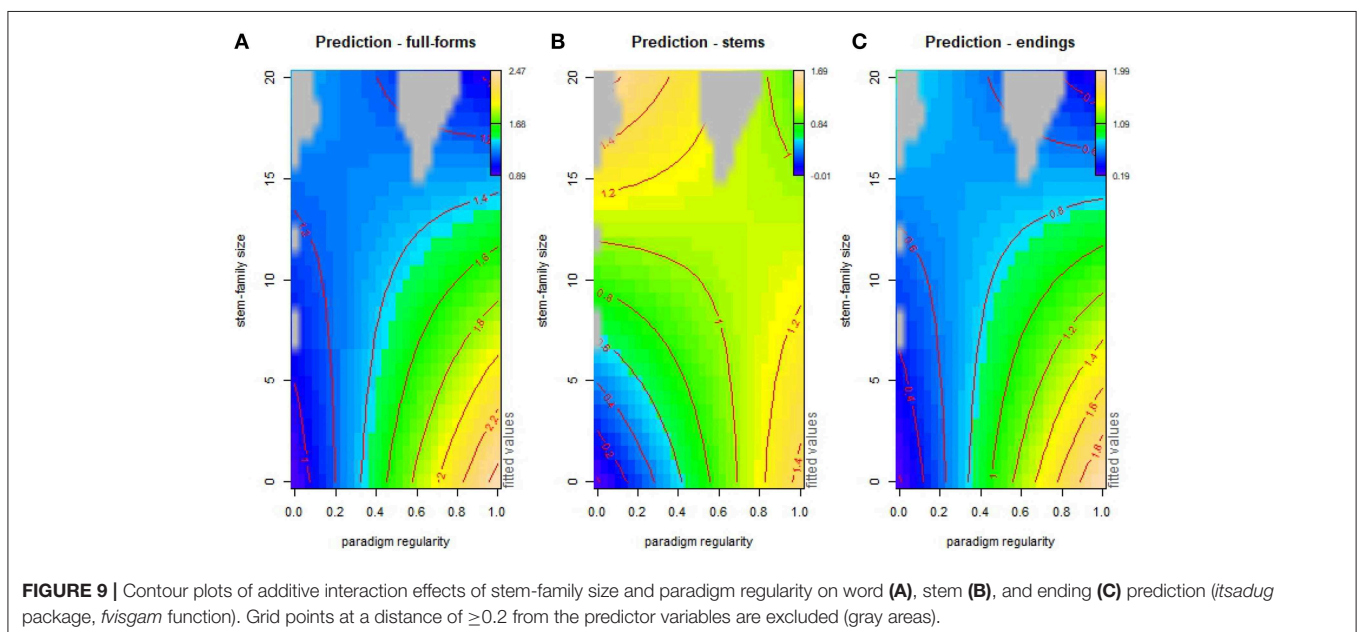
Arabic inflection provides a somewhat exemplary illustration of this dynamic. In Arabic, all verb forms present vowel alternating stems, irrespective of their belonging to regular or irregular paradigms. Nonetheless, irregulars are predicted less easily than regulars (**Figure 5**), due to the greater formal diversity that irregular stem allomorphs exhibit. Compare, for example, the regular forms *katab-tu/katab-ta/katab-a* “I wrote”/“you (singular masculine) wrote”/“he wrote” with the second weak forms *qul-tu/qul-ta/qāl-a* “I said”/“you (singular masculine) said”/“he said”).

The facilitation in processing stems of regularly inflected forms is however counterbalanced by the processing uncertainty incurred at the stem-suffix boundary. In fact, the processing advantage that more regularly inflected forms enjoy across stems is offset by a deeper drop in the prediction rate for an upcoming suffix (**Figure 5**). This is confirmed when we partial out the interacting influence of paradigm regularity, stem-family size, word length and distance to stem-suffix boundary (*MB*) in a generalized additive model of prediction rates (**Figure 8**). Despite the strong positive correlation of paradigm regularity and stem-family size, when these predictors interact, the contributions that they make to the processing of full words go in different directions. When we model the interacting effect of each predictor for stem and ending independently, the facilitation effect of family size on stem processing (**Figure 8B**, second panel from the left) is reversed into a negative effect on endings (**Figure 8C**, second panel from the left).

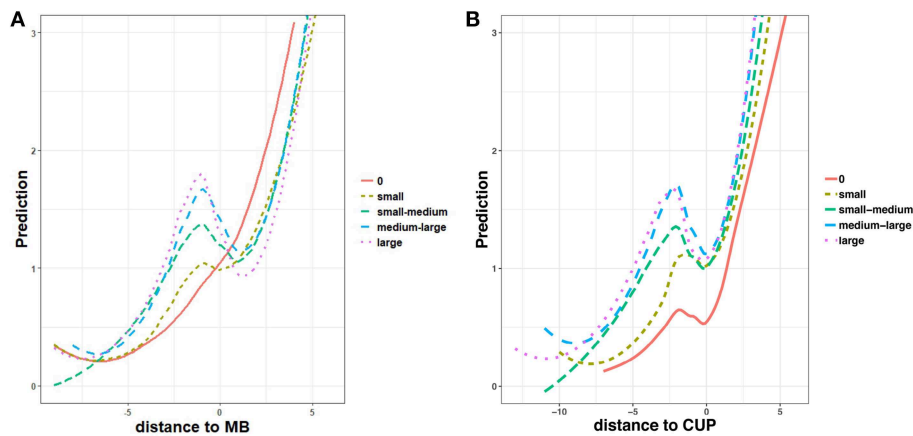
The interaction of paradigm regularity and stem-family size on word processing is illustrated in more detail through the use of

the perspective or contour plots of **Figure 9**, showing the additive interacting effects of paradigm regularity and stem-family size as predictors for processing prediction of full-forms, stems and suffixes. In the plots, contour lines represent prediction values: brown-yellow shades mark areas where items are processed more easily, and blue shades mark areas where items are processed less easily. **Figure 9A** shows that forms in more irregular paradigms are always processed with greater difficulty. However, starting from level 0.4 of paradigm regularity, forms are processed with increasing difficulty if they have large stem-families. Conversely, **Figure 9B** shows that stems appear to be favored by increasing stem-family size, with a mild reversal of this effect only for items in fully regular paradigms (level > 0.8 of paradigm regularity). We can explain these effects by observing that more regular stems are typically followed by a wider range of inflectional endings than highly irregular stems are, and that the number of different endings is proportional to the size of the stem-family. Hence, the larger the stem-family, the higher the processing “surprisal” for upcoming endings (Ferro et al., 2018), as shown in **Figure 9C**.

The consequences of these pervasive stem-family size effects on the perception of morphological structure during word processing are modeled in **Figure 10A**, where non-linear prediction rates are plotted as a function of *distance to MB* for classes of inflected forms with increasing stem-family size (ranging from empty to large). Here, processing curves are aligned on the structural joint between stem and suffix (*distance to MB* = 0), confirming that stem predictability increases with the stem-family size, together with the perception of a structural discontinuity at the stem-suffix boundary. In contrast, forms with little or no support from stem-sharing items show lower prediction rates for stems, and higher prediction rates for suffixes. Finally, smaller or no prediction drops at *distance to MB* = 0 suggest that an inflected form with an empty-to-small stem-family size is processed and perceived as mono-morphemic.







**FIGURE 10** | Regression plots of interaction effects between zero, small, small-medium, medium-large and large stem-family sizes and (A) distance to stem-suffix boundary (*MB*), and (B) distance to *CUP*, in non-linear models (GAMs) fitting processing prediction rates.

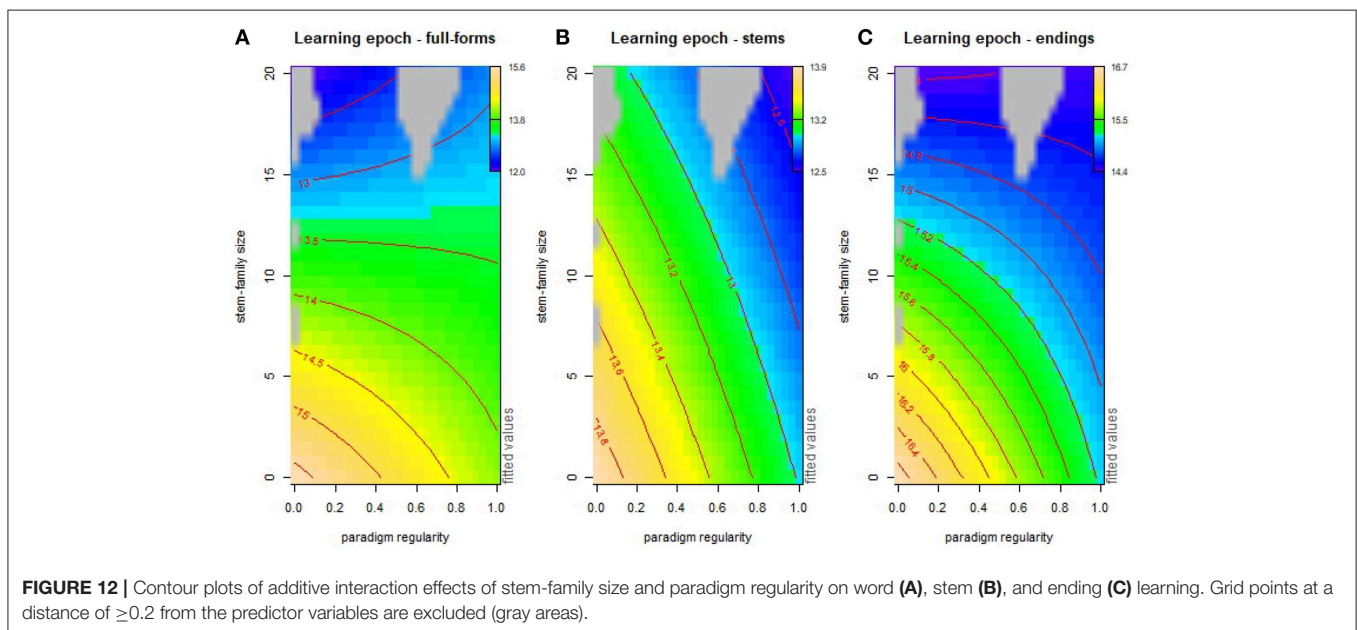
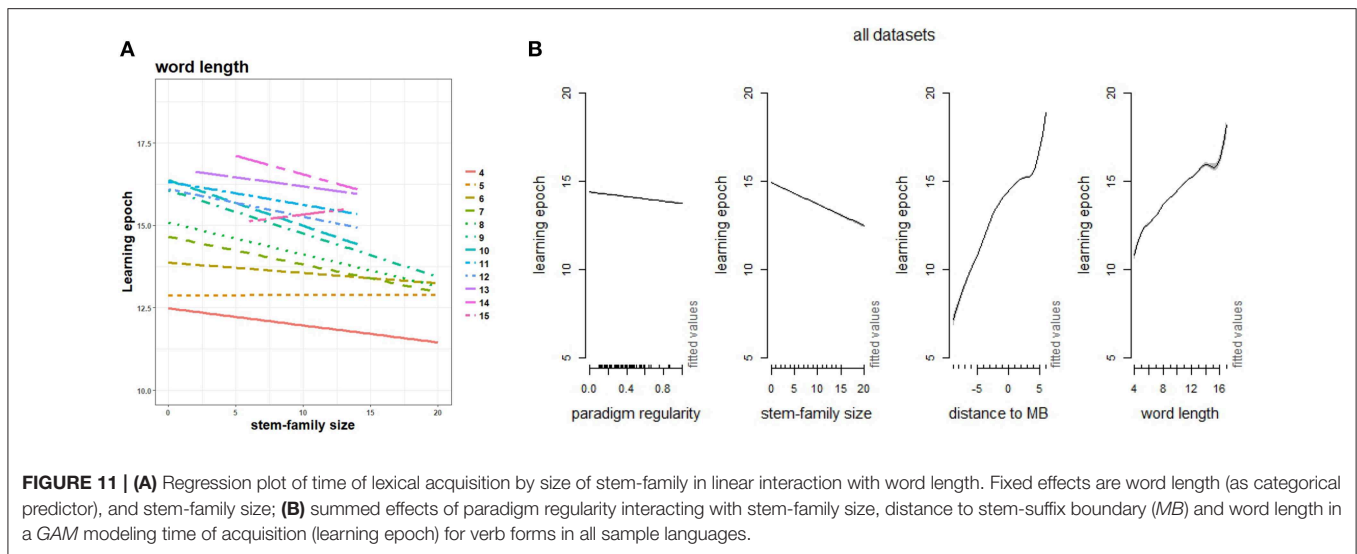
Another processing effect worth emphasizing in this connection is how easily an inflected form is discriminated from its paradigm members. Discriminability is somewhat related to the predictability of an input sequence. However, whereas predictability is related to the entrenchment of a recurrent sequence in our mental lexicon, discriminability is a function of how confusable an input sequence is with other similar sequences. In fact, full form discrimination requires identification of the form's Complex Uniqueness Point (or *CUP*). Intuitively, the earlier the *CUP* of an inflected form, the more quickly the form is singled out and accessed in serial recognition. Consider two forms like *thought* and *walked*. Unlike *walked*, whose paradigmatic *CUP* is positioned at the beginning of the inflectional ending *-ed*, *thought* is discriminated from all other forms of THINK when *-o* is input. Thus, *thought* is discriminated at an earlier point in time than *walked* is, because of the shorter distance between the form onset and its *CUP* (2 letters, vs. 4 letters for *walked*) and the longer tail of predicted symbols after *CUP* (4 letters, vs. only 1 letter predicted for *walked*). This tendency is confirmed by our analysis of *TSOM* data. Irregulars are, on average, easier to discriminate than regularly inflected items. In **Figure 10B**, we plot non-linear prediction rates as a function of *distance to CUP*, for the same five classes of stem-family size used in **Figure 10A**. For all forms, prediction lines are centered on *CUP* (i.e., for *distance to CUP*=0). Forms with empty stem families show a shorter time lag between their onset and their *CUP*. In addition, they have a longer tail of predicted symbols after *CUP*. As we move from isolated forms to forms with increasing stem-family size, the time interval between onset and *CUP* increases, and the tail of symbols after *CUP* shortens. Family size is a significant predictor of this trend, even when the length of inflected forms is added in interaction to the GAM.

To sum up, stem-family size appears to influence the rate at which *TSOMs* process verb forms, confirming that paradigm regularity facilitates processing. The stems of inflected forms with a large stem-family size are easier to predict, but this facilitation is compensated at the stem-suffix boundary, where a significant reduction in processing prediction can be

interpreted as a functional correlate of structural discontinuity. Conversely, the stems of inflected items with empty-to-small stem-family size are more difficult to predict, and take more processing effort, but show a considerably smaller drop in prediction at *MB*, which suggests that they are processed more holistically. In addition, irregulars are discriminated more quickly from their paradigmatic companions than regularly inflected forms are. It is noteworthy that this effect is not an artifact of irregulars being, on average, shorter than regulars, but reflects a genuine morphological pattern: irregulars tend to mark, through stem allomorphy, information that regularly inflected forms mark with their suffixes. Ultimately, irregularly inflected forms are easier to discriminate because they are part of a more contrastive network of formal oppositions.

### 5.2.2. Learning Effects

From a learning perspective, being part of a larger stem-family is an advantage. Intuitively, the size of a stem-family defines the number of distinct affixes the stem can combine with: the larger the stem-family size, the greater the potential of the stem for filling in more paradigm cells. Hence, a stem-family defines the analogical space where a verb establishes its connections with other paradigms. Other things being equal (e.g., length, cumulative frequency, and wordlikeness), a verb form with a large stem-family is learned more easily than an isolated form, as shown in **Figure 11A**, where we plot a largely predominant facilitation effect of stem-family size on word learning across the entire length range. A regular paradigm is a classical example of such a stem-family, where all family members share the same stem followed by a systematic pool of inflectional endings (which are, in turn, shared by other paradigms). Being associated with a large range of differently inflected forms makes it possible for a *TSOM* to consolidate intra-paradigmatic formal redundancies, and infer missing forms more accurately. Conversely, more discriminated irregular forms are acquired more slowly for exactly the same reason that they are



accessed more holistically and effectively: because they happen to be isolated.

In **Figure 11B**, we assess the interacting influence of paradigm regularity, stem-family size, word length and *distance to MB* in a generalized additive model of the pace of word acquisition. In this model, acquisition is jointly facilitated by both factors, unlike what we observed for processing prediction (**Figure 8A**) where paradigm regularity and stem-family size have contrasting effects. The contour plots of **Figure 12** show the interaction of these factors in more detail. Stem-family is shown to have a main facilitation effect on word learning, which is stronger within weakly regular paradigms. This suggests that even when a verb is associated with many unpredictable stems, the distribution of these stems in their families affects

learning. Regular paradigms are facilitative too, but their influence is comparatively less prominent. It is noteworthy that this general word-level effect is differently apportioned when we focus on the pace of stem learning: stems are learned significantly more quickly within regular paradigms, whereas the size of their stem-family has only a marginal (positive) effect in the process. Finally, endings are learned more quickly in regular paradigms, but the facilitative influence of the size of the stem-family in this case is considerably more significant.

Finally, to assess the independent impact of stem-family size on word learning, we ran a generalized additive model including stem-family size, word length and distance to stem-suffix boundary as predictors for learning epoch ( $R^2(\text{adj}) = 0.53$ ), and

**TABLE 2** | GAM fitted to word learning epochs using stem-family size as the only paradigmatic predictor:  $learning\ epoch \sim stem\text{-}family\ size * distance\ to\ MB * word\ length + s(distance\ to\ MB) + s(word\ length)$ .

Parametric coefficients	Estimate	Std. Error	t value	Pr(>t)
(Intercept)	0.1677863	0.0648875	2.586	0.00972
Distance to MB	4.7535561	0.1025123	46.371	< 2e-16
Stem-family size	-0.1873784	0.0105171	-17.816	< 2e-16
Word length	1.9595085	0.0188123	104.161	< 2e-16
Distance to MB:stem-family size	-0.0553514	0.0031115	-17.789	< 2e-16
Distance to MB:word length	-0.1973904	0.0031048	-63.577	< 2e-16
Stem-family size:word length	0.0047230	0.0011342	4.164	3.13e-05
Distance to MB:stem-family size:word length	0.0060111	0.0003114	19.305	< 2e-16
<b>Significance of smooth terms:</b>				
s(distance to MB)				< 2e-16
s(word length)				< 2e-16
$R^2$ (adj) = 0.53				

compared it with a similar model where the paradigmatic predictor is paradigm regularity ( $R^2$ (adj) = 0.28). The robustness of the stem-family model (see **Table 2**) provides solid support for the hypothesis that family size is the driving paradigmatic force in word learning<sup>15</sup>.

## 6. GENERAL DISCUSSION AND CONCLUDING REMARKS

Inflectional complexity is inherently multidimensional. It lends itself rather reluctantly to an assessment in terms of a single factor or measure. Traditional approaches to complexity are based on either an inventory of morphosyntactic features and their markers, or on a full grammatical description of an inflection system. Both strategies require considerable preliminary knowledge about lexical/grammatical units as well as rules/processes for their segmentation and recombination. Ultimately, they appear to place more emphasis on the descriptive adequacy of some system of formalized knowledge, than on inflectional complexity *per se*.

More recently, information-theoretic approaches have tried to eschew such a circular assessment of system complexity, by looking at patterns of interpredictability in the distribution of inflectional data. These patterns are not scattered randomly across inflectional paradigms. On the contrary, they are distributed in ways that reduce the amount of uncertainty in mastering inflection. Such a structured system of implicative relations addresses a few learnability issues by constraining an otherwise very large hypothesis space. This is certainly a step forward in understanding inflection and measuring its complexity. However, there are a number of important issues that it leaves unaddressed.

Form interpredictability requires preliminary identification of patterns of morphological redundancy, such as those allowing

the resolution of a simple analogical proportion like  $\langle walk :: walked = talk :: ? \rangle$ . However, the hypothesis space of formal mapping may vary considerably from language to language, as witnessed by proportions like  $\langle machen :: gemacht = lachen :: ? \rangle$  (German) and  $\langle kataba :: yaktubu = hadama :: ? \rangle$  (Arabic). For the idea of measuring the complexity of an inflectional system in terms of information entropy to be empirically verifiable, we have to be fairly specific about how speakers can acquire these patterns in the first place, and what learning principles provide the algorithmic basis for bootstrapping patterns with no *a priori* knowledge about them. What cues allow the identification of sublexical parts? Do these parts provide, in turn, functional cues to lexical processing? Are all morphological systems equally complex to process and learn? And if they are not, why?

To meet its communicative goals any inflection system needs to be *learnable* in the first place. In addition, it must also be *functional* from the standpoint of processing requirements, and its inner organization must address fundamental discriminative concerns about efficiency in lexical access. In particular, inflected forms should not simply be easy to generalize, but also easy to process and amenable to accurate and efficient access. Issues of learnability, processability and discriminability are not necessarily mutually contradictory, but they may pull in different directions. Examining their complex interaction requires much more than just a way to gauge inferential entropy in a static repository of inflected forms. In this paper, we suggested using basic discriminative learning principles and a type of recurrent artificial network to clarify the multidimensional nature of inflectional complexity in the light of our understanding of the interaction between learning principles and human word processing behavior.

As a general point, the evidence offered in this paper shows that the processing cost of typologically different inflectional systems oscillates within a fairly narrow range (**Figure 4**, center panel), and that this range is actually modulated by morphological structure (**Figure 4**, right panel). It is noteworthy that the steepest linear slopes of processing prediction in the center panel of **Figure 4** are associated with Arabic and

<sup>15</sup>In **Table 2**, predicted, standard error and *p* values are detailed for each of the independent variables. The adjusted *R-squared* expresses the percentage of explained deviance. The intercept value is referred to our dependent variable (learning epoch) when all the independent predictors are 0.

English, while German, Greek, Italian and Spanish present less steep word processing trends. It would be an unwarranted oversimplification, however, to conclude that Arabic and English have *less* complex inflection systems. In Arabic, the effect is mainly due to the discontinuous structure of verb stem allomorphs, which systematically anticipate the marking of a few morphosyntactic features in both regulars and irregulars, and make endings easier to predict. The result is a lower rate of processing uncertainty at the stem-suffix boundary, compared with other languages. A similar processing facilitation is observed in English for a different reason: the small range of endings marking inflectional contrast. Conversely, German, Greek, Italian and Spanish show higher prediction rates for stem processing, followed by a deeper drop in prediction at the stem-suffix boundary, due to a richer set of (possibly nested) inflectional suffixes. Languages typologically vary in the ways they apportion morpho-syntactic information across inflected words. This variation has a significant impact on word processing strategies, because finding information at certain points in the input word may reduce processing uncertainty at later points. Nonetheless, when the amount of morpho-syntactic information to convey through inflection is approximately constant across languages<sup>16</sup>, cross-linguistic variation in processing uncertainty can only oscillate within a narrow range.

This has also interesting repercussions on learning. Judging from the distribution of per-word learning epochs (**Figure 3A**), Arabic is arguably the most difficult language to learn in our sample. In *TSOMs*, this is caused by the strong paradigmatic competition between discontinuous roots intercalated by different vowel patterns. Nonetheless, the system appears to substantially benefit from interpredictability patterns, as shown by the distribution of learning span values in **Figure 3B**. This suggests that the higher cost of learning discontinuous stems in Arabic is compensated by the relatively shorter length of inflected forms (compared with the length of inflected forms in other languages), and by the fact that inflectional class information is conveyed by the stem. In other languages like Greek, Italian and Spanish, where class information is mostly conveyed after the stem, selection of the appropriate inflectional ending is considerably more uncertain (in line with Ackerman and Malouf's LCEC, Ackerman and Malouf, 2013).

From a functional perspective, the simulation evidence offered in this paper can be interpreted as the result of a balancing act between two potentially competing communicative requirements: (i) a recognition-driven tendency for a maximally contrastive system, where all inflected forms, both within and across paradigms, present the earliest possible (complex)

uniqueness point of recognition; and (ii) a production-driven bias for a maximally generalizable inflection system, where most forms in a paradigm can be inferred from any other form in the same paradigm. In an efficient communication system, both requirements should be balanced. A poorly contrastive system would be dysfunctional for practical communication purposes, because the elements in the system are harder to discriminate. A communication system, however, must also be open and adaptive, because new elements must continuously be added to be able to refer to an ever changing pragmatic environment. Clearly, a maximally contrastive system of irregular forms would take the least effort to process, but would require full storage of unpredictable items, thus turning out to be slow to learn. A maximally generalizable system, on the other hand, would be comparatively easier to learn, but rather inefficient to process, especially when it comes to low-frequency items.

To conclude, there are a few implications of the present work that are worth emphasizing here because of their impact on our current understanding of word knowledge. First, from observing discriminative learning principles in action, we get a very concrete sense of the view that processing and learning issues are strongly inter-related and mutually-implied in language. Although they may pull in different directions, they are, in fact, two sides of the same coin. More precisely, they define two distinct temporal dynamics (a short-term one for processing, and a long-term one for learning) of the same unitary underlying process. Accordingly, representations of word forms in our mental lexicon are only stored patterns of their processing history: what we learn of language is basically how we process it (Marzi and Pirrelli, 2015). Secondly, temporal patterns of discontinuous redundant units in time-series are known to be more difficult to process by humans (Hahn and Bailey, 2005). Hence, it is expected that they should be more difficult to learn and organize in our mental lexicon. This point has interesting implications both for our categorization of inflectional processes into regular and irregular, and in cross-linguistic terms. Systems of formally alternating complex units are easier to discriminate, since they provide shorter *CUPs* and thus take, overall, a smaller processing surprisal (Balling and Baayen, 2008, 2012). However, they are more difficult to acquire, since they are more isolated from other existing forms, and thus harder to infer from familiar, redundant patterns. Less discriminative, highly syncretic systems are much easier to generalize and learn, and, for the same reason, more ambiguous (less informative) and more difficult to interpret in their context of use. Such a complex dynamic of co-existing and conflicting processing requirements has to find a balance, both within the same language (as a function of how regulars and irregular items are stored and co-organized in the mental lexicon), and cross-linguistically (as a function of typologically diverse processes of inflection marking). In the end, each language (and arguably each individual learner) is likely to strike a different balance, which nonetheless falls within a reasonably tight range of variation, bounded by a few learnability and processability requirements. This suggests that full investigation of morphological systems will likely benefit

<sup>16</sup>We are not suggesting that such an invariance in the amount of inflectional information holds for all languages. For example, Basque verb agreement marks an inflected verb form with affixes for subject, direct object and indirect object case (Austin, 2010, 2012). The system is agglutinative, and the number of possible distinct affix combinations for ditransitive verbs soon gets very large (up to 102 different forms in the present indicative of the auxiliary). Thus the amount of syntactic context that must be processed for a child to check case assignment on the main verb form, is considerably larger than what is needed for languages like German, Italian or Spanish.

from the use of basic concepts from the toolkit of complexity theory in biological networks, such as emergence, non-linearity and self-organization.

Over the past few decades, morphological paradigms have acquired growing importance in our understanding of complex inflectional systems. While our work provides novel evidence supporting this trend, it also suggests that paradigms are functionally specialized by-products of more general principles of lexical self-organization, based on the more primitive notion of word neighborhood. The morphological correlate of this notion, namely the family of inflected types sharing the same stem, or stem-family, turned out to be key to understanding processing and learning issues. The size and distributional entropy of stem-families can ultimately account for the effects of ease of generalization, thus providing a more general, process-oriented basis for understanding patterns of interpredictability in morphology learning. This perspective lends strong support to the view that the complexity of the inflectional system of a language is a collective, emergent property that cannot be deduced from its individual forms. In addition, it suggests that a processing-oriented, discriminative view of inflection systems is not incompatible with the idea that their systemic

self-organization rests on smaller “morphomic” patterns of structural redundancy.

## AUTHOR CONTRIBUTIONS

CM ran the experiments on German, English, Arabic and Spanish, conducted data analysis and statistical modeling of the results, and developed the conceptual and theoretical framework of this work. MF was responsible for computational modeling, ran the experiments on Italian and Greek, designed and extracted functional responses and structural evidence of TSOMs for quantitative data analysis. VP developed the linguistic framework and the theoretical background of the present study. Theoretical implications and concluding remarks were jointly discussed. CM and VP critically revised previous versions of the paper.

## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fcomm.2019.00048/full#supplementary-material>

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