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Syllables and their beginnings have a special role in the mental lexicon

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The beginnings of words are, in some informal sense, special. This intuition is widely shared, for example, when playing word games. Less apparent is whether the intuition is substantiated empirically and what the underlying organizational principle(s) might be. Here, we answer this seemingly simple question in a quantitatively clear way. Based on arguments about the interplay between lexical storage and speech processing, we examine whether the distribution of information among different speech sounds of words is governed by a critical computational unit for online speech perception and production: syllables. By analyzing lexical databases of twelve languages, we demonstrate that there is a compelling asymmetry between syllable beginnings (onsets) versus ends (codas) in their involvement in distinguishing words stored in the lexicon. In particular, we show that the functional advantage of syllable onset reflects an asymmetrical distribution of lexical informativeness within the syllable unit but not an effect of a global decay of informativeness from the beginning to the end of a word. The converging finding across languages from a range of typological families supports the conjecture that the syllable unit, while being a critical primitive for both speech perception and production, is also a key organizational constraint for lexical storage.

lexicon | speech communication | functional load | syllable | phonology

Speech communication hinges on two fundamental components. One component is the *mental lexicon*, an internal collection of stored sound-meaning pairings (informally speaking, "words") that are used in the language, along with various linguistic properties of these words (1–3). The second consists of the suite of operations that underwrite the transmission of stored lexical representations from a speaker to a listener via the speech signal. These operations can be subsumed under *speech production*, allowing the speaker to transform internally stored word representations into motor articulatory gestures to generate the speech signal; and *speech perception*, allowing listeners to map input speech signals onto the corresponding word representations. Although lexical storage and speech operations are governed (at least in part) by distinct organizational and computational principles, it has been demonstrated that strong interaction exists between the two components in the service of successful communication (4–6).

Successful speech communication overcomes considerable challenges. Linguistic information mediated by speech is typically accompanied by various forms of adversity, such as errors in production and perception (7, 8), the presence of background noise or competing talkers (9, 10), as well as different types of linguistic variation and ambiguity (11). In light of these obstacles, words intended by a speaker can be misperceived. The potential for *miscommunication* is amplified by the degree of similarity in the phonological forms of different words (12). For instance, "cable" (/ˈ**k**eɪbəl/) and "fable" (/ˈ**f**eɪbəl/) differ by only a single speech sound, or phoneme[*], and thus have a higher chance to be confused during speech communication than words that are phonologically distant (e.g., "cat" /kæt/ and "rose" /rəʊz/). Linguists refer to word pairs like "cable" and "fable" as *minimal pairs*, due to the minimal amount of phonological difference between their forms. Specifically, the lexical distinction between "cable" and "fable" relies solely on the identity of the first phoneme of the two words.

The speech communication system has been shown to respond to the level of phonological similarity between words, particularly in facilitating accurate transmission of the identity of phonemes crucial to distinguish minimal word pairs. For instance, speakers exaggerate their articulation of specific phonemes of the word, if the identity of these phonemes distinguishes the word from other words in the lexicon (15, 16). These data illustrate a functional interplay between lexical storage, on the one hand, and speech operations, on the other hand, in the service of improving accuracy in communication.

[*]Linguistic theories typically posit that the sound patterns of words are stored in memory as sequences of phonemes, which are defined as discrete phonological units with the size of a single sound segment (13, 14).

Significance

How spoken words are stored in the mind/brain is a fascinating question for our understanding of language as well as for practical applications, e.g., in clinical contexts. Since words are built as temporal sequences of speech sounds, a relevant but not yet clearly answered question is whether individual speech sounds within these sequences contribute equally to the encoding of words. Our quantitative analysis of lexicons from 12 languages demonstrates that the distribution of lexical informativeness among speech sounds within words is organized by the syllable unit, which is a computational primitive in the production and perception of words. Specifically, the beginnings of syllables, rather than the beginnings of words, hold a privileged role in representing words in the mental lexicon.

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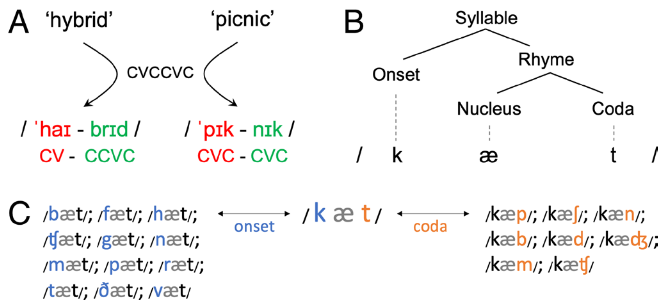

Fig. 1. Phonological representation of words. (*A*) Syllabification provides chunking to the phoneme sequence of words. While the phonological wordforms "hybrid" and "picnic" have the same sequence of consonants (C) and vowels (V), the two sequences are decomposed into syllables of different structures following syllabification rules of English. (*B*) Subunits and internal structure of syllables with the illustration of the word "cat" (/kæt/-/CVC/). In principle, a syllable is composed of a vowel as *nucleus* (i.e., /æ/) that can be preceded and followed by one or more consonants. The consonants before the vowel are referred to as *onset* (i.e., /k/) and those after the vowel as *coda* (i.e., /t/). The three components of the syllable are argued to be organized in a hierarchical structure (17), with nucleus and coda most commonly grouped into a subunit called *rhyme.* (*C*) English words (indicated as their phonemic transcription) that contrast with the word "cat" by changing a single consonant. According to a search in the English lexicon (Celex), the word "cat" forms a minimal pair with 12 other words in English by changing the consonant at syllable onset, while it forms a minimal pair with 8 other words by changing the consonant at syllable coda. This case illustrates a higher contribution of syllable onset than of coda in distinguishing minimal pairs involving the word "cat".

The dynamics between storage and computation are also reflected in the influence of speech operations on lexical storage. For instance, the operations involved in speech production and perception consistently facilitate the processing of phonemes that occur at specific positions of words (e.g., phonemes at the beginning of words). If such processing regularities reflect an important principle of speech production and perception, one might expect that phoneme positions which consistently result in more accurate transmission of information are given higher functional relevance for distinguishing minimal pairs of words in the lexicon. On this hypothesis, how stored phonological wordforms differ from each other can be influenced by computational principles germane to speech operations. In short, the contingencies of storage influence computation, and the properties of computation influence storage. One rather banal idea is that the beginnings of representations play a special role. This is a plausible intuition, but empirical data are sparse.

The current study examines the impact of a fundamental principle in speech production and perception—*syllabification*—on the storage of phonological wordforms. Syllabification is a process that chunks the phoneme sequence of a word into one or multiple groups (Fig. 1*A*). The resulting *syllables* can be further decomposed into subunits which have been argued to be organized hierarchically (17) (Fig. 1*B*). Empirical and theoretical research has posited the syllable as an essential computational primitive for both speech production (18, 19) and perception (20, 21). Importantly, previous work provides converging evidence for differential processing reliability of phonemes as a function of their position within syllables. This effect is particularly salient for consonants, as they can occur at both syllable onset and coda. For instance, it has been demonstrated that consonants at syllable onset are more robustly articulated (22), which in turn generates better acoustic signals than consonants at syllable coda (23–25). Greater acoustic distinctiveness of consonants at syllable onsets leads to the hypothesis of more robust recognition of syllable-onset consonants in speech perception, which is supported by psycholinguistic studies (24, 26). Therefore, if there is consistency between i) computational principles that privilege processing of certain phoneme positions within words and ii) storage principles that vary the relative importance of different phoneme positions for the lexical distinction of these words, then syllable onset should be granted a higher level of importance than syllable coda for distinguishing minimal word pairs (Fig. 1*C*).

Here, we provide the characterization of a principle that highlights the interplay between the operations mediating speech communication, on the one hand, and the constraints on storage, on the other hand. Based on a crosslinguistic corpus study, we demonstrate that the "syllable" unit—a critical primitive both for perception and production—is also a key organizational constraint for lexical storage. We analyzed lexicons from 12 languages, all of which allow consonants to occur at both syllable onset and coda. For each language, we compare the relative involvement of syllable onset and coda in distinguishing phonological minimal pairs. In the field of linguistics, this measurement is referred to as the *functional load*, which describes the extent to which a language makes use of a particular phonological unit or structure to distinguish (or contrast) words from one another (27–29). Counting the number of minimal pairs that are associated with a specific phonological unit is one of the methods to quantify functional load of that unit (29–32). Research of functional load has been conducted on individual phonemes (29), categories of phonemes (31), phonetic features (33), lexical tones (31). The current study, however, characterizes the functional load of specific syllabic positions (SPs) (i.e., onset vs. coda) across different languages, allowing us to align questions about *storage* with questions about *perception and production*. There is continued debate on the role of syllable-level representations in linguistics, psycholinguistics, and neurolinguistics. We show that syllables and their onsets can provide a unifying role that aids our understanding of how storage and processing interact.

Results

Distribution of Functional Load between Syllable Onset and Coda. We analyzed lexical databases of 12 languages from 7 typological families: West Germanic: German, English, Dutch; North Germanic: Swedish, Norwegian; Romance: French, Italian, Spanish; West Slavic: Czech; Greek: Greek; Turkic: Turkish; Koreanic: Korean. Words in these databases were phonemically transcribed and syllabified (see *Materials and Methods* for more details). For each language, we first identified all word pairs that differ from each other by substitution of a single consonant. We then labeled the SP (onset or coda) of the consonants that contrast each identified minimal pair and measured the *functional load* (*FL*) of each SP by calculating the proportion of minimal pairs that involved each position among all identified minimal pairs (see *Materials and Methods* for more details). This measurement of the functional load indicates the relative frequencies with which the syllable onset and coda are involved in distinguishing words from each other.

Comparison between syllable onset and coda showed compelling higher functional load for syllable onset in all examined languages (Fig. 2*A*). The onset bias (FL_{onset}–FL_{coda}) across the 12 languages averaged at 62.85% (SD = 21.63%) (Fig. 2*A*, see *SI Appendix*, Table S1 for detailed results). Next, we confirmed that the onset bias in functional load can be consistently observed across the two major types of consonant clusters that can occupy the syllable onset and coda positions (C cluster: mean = 63.05%; SD = 20.89%; CC cluster: mean = 56.78%; SD = 29.42%; Fig. 2*B*, see *SI Appendix, Supporting Text 1* for more details) as well as across words with different number of syllables (monosyllabic words:

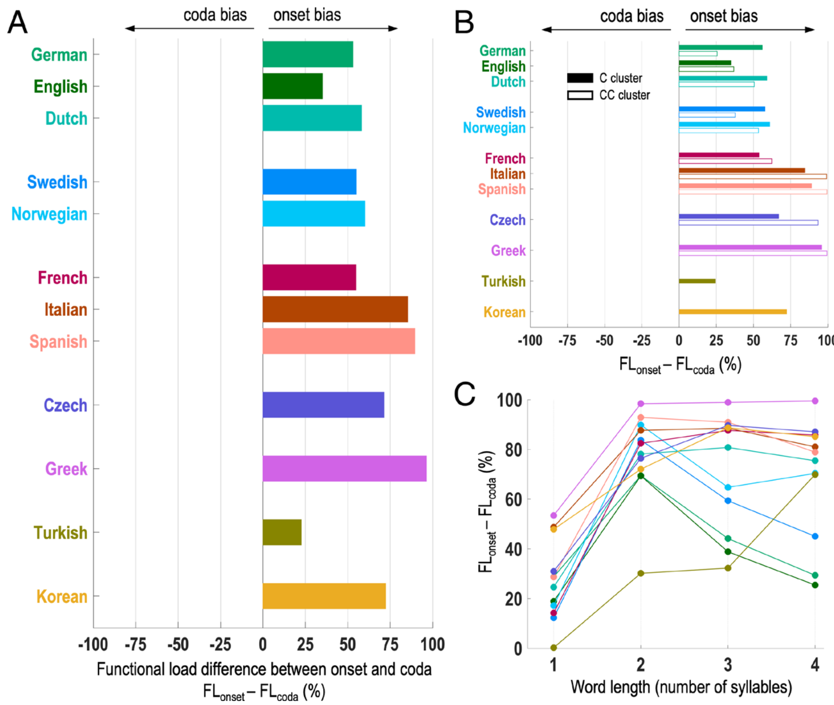

Fig. 2. Comparison of functional load between syllable onset and coda. (*A*) Difference in functional load (in percentage) between syllable onset and coda in 12 languages. Languages are grouped according to typological criteria. (*B*) Difference in functional load between syllable onset and coda for C and CC clusters. (*C*) Onset biases in functional load (FL_{onset}–FL_{coda}) across words with different lengths of each language. Languages are color coded as in (*A*) and (*B*).

mean = 27.16%; SD = 16.21%; disyllabic words: mean = 77.54%; SD = 17.56%; trisyllabic words: mean = 72.04%; SD = 23.23%; quadrisyllabic words: mean = 69.41%; SD = 23.60%; Fig. 2*C*, see *SI Appendix, Supporting Text 2* for more details analyses and a discussion on the consistent increase of the onset bias from monosyllabic to disyllabic words). In summary, we demonstrate a cross-linguistic asymmetry between syllable onset and coda for lexical contrasts: Syllable onset consistently yields higher functional load than syllable coda across cluster categories and word lengths.

Syllables Are the Organizational Unit for the Modulation of Functional Load within Phonological Wordforms. Despite showing an overall asymmetry in functional load distribution between syllable onset and coda, does this effect reflect a modulation of functional load by the syllable unit per se? In fact, the higher functional load of syllable onset than coda could also emerge from a global modulation of lexical informativeness across all phoneme positions within a word. The directional nature of time in speech production and perception arguably favors processing of phonemes occurring earlier in words (34, 35)—which, in the extreme case, could lead to a serial decay of functional load from phonemes at the beginning of words to those at the end of words. If the variation of functional load within words is primarily driven by this global modulation, then decreases of functional load are expected to occur not only within each syllable (i.e., from the onset to coda of a given syllable) and but also across the boundaries of consecutive syllables (i.e., from the coda of a given syllable to the onset of the following syllable). Fig. 3*A* illustrates this hypothesis for the case of disyllabic words. Meanwhile, if the higher functional load at syllable onset than coda mainly reflects a modulation of lexical informativeness by the *syllable* unit, decreases of functional load should be expected to occur primarily within each syllable. That is, one should expect a rebound of functional load from the coda position of a syllable to the onset position of the following syllable (Fig. 3*B*). To adjudicate between these hypotheses, we next focused on words with more than one syllable and examined the variation of functional load across all individual syllable onset and coda positions.

For each word length (2 to 4 syllables), we measured the functional load of the onset and coda positions of each syllable (Fig. 3*C*, labels for SPs were given in the blue row). To assess whether the variation of functional load across individual onset and coda positions reflects an effect of their global order (GO) following the direction of time, we also attributed a second label to each SP according to the GO (Fig. 3*C*, labels in yellow row). Visual inspection of these data revealed clear cyclic modulation of functional load from the beginning to the end of words, with the modulation cycles corresponding to the syllable unit. Specifically, while typically the functional load decreases from onset to coda of the same syllable, this measurement increases systematically from the coda of a syllable to the onset of the following syllable. We then analyzed, for each word length, the effect of SP and GO on the variation of functional load. We constructed two linear mixed models with Functional Load as the dependent variable: the first model used SP as the fixed effect; the second model used GO. Both models included Language as the random effect for both intercept and slope of the fixed effect. These analyses showed that, for every word length, both SP and GO exhibited a significant effect on functional load (Table 1). These results indicate that the decay of functional load occurs both within the syllable unit and from word-beginning syllables to word-ending syllables. However, for every word length, the SP model outperformed the GO model in accounting for the variation of functional load within phonological wordforms: higher adjusted r^2 for the SP model than for the GO model for each word length (Table 1). These results suggest that the modulation of functional load within multisyllabic words is primarily driven by the asymmetry between the onset and coda positions of the same syllable unit, not by an overall decrease of functional load at the whole word level. Jointly, the data show that syllables (Fig. 3*C*) and their onsets (Fig. 2*A*) provide a fundamental

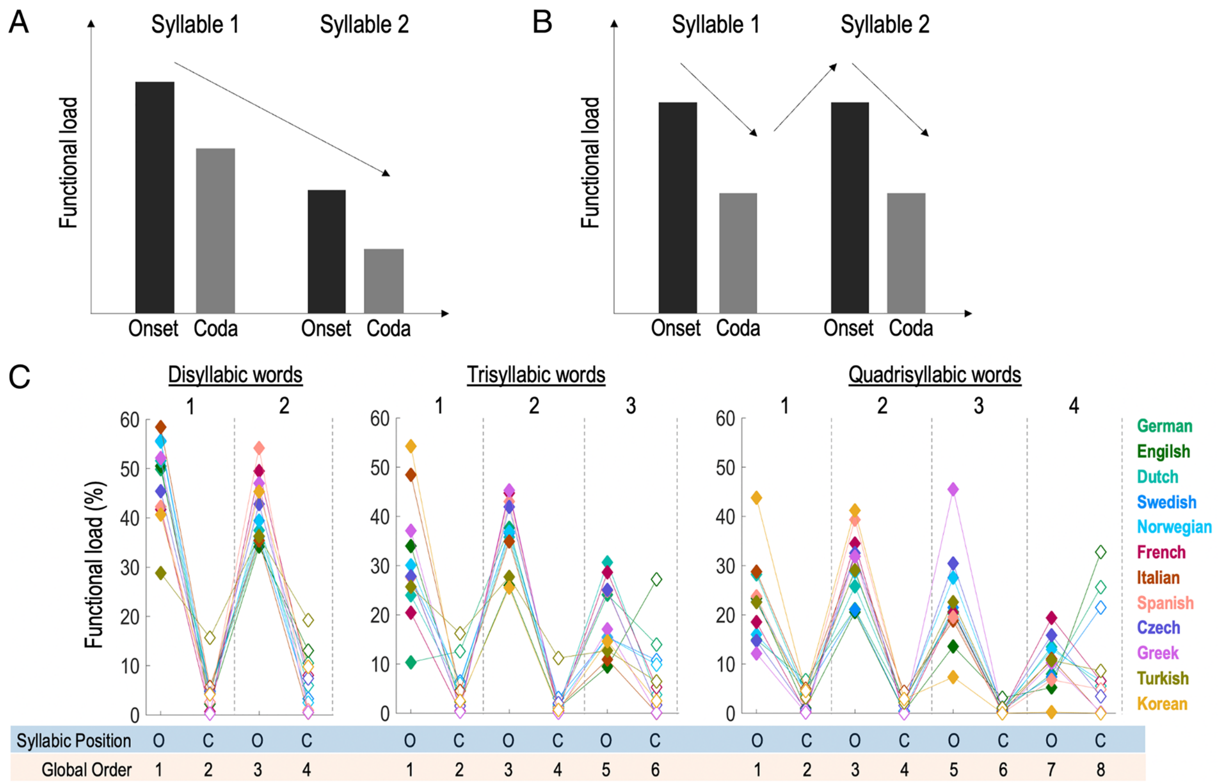

Fig. 3. Modulation of functional load across syllable onset and coda positions within multisyllabic words. (*A*) Hypothesis for a global modulation of functional load, illustrated in disyllabic words. (*B*) Hypothesis for a cyclic modulation of functional load by the syllable unit, illustrated in disyllabic words. (*C*) Variation of functional load across the onset and coda positions of each syllable in words with multiple syllables (disyllabic: *Left*; trisyllabic: *Middle*; quadrisyllabic: *Right*). Filled diamonds indicate the functional load of the onset of each syllable and open diamonds indicate the functional load of the coda of each syllable. The numbers on top of each graph indicate the position of each syllable within the corresponding multisyllabic words. Dashed lines indicate the boundaries between syllables. Individual SPs (labelled accordingly as O: onset; C: coda, indicated in the blue row of the *x* axis) are also given a second label based on the GO of these position within the corresponding multisyllabic words (indicated in the orange row of the *x* axis).

organizational constraint both on lexical storage and the dynamic interplay with processing.

The Higher Functional Load at Syllable Onset Reflects More than a Basic Size Advantage of Its Phonological Attributes. The asymmetrical involvement of syllable onset and coda in distinguishing words complements existing findings on phonological asymmetries between the two positions. First, languages preferentially use syllables with an onset position than those with a coda position to construct words (36, 37), which leads to higher occurrence of syllable onset than syllable coda across the consonant-vowel (CV) skeletons of wordforms. Second, it is typical that languages allow larger inventories of consonants to occur at syllable onset than at syllable coda (38). In the current study, all 12 languages exhibit higher skeletal occurrences of syllable onset than of syllable coda across wordforms (Fig. 4*A*); 9 of the 12 languages exhibit larger consonant inventories at syllable onset than at syllable coda (Fig. 4*B*).

Size advantages in skeletal and inventorial attributes should probe higher functional load for syllable onset. Meanwhile, it is unclear whether the onset biases in functional load merely reflect basic size differences in the two phonological properties between syllable onset and coda. We developed a quantitative approach to examine to what extent skeletal and inventorial attributes of syllable onset and coda jointly account for the functional disparity between the two positions. For each language, we simulated a series of 50 "pseudolexicons" by recreating all consonants of each word of the real lexicon. The simulation procedure refills each skeletal slot of syllable onset and coda positions of each word with a consonant (or a consonant cluster) that is randomly selected from the broad inventory that is associated with the corresponding SP (see Fig. 5*A* for an example and *Materials and Methods* for more details). Accordingly, the simulated lexicons match with the real lexicon in i) the total number of skeletal slots of syllable onset and coda positions and ii) the size of consonant inventory that is associated with each of the two positions. We purposefully used the broad consonant inventories of syllable onset and coda in order to specifically test whether the basic size difference in consonant inventory between the two positions is sufficient to account for the amount of functional disparity between them.

We measured the onset bias in functional load for each of the 50 simulated lexicons, which gave a baseline distribution of the onset biases that result from differences in skeletal and inventorial sizes

Table 1. Two linear mixed models for each word length (2 to 4 syllables) with functional load as the dependent variable and either syllable position or GO as the fixed effect

Word length	Fixed effect	*t*	*P*	r^2
2	Syllable position	−15.98	<0.001	0.93
	Global order	−3.69	<0.001	0.20
3	Syllable position	−11.22	<0.001	0.65
	Global order	−3.27	<0.001	0.12
4	Syllable position	−10.01	<0.001	0.51
	Global order	−2.78	<0.01	0.06

r^2 indicates the adjusted r-squared.

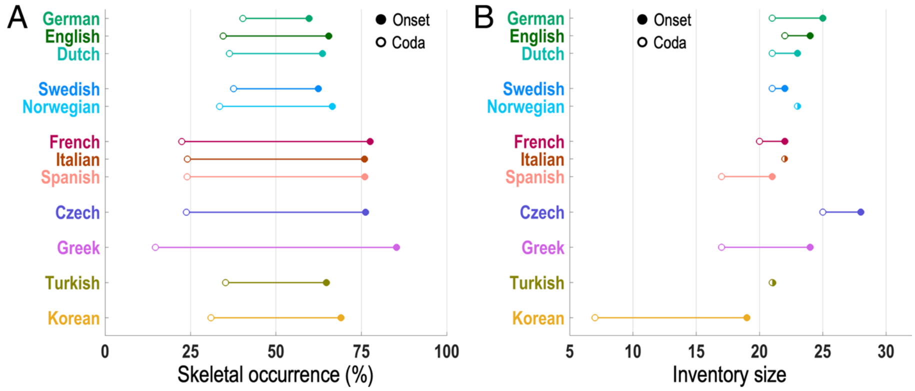

Fig. 4. Skeletal and inventorial attributes of syllable onset and coda across the 12 languages. (*A*) Skeletal occurrence: frequency of occurrence of structural slot of syllable onset and coda across CV skeletons of wordforms. (*B*) Inventory size: the number of unique consonants that occur at syllable onset and coda.

between syllable onset and coda. We then compared the onset bias in functional load observed in the real lexicon to those from the simulated lexicons, using a z-test analysis (12) (see *Materials and Methods* for details). In all the examined languages, the simulated lexicons exhibited positive onset biases in functional load (Fig. 5*B* and *SI Appendix*, Table S3). However, in 9 of the 12 languages, the real lexicon exhibited significantly higher onset bias than the simulated lexicons (Fig. 5*B* and *SI Appendix*, Table S3). Across the 12 languages, the average disparity between the onset bias in real lexicons and those in simulated lexicons is 8.80% (SD = 9.76%). These results indicate that, for the majority of the examined languages, the size differences in skeletal and inventorial attributes between syllable onset and coda are not sufficient to account for the level of onset bias in functional load observed in the real lexicon.

Syllable-Level Phonotactics Govern Both Similarity and Contrast between Wordforms. While the onset bias in functional load cannot be reduced to a byproduct of the combined size difference of skeletal and inventorial attributes between syllable onset and coda, it is noteworthy that our simulated lexicons, by design, do not exhibit the same level of phonological regularities across their wordforms as the real lexicons do. Specifically, while we used the broad phoneme inventories to simulate a language's overall constraints on the occurrence of consonants at syllable onset and coda, it is well known that all languages exhibit more complex phonotactic restrictions which usually disallow certain phonemes from the broad sound inventory to appear in specific syllables based on the characteristics of the syllable (39, 40).

Additional restrictions on the occurrence of onset and coda consonants may be triggered by meta-properties of the host syllable (e.g., CV structure, stress, tone) as well as the position of the syllable in the word (41). For instance, in Korean, the consonant /ŋ/ can occur at syllable onset except when the syllable is the first syllable of a word (41). We refer to these restrictions as *hierarchical constraints*, since the restrictions on subsyllabic units (e.g., onset and coda) originate from the properties of their host syllable. The occurrence of onset and coda consonants also depends on restrictions on onset–nucleus and nucleus–coda cooccurrence inside the same syllable (39, 42). For instance, English does not allow voiced fricatives (e.g., /v/) to occur as syllable onset before the vowel /ʊ/ (39). We refer to these restrictions as *transitional constraints*, given that they reflect transitional regularities of consecutive subsyllabic units.

Across the 12 languages, the application of hierarchical and transitional constraints reduces the size of consonant inventory for both syllable onset and coda, with stronger inventory reduction at syllable coda than syllable onset in all languages except for Korean (*SI Appendix*, Fig. S1). These results lead to two expectations. First, inventory reduction at both SPs should decrease the total number of syllables that a language uses to make words, which should increase phonological similarity among wordforms, and hence, the total number minimal pairs identified in each language. Second, stronger inventory reduction at syllable coda than at syllable onset should enhance the functional disparity between the two positions in distinguishing words, which leads to an increase in the onset bias in functional load.

To test these hypotheses, we generated two new series of simulated lexicons, which, respectively, implemented Hierarchical constraints (H) or both Hierarchical and Transitional constraints (H+T) in the deduction of consonant inventories associated with each skeletal slot of syllable onset and coda during the generation of wordforms (see *Materials and Methods* for details). Accordingly, we refer to the simulated lexicons that were previously generated with broad inventories as Basic lexicons (B). Fig. 6*A* shows, for each language, the ratio between the total number of minimal pairs observed in each type of simulated lexicons and the total number of minimal pairs observed in the real lexicon. Our results showed that the number of minimal pairs increases as more syllable-specific phonotactics are taken into account during the generation of wordforms. Specifically, across the 12 languages, wordforms from Basic lexicons (B) generated on average 33.96% (SD = 10.06%) of the amount of the minimal pairs observed in the real lexicons. This ratio increased to 61.39% (SD = 11.04%) when hierarchical constraints on consonant occurrence were taken into account (H) and to 80.66% (SD = 8.08%) for when both hierarchical and transitional constraints were taken into account (H+T).

For the distribution of functional load between syllable onset and coda, our results revealed significant increases of the onset bias in 9 languages following the implementation of additional phonotactic constraints (Fig. 6*B* and *SI Appendix*, Table S4). Across these languages, the implementation of hierarchical constraints alone yielded an average increase of the onset bias by 6.63% (SD = 6.33%) compared to the level observed in the Basic lexicons, and the implementation of both hierarchical and transitional constraints resulted in larger increases that averaged at 11.78% (SD = 8.38%). Three languages (Italian, Spanish, and Korean) showed decreases of the onset bias in functional load after additional phonotactic constraints were implemented (Fig. 6*B* and *SI Appendix*, Table S4). Such observation may be expected for Korean, for which the implementation of phonotactic restrictions reduced the onset bias in inventory size (*SI Appendix*, Fig. S1). Meanwhile, it is rather surprising to observe the decreases in Italian

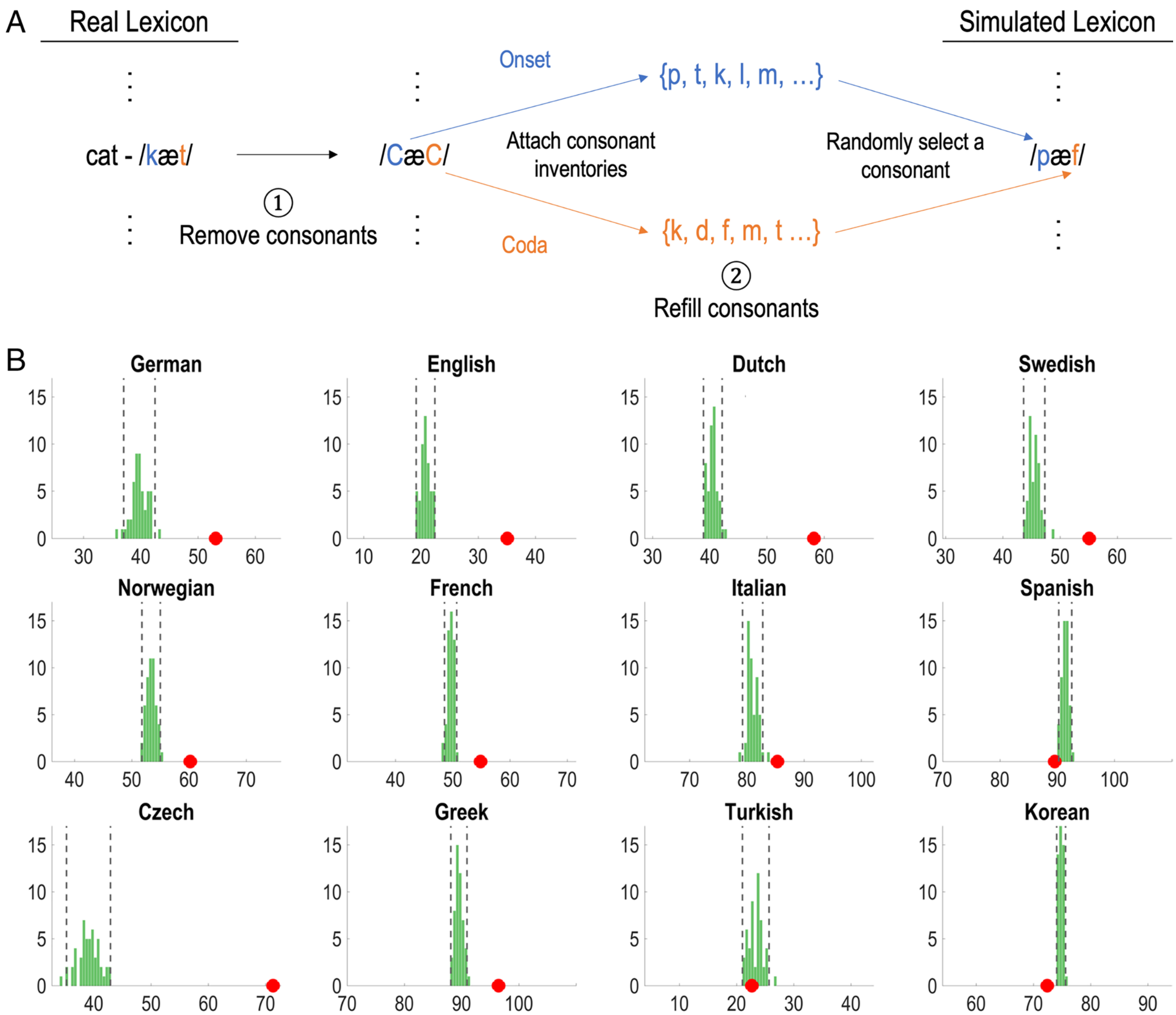

Fig. 5. Procedure and results of the lexicon simulation analysis. (*A*) Procedure of generating a new wordform (/pæf/) from a real word in the English database ("cat"-/kæt/). (*B*) Comparison between the level of onset biases in functional load observed in the real lexicon (red circle) and those across the 50 simulated lexicons (green distribution). Gray lines indicate the 95% CI of each distribution.

and Spanish, both of which showed greater onset-coda asymmetries in inventory size following the implementation of phonotactic constraints (*SI Appendix*, Fig. S1) (see *SI Appendix*, *Supporting Text 4* for more detailed assessments of these findings). Finally, 7 of the 12 languages showed larger onset bias in functional load in the real lexicon than in the Hierarchical+Transitional lexicons (*SI Appendix*, Table S5).

Discussion

This study states two generalizations. First, there is a higher functional load of syllable onset than syllable coda in all examined, typologically different languages, which reflects an asymmetrical distribution of lexical informativeness within the syllable unit and not an effect of a global decay of informativeness from the beginning to the end of a word. Second, our lexicon simulations demonstrate that phonological regularities at the syllable level are crucial in determining both the amount of lexical contrast among wordforms and the level of asymmetry between syllable onset and coda for lexical contrast.

Given the central role of syllables in grouping phonemes during speech operations, the distribution of phonemes within syllables has been a long-standing topic in phonological research (39, 42). This body of work has highlighted differences in various phonological attributes between syllable onset and coda (36–38). The current study extends previous research and demonstrates that syllable onset plays a stronger role than syllable coda in distinguishing words. Importantly, our study provides insights into the quantitative connection between phonological regularities associated with syllable onset and coda and the functional asymmetry between the two positions in lexical contrast. We developed a lexicon simulation approach which examines separate and joint contributions from three streams of phonological regularities to the distribution of functional load between syllable onset and coda. These regularities include 1) basic skeletal and inventorial size, 2) additional constraints on consonant occurrence from structural and positional properties of the host syllable, and 3) transitional regularities between the syllable nucleus and the consonants at onset and coda. Our results indicate that the mixture of all the three streams of phonological regularities is necessary to generate "pseudolexicons" that match the real lexicon in both the number of minimal pairs and the advantage of syllable onset in contrasting words.

We hypothesized higher functional load at syllable onset than coda based on greater reliability of syllable onset consonants during production and perception of speech. While our findings

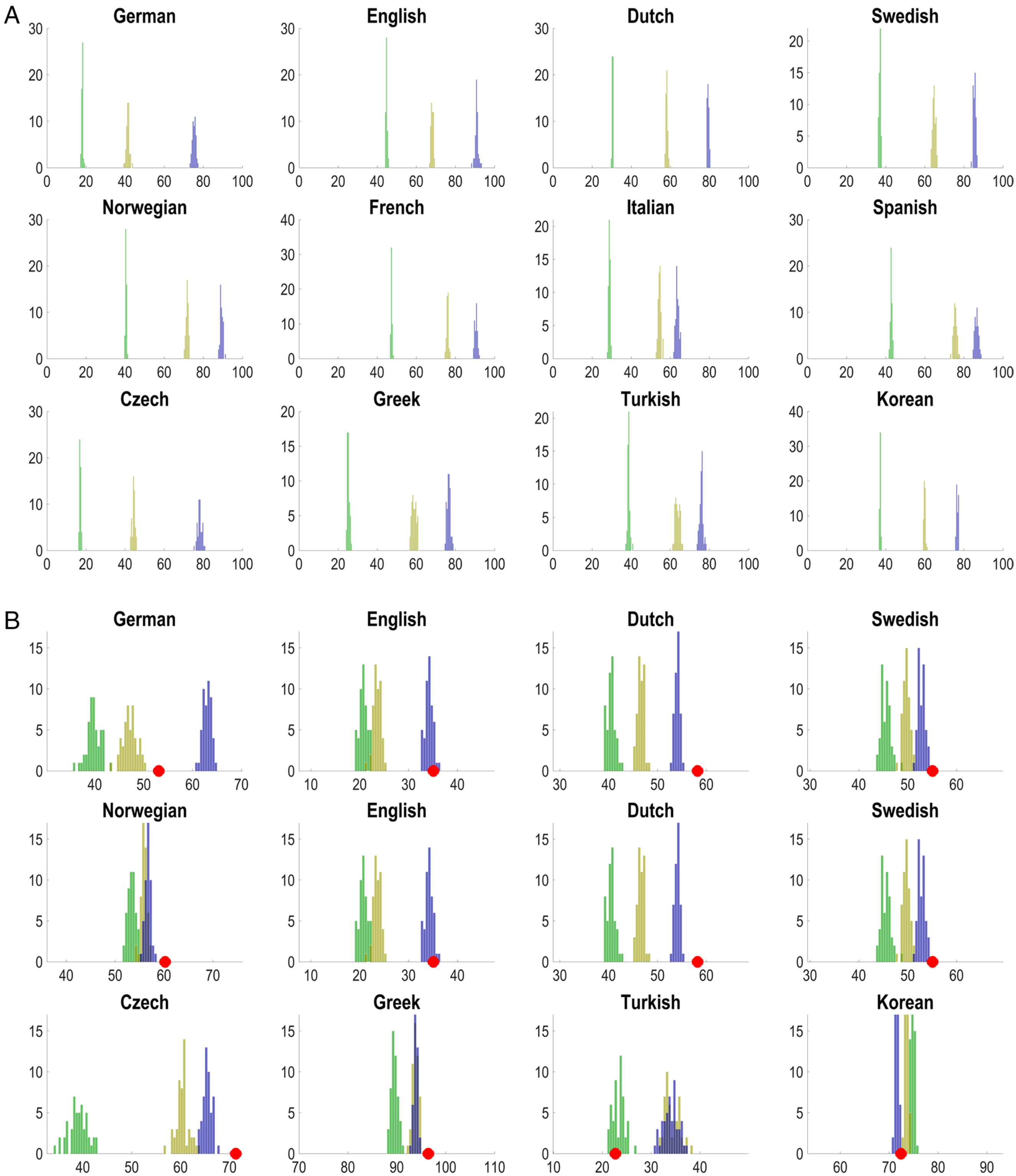

Fig. 6. Comparisons between three types of simulated lexicons and the real lexicon. (*A*) Ratio (in percentage) between the number of minimal pairs observed in Basic (green), Hierarchical (yellow) and Hierarchical+Transitional (purple) lexicons and that observed in the real lexicon. The ratio is 100% when the number of minimal pairs observed in a simulated lexicon equals to the number observed in the real lexicon of that language. (*B*) Comparison between the level of onset biases in functional load (in percentage) observed in the real lexicon (red circle) and those in the Basic (green), Hierachical (H) and Hierarchical+Transitional lexicons (purple).

confirm consistent positional biases between processing reliability and the storage of lexical informativeness, results from lexicon simulations suggest that the onset bias in functional load is not *solely* underpinned by the pressure to maximize reliability or efficiency during speech operations. First, it is generally assumed that skeletal and inventorial disadvantages of syllable coda reflect the inferior processing reliability of syllable coda consonants, as reduced articulatory gestures have been linked to weakening or loss of syllable coda consonants during diachronic change of languages (43–46). However, our results show that size differences in skeletal and inventorial attributes between syllable onset and coda cannot fully account for the level of onset bias in functional load (Fig. 5*B*, see *SI Appendix*, *Supporting Text 4* for an assessment of discrepancies among the examined languages). Additionally, while the application of hierarchical and transitional constraints further enhances the onset-coda asymmetry in both inventory size and functional load in most examined languages (*SI Appendix*, *Supporting Text 4* for more detailed discussions), it is important to note that these syllable-specific "phonotactic" constraints reflect a mixture of phonological and morphological factors. For instance, in German, the consonant /j/ is only allowed to occur at the onset of a word- or morpheme-initial syllable (47). Similarly, in Norwegian and Dutch, certain consonant clusters are not allowed at the beginning of any native words of the language, while speakers have no difficulty pronouncing these clusters at the beginning of loan words (48, 49). In these cases, the exclusion of certain phonemes from a position-specific inventory is not due to low processing reliability in speech perception or production but is governed by specific morpheme structure rules of the language.

In fact, even without considering articulatory and auditory asymmetries between the two positions, it is uncontroversial to assume higher impact of consonants at syllable onset than those at syllable coda for lexical retrieval. Since onset always precedes coda within the same syllable, lexical retrieval would be more efficient if word-contrasting information is provided at the beginning of syllables rather than at the end. Studies on speech perception and production support this view (50–52). For instance, speakers have more difficulties producing a pair of CVC words that contrast with each other by coda consonants (e.g., "cat"—"cab") than by onset consonants (e.g., "cat"—"bat") (50). This finding is interpreted as a *sequential interference effect* from competitions among words that shared the initial phonemes (referred to as *cohort* in speech perception literature). Similarly, speech perception studies showed response facilitation to words that follow a prime with an onset contrast (e.g., "cat"—"bat") (52) and inhibition following a prime with a coda contrast (e.g., "cat"—"cab") (51). These findings suggest benefits for lexical retrieval if the lexicon contains more wordform neighbors with onset contrast than those with coda contrast (53). Our findings align with this view. It is important to note that previous studies mainly used monosyllabic CVC words, for which syllable and word boundaries overlap. Our results with multisyllabic words dissociate syllable boundaries from word boundaries and demonstrate that the functional load primarily decreases from the onset to coda within the syllable unit. This finding offers a new perspective on the impact of sequential position of phoneme difference during lexical retrieval. Specifically, one would expect a cyclic occurrence of the sequential interference effect from the onset to coda of each syllable of multisyllabic words.

Linguistic theories typically posit that words are stored in the mental lexicon as sequences of phonemes (13, 14). Our findings do not challenge phonemes (or phone-sized units) as the essential representational unit for representing words in the mental lexicon, as these units present both the optimal level of abstraction and size to account for most phonological and morphological phenomena cross-linguistically (54, 55). However, our data demonstrate that considering phonological wordforms as mere serial sequences of phonemes cannot fully capture important characteristics of the organization of wordforms in the lexicon. Specifically, we show that a phoneme's position within the syllable is more informative than its position within the word for determining the importance of the phoneme in distinguishing the word from its phonological neighbors. This is consistent with previous research showing that listeners have a stronger sensitivity to syllable position as opposed to word position when learning novel phonotactic rules (56). The strong imprint of syllables in the organization of segmental units within wordforms raises the possibility that the SP of phonemes may also be part of lexical storage. This idea resonates with speech production models that propose the storage of syllable structure in the mental lexicon (19, 57, 58). Meanwhile, to what extent syllabic information of phonemes can be deduced by phonological processing outside the mental lexicon during speech operations is still a matter of debate (see ref. 59 for a competing view). Since lexical wordforms lie at the intersection of acoustic-articulatory correlates and semantic-morphological representations, further investigation of semantic-morphological attributes of phonemes at different SPs may shed light on the status of syllabic information in the mental lexicon.

An imprint of syllables in organizing wordforms in the mental lexicon can also be related to the crucial role of syllables in the initiation of infants' phonological repertoire. Infants show sensitivity to syllable-size units from the earliest days of their life (60, 61). This sensitivity is strengthened by exposure to child-directed speech which presents slower speech rates and more regularized rhythmicity than adult-directed speech (62, 63). In parallel, infants from 1 to 3 mo quickly become sensitive to subsyllabic constituents, such as onset (64) and coda (65), which correspond to phone-size units. These findings show that infants are capable of extracting acoustic information delivered at both phone-size and syllable-size time windows from speech input to initiate their phonological and lexical repertoire. It remains unclear what factors and mechanisms contribute to the determination of disparate functional roles of phone-size units and syllable-size units in storing phonological wordforms in the mental lexicon.

In conclusion, our findings support the conjecture that the SP that is more reliably processed during online speech perception and production is also granted a more prominent functional role in the organization of phonological wordforms in the lexicon. This seems intuitive, but a quantitative cross-linguistic demonstration provides definitive data. Our simulation data further indicate that the syllables, besides being a central computational unit during speech operations, play an essential role in maintaining both phonological similarities among wordforms and consistent positional asymmetries in contrasting phonologically neighboring words. These involvements support the representation of the syllable as a grain-size organizing principle for storing the network of phonological wordforms in the human lexicon.

Materials and Methods

Lexical Databases. Table 2 gives a description of lexical databases from the 12 languages that were analyzed in the current study. Our analyses required following information from each database: lemma status; phonemic transcription; syllabification; additional phonological properties, such as stress pattern and tonal pattern, if they are used in the languages. Most databases provided all the information except for two languages for which we retrieved certain phonological information from another source or create them by ourselves (*SI Appendix, Supporting Text 3*). We focused the analysis on the *lemma* representation of words (*SI Appendix, Supporting Text 3*) and removed duplications of phonological wordforms in order to avoid repetitive counting of the same minimal pairs. The total number of unique lemmas from each database that were induced in the analysis was given in Table 2.

Computation of Functional Load of Syllable Onset and Coda. We computed the functional load of syllable onset and coda via the measurement of minimal pairs (see *SI Appendix, Supporting Text 3* for more information). For each language, we first identified all minimal pairs that differ with each other by substituting a single consonant (Table 2). This procedure revealed that on average 25.71% (SD = 9.63%) of the words from each lexicon form at least one minimal pair with another word by substituting a single consonant (Table 2). We then labeled each minimal pair with the SP (*onset* or *coda*) of the consonants that

Table 2. Description of lexical databases

Language	Database	Number of examined wordforms	Number of minimal pairs	Percentage of words with phonological neighbors
German	WebCelex	50,655	13,289	22.41
English	WebCelex	38,890	24,063	29.01
Dutch	WebCelex	117,237	30,503	17.16
Swedish	NST lexical database for Swedish	97,325	18,842	13.38
Norwegian	NST lexical database for Norwegian	65,142	20,239	17.63
French	Lexique 3.81	40,138	22,893	31.53
Italian	PhonItalia 1.10	42,232	11,617	22.39
Spanish	BuscaPalabras	26,349	10,494	26.41
Czech	Phonological Corpora of Czech	44,869	11,123	25.09
Greek	GreekLex 2.1	35,047	5,964	17.58
Turkish	Turkish Electronic Living Lexicon (TELL)	15,259	9,079	41.88
Korean	K-SPAN	55,599	45,019	44.01

All lexical databases can be accessed freely online: German, English and Dutch: WebCelex (http://celex.mpi.nl/); Swedish: NST lexical database for Swedish (https://www.nb.no/sprakbanken/en/resource-catalogue/oai-nb-no-sbr-22/); Norwegian: NST lexical database for Norwegian (https://www.nb.no/sprakbanken/en/resource-catalogue/oai-nb-no-sbr-23/); French: Lexique 3.81 (http://www.lexique.org) (66); Italian: PhonItalia1.10 (67); Spanish: BuscaPalabras (68); Czech: Phonological Corpus of Czech (https://ujc.avcr.cz/phword/); Greek: GreekLex 2.1 (69); Turkish: TELL (http://linguistics.berkeley.edu/TELL/); Korean: K-SPAN (70).

differed between the two words and counted the total number of minimal pairs that involved the substitution of consonants at syllable onset (MP_{onset}) and at syllable coda (MP_{coda}). Finally, we computed the functional load of each SP (FL_{onset} and FL_{coda}) by calculating the proportion of minimal pairs that involved each SP among all the identified minimal pairs (i.e., $MP_{onset} + MP_{coda}$), following (**1**).

$$FL_{position} = \frac{MP_{position}}{MP_{onset} + MP_{coda}} \times 100\% \cdot \qquad [\mathbf{1}]$$

Note that our measurement of functional load does not take into account word frequency. Combining this measure with the use of the lemma representation of words, our approach aims to characterize how syllable onset and coda contribute to the interconnection of wordforms within the "core" lexicon of the language, rather than investigating the relevance of the two positions for the retrieval and processing of the stored wordforms during language use. This measurement also allows for more straightforward examination of phonological underpinnings for the onset bias in functional load in our follow-up analyses using a lexicon simulation approach (*SI Appendix*, *Supporting Text 3*).

Analyses of the Variation of Functional Load across Individual Onset and Coda Positions within Multisyllabic Words. We focused on words that contain from 2 to 4 syllables and computed, for each word length, the functional load of onset and coda positions of each syllable (see *SI Appendix*, *Supporting Text 3* for more details). We then examined, for each word length, whether the variation of functional load across individual syllable onset and coda positions can be better accounted for by the asymmetry between SPs (onset vs. coda) or by an overall decay following the GO of these positions from word beginnings to word endings. We constructed two linear mixed models using Functional Load as the dependent variable: The first model used SP as the fixed effect; the second model used GO as the fixed effect. Both models included Language as the random effect for both intercept and slope of the fixed effect. These analyses were conducted using the "fitlme" function of MATLAB (R2022a) (The MathWorks, Natick, MA, USA).

Skeletal Occurrence and Inventory Size of Syllable Onset and Coda. For each language, we defined the *skeletal occurrence* of syllable onset and coda as the respective frequencies of occurrence of syllable onset and coda positions across the syllabified CV skeletons of all the words in the lexicon (see *SI Appendix*, *Supporting Text 3* for more details). For the measurement *of inventory size* of syllable onset and coda, we counted the number of unique consonants that were found to occur at each SP in summarizing all skeletal slots that contain a single consonant (i.e., C-slots), assigned to that position (see *SI Appendix*, *Supporting Text 3* for more details).

Lexicon Simulation. The goal of lexicon simulation is to generate wordforms based on specific skeletal and inventorial regularities of syllable onset and coda positions, which enable us to explore how these regularities influence the way wordforms contrast with each other. Since the current study focuses on syllable onset and coda, we restricted our simulation procedure to consonants only. That is, our procedure recreates all consonants of each real word in the lexicon of a language, while leaving the vowels in these words unchanged. Each new wordform is generated by i) removing the consonant (or consonant cluster) from each skeletal slot of syllable onset and coda of the original real word and ii) refilling the vacated skeletal slot with a consonant (or consonant cluster) that is randomly selected from an inventory of consonants (or consonant clusters) that is associated with the SP of the skeletal slot (Fig. 5*A*). The procedure ends when a new wordform has been generated for each real word of the lexicon.

For each language, we generated three types of simulated lexicons which differed in the phonological/phonotactic specificity of consonant inventories that were deduced for each slot of syllable onset and coda (see *SI Appendix*, *Supporting Text 3* for more details). *Basic* (B): For this simulation type, all skeletal slots, of the same size, of syllable onset or coda were associated with a common, broad, consonant inventory of that SP. *Hierarchical* (H): For this simulation type, each skeletal slot of syllable onset or coda was associated with a consonant inventory that was specific to positional and structural properties of the syllable that hosted the slot. *Hierarchical+Transitional* (H+T): for this simulation type, each skeletal slot of syllable onset or coda was associated with a consonant inventory that was specific to positional and structural properties and the nucleus of the host syllable.

We used a *z*-score analysis (12) to compare the onset bias in functional load observed in the real lexicon to those from each type of simulated lexicons. We computed the *z*-score of the onset bias from the real lexicon using the mean and SD estimated from the distribution of the amount of onset biases in the simulated lexicons. We then deduced the probability (*P*-value) with which each measurement of onset bias from the real lexicon could have arisen by chance from the distribution of the amount of onset biases observed in the simulated lexicons.

Data, Materials, and Software Availability. All data used for and generated from various analyses in the study as well as the scripts for data analysis and figure generation are available at the Edmond Open Access Data Repository of the Max Planck Society (https://doi.org/10.17617/3.WYTLIE) (71).

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