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On the Origins of Phonology

Iris Berent
Department of Psychology, Northeastern University

Abstract

Why do humans *drink* and *drive* but fail to *rdink* and *rdive*? Here, I suggest that these regularities could reflect abstract phonological principles that are active in the minds and brains of all speakers. In support of this hypothesis, I show that (a) people converge on the same phonological preferences (e.g., *dra* over *rda*) even when the relevant structures (e.g., *dra, rda*) are unattested in their language and that (b) such behavior is inexplicable by purely sensorimotor pressures or experience with similar syllables. Further support for the distinction between phonology and the sensorimotor system is presented by their dissociation in dyslexia, on the one hand, and the transfer of phonological knowledge from speech to sign, on the other. A detailed analysis of the phonological system can elucidate the functional architecture of the typical mind/brain and the etiology of speech and language disorders.

Keywords

phonology, language universals, universal grammar, domain specificity, sign language, dyslexia

Traffic laws ban *drinking* and *driving*. Far less clear, however, are the principles that prompt people to avoid *rdinking* and *rdiving*. These restrictions, to be sure, are not unique to English. Every spoken language forms words by combining meaningless elements (i.e., phonology), and across languages, sequences such as *rda* are systematically underrepresented (Greenberg, 1978). What is the basis of such restrictions? Could these facts unveil the architecture of the cognitive system and its specialization for phonology?

To appreciate the phonological patterns of humans, it is useful to compare them with the vocal communication patterns of nonhuman species. This broader biological perspective also informs our analysis of specialization in cognitive/neural systems. Against this background, I proceed to evaluate the specialization of the phonological system and its universality across input modalities (speech and sign). I conclude by considering some implications of this approach for speech and language disorders.

Vocal Sound Patterns in Nature: Generic Sensorimotor Pressures or a Specialized Biological System?

Many species rely on vocal patterns of communication, and as in human phonology, their structure is often constrained. Just as humans favor *dra* over *rda*, swamp sparrows from the New York area generate I_VI syllables (where I and VI are two notes, and _ stands for any note) but not VI_I sequences (Balaban, 1988).

Faced with the restrictions on swamp sparrow songs, one immediately wonders whether these patterns are the product of a specialized biological system. "Specialized," here, refers to a system designed for vocal communication, specifically. It shapes not bird intelligence generally nor motor dexterity or auditory acuity. Rather, this birdsong system has specifically evolved to constrain the structure of song (in mature animals) and guide its acquisition (in development). Those innate constraints, in turn, are universally active in all members of the species, and possibly unique to them alone.

Unlike vocal patterns in nonhumans, for which domain-specific constraints are typically invoked, when it comes to vocal patterns in our own species, this possibility is usually dismissed outright. When asked, "Why *dra*, but not *rda*?", the answer would seem trivial. First, many English words begin with *dr*, but none with *rd*. Second, sequences such as *dra* are easier for the sensory and motor channel to process. Linguistic sound patterns, then, are molded by linguistic experience and sensorimotor

Corresponding Author:
Iris Berent, Department of Psychology, Northeastern University, 125 Nightingale Hall, 360 Huntington Ave, Boston, MA 02115
E-mail: i.berent@neu.edu

constraints—no specialized biological system for phonology is required.

Do we humans possess the seemingly unique biological capacity to weave our vocal communicative patterns using mechanisms that are not specifically designed for this purpose? Put differently, are human brains special in their nonspecialization? To address these questions, we must take a closer look at the notion of "specialization."

Specialized Biological Systems: The Argument From Design

Whether the human mind/brain is innately equipped with specialized cognitive systems has been the topic of a heated debate. Some researchers assert that specialized systems are (a) encapsulated from external sources of information and (b) implemented in discrete brain regions that are segregated from those controlling other functions (Fodor, 1983). In the case of language, this approach would assume that processing in the language system is immune to nonlinguistic sources of information and that it is localized in a brain region that responds to language alone. But as Jerry Fodor himself noted, these conditions are both too strong and too weak.[1]

They are too strong inasmuch as a specialized cognitive system could well interact with other systems, contrary to (a), and it could be implemented in a distributed brain system whose components serve other cognitive functions, contra (b); in fact, given that evolution is a tinkerer, this scenario is only expected (Marcus, 2008). At the same time, the segregation and encapsulation assumptions are also too weak inasmuch as they also characterize acquired skills, such as chess playing and wine tasting—skills that couldn't possibly be innately specialized.

In what follows, I therefore suggest a different approach. My analysis focuses on a well-known hallmark of biological specialization, namely, design. Specialized biological systems are defined by their unique design, which is specifically selected for their function (Dawkins, 1987). Human eyes and lungs exhibit unique anatomies that are specifically designed for analyzing optical inputs and extracting oxygen, respectively.

Unique, universal design likewise defines specialization of cognitive systems, such as language. Just as the unique structure of the swamp sparrow song suggests a specialized song mechanism, so would phonological universals in humans imply a specialized phonological system. Note that a specialized phonological system could still give rise to certain variation across languages, akin to the individual differences in eye color and shape. Similarly, because the structure of specialized biological systems is designed to support their function, phonological structure is expected to optimize language transmission by the sensorimotor channel. Accordingly, finding that a certain principle improves speech perception and production but is occasionally violated does not show that it cannot be universal or innate. Universal phonological principles need not be functionally arbitrary or absolute. However, putative phonological universals should emerge even if the relevant structures are absent in an individual's own language, and they should demonstrably differ from sensorimotor pressures. Some examples follow.

The Design of Phonological Patterns

Phonological systems follow two broad design properties (Berent, 2013). First, they rely on abstract principles that are discrete and combinatorial (i.e., rules). Second, certain phonological rules appear to be universal across languages. The abstraction of phonological rules distinguishes them from sensorimotor pressures. As such, phonological preferences (e.g., for *dra* over *rda*) cannot be sensorimotor.

A discrete combinatorial pattern maker

To appreciate the distinction between the phonological and the sensorimotor systems, let us consider two general types of biological systems: blending and combinatorial systems (Abler, 1989). Combinatorial systems (e.g., DNA) form new combinations from discrete building blocks (e.g., the bases A, C, T, and G) whose individual identities are maintained in combinations (e.g., the base A is identifiable in the genetic code for hemoglobin, GAG). By contrast, in blending systems (e.g., color perception), the identities of the ingredients (e.g., the colors blue and yellow) are lost when they are mixed together (e.g., in green).

The sensorimotor speech system is a blending system. Just as the color green presents no identifiable yellow bit, so do the acoustic signals corresponding to *di, da*, and *du* include no invariant *d* portion—our *d* percept is the product of context-sensitive mixing of cues (Liberman, Cooper, Shankweiler, & Studdert-Kennedy, 1967). Phonology, by contrast, is a combinatorial system. Accordingly, when the syllables *ma* and *ma* are combined to form a sequence, they yield not to a single, louder *ma* blend but rather a disyllabic *mama*.

It is precisely because phonological elements are discernable in combination that phonology can form patterns. Doubling (generally, XX, where X is a single phonological element), as in *mama*, is one such abstract pattern that is central to every known phonological system (Suzuki, 1998) and is arguably formed by powerful, algebraic rules (X $\rightarrow$ XX; Berent, 2013; Marcus, 2001). The possibility that phonology is an abstract combinatorial system, distinct from the sensorimotor channel, is further supported by the finding that sensitivity to phonological patterns is dissociable from the acoustic and motor demands of the stimulus (see "Phonological universals in the brains of individual speakers" below) and that certain phonological restrictions apply to both speech and signs (see "Amodal Design: Phonology by Mouth and by Hand" below). Given that the computational properties of phonology are distinct from the sensorimotor system, the two systems cannot be one and the same.

Phonological universals in the brains of individual speakers

Not only are phonological patterns formed by abstract rules, but those rules are potentially universal (Prince & Smolensky, 1993/2004) and possibly specialized for phonology. As a case study, I consider the restrictions on syllable structure.

Across languages, syllables such as *blif* are preferred (e.g., more frequent) relative to syllables such as *bnif*, which in turn are preferred to syllables such as *bdif* or *lbif* (Berent, Steriade, Lennertz, & Vaknin, 2007). The syllable hierarchy has been attributed to abstract phonological principles that are universal (Smolensky, 2006).[2] Our question is whether speakers represent the syllable hierarchy even when most or all syllable types do not occur in their language.

We gauge people's phonological preferences from a phenomenon of phonological repair. We reason that if the syllable hierarchy is the product of universal phonological principles, then syllables that violate these principles will not be encoded faithfully by the language system; instead, violators will be recoded (i.e., repaired). And since repairs often separate the illicit consonant sequence by inserting an intermediate vowel (e.g., *Bnei Israel* → *Benei Israel*), we expect ill-formed monosyllables (e.g., *lbif*) to be misidentified as disyllables (e.g., *lebif*)—the worse formed the syllable, the more likely its repair.

Systematic misidentification, then, could potentially reflect universal phonological rules. Our research asked two questions. First, do speakers of different languages converge on the same pattern of misidentification? Second, does misidentification indeed reflect universal phonological rules?

Results (see Fig. 1) showed that as the syllable became ill-formed on the hierarchy, misidentification systematically increased, and these findings obtained in speakers of English (Berent et al., 2007), Spanish (Berent, Lennertz, & Rosselli, 2012), Korean (Berent, Lennertz, Jun, Moreno, & Smolensky, 2008), and Chinese (Zhao & Berent, 2016). The results from Korean and Chinese are particularly interesting, given that these languages lack complex onsets of any kind, so these preferences are not easily explained by experience with similar syllables.

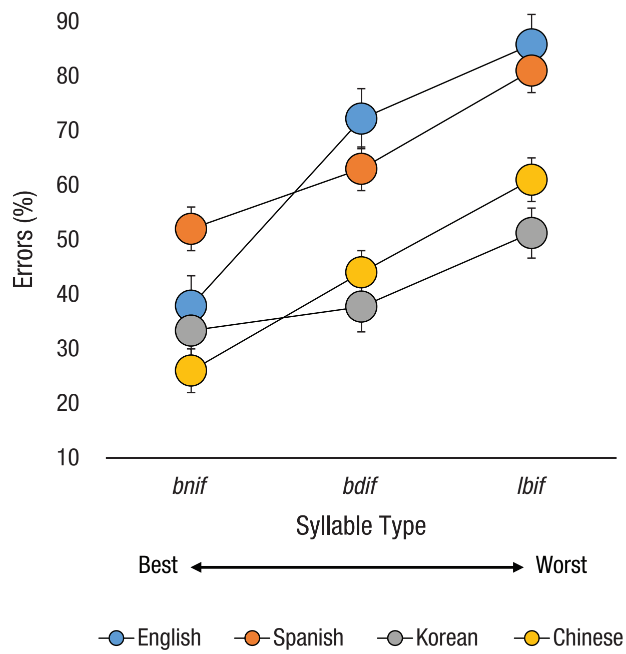
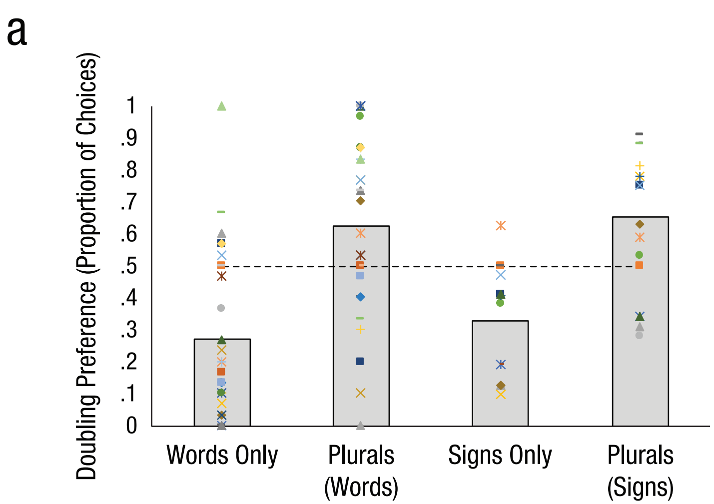


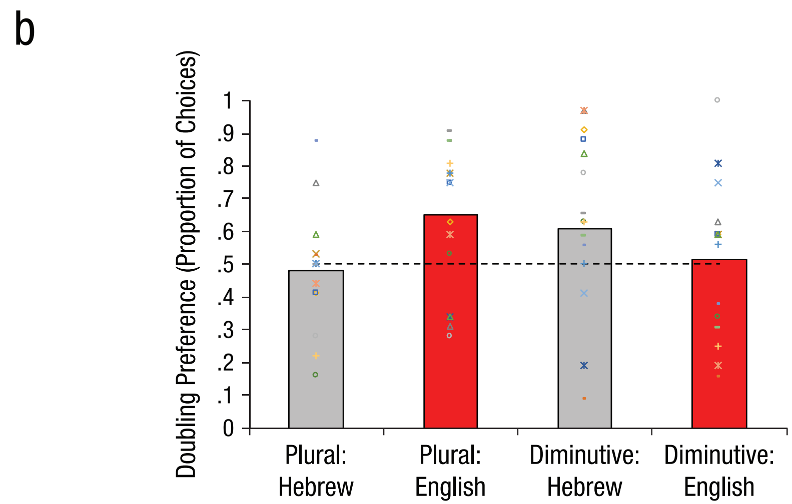
Fig. 1. Findings showing sensitivity to the syllable hierarchy. Participants in these experiments were presented with spoken monosyllables (e.g., *lbif*) and their disyllabic counterparts (e.g., *lebif*). Participants performed one of two tasks. In the syllable-count task, people heard one stimulus at a time and provided a syllable count (e.g., does *lbif* comprise one syllable or two?); in the identity-judgment task, participants were presented with two stimuli in succession (e.g., *lbif-lbif; lbif-lebif*) and determined whether they were identical. Results from the two tasks show that as the monosyllabic stimulus became worse formed, errors monotonically increased. Results from English, Spanish, and Korean are based on Experiment 1 of Berent, Steriade, Lennertz, and Vaknin (2007), Berent, Lennertz, and Rosselli (2012), and Berent, Lennertz, Jun, Moreno, and Smolensky (2008), respectively; the Chinese results are from nonidentical trials in Experiment 2 of Zhao and Berent (2016). Error bars show 95% confidence intervals for the difference between the means.

Misidentification unlikely originates solely from auditory/phonetic difficulties, given that similar results obtained with printed stimuli (Berent & Lennertz, 2010). It is also unlikely that people misidentify ill-formed syllables only because they overtly simulate their production (e.g., they are unable to articulate *lbif*). If that were the case, then sensitivity to the syllable hierarchy would be attenuated when the motor system is disrupted. However, people remained fully sensitive to hierarchy even when the lip motor area in the brain was disrupted using transcranial magnetic stimulation (Berent et al., 2015). Similarly, an fMRI experiment showed that ill-formed syllables did not increase activation in motor areas, but they did engage the posterior part of Broca's area—a classical language region (Berent et al., 2014).

Another set of experiments using near-infrared spectroscopy demonstrated that the preference for well-formed syllables obtains in neonates (Gómez et al., 2014). In these experiments, infants heard a stream of monosyllables produced by a Russian talker[3]—either well-formed



	Words Only	Plurals (Words)	Signs Only	Plurals (Signs)
Step 1		X__=		X__=
Step 2	*slaflaf/slafmak*?	?__=	=?	?__=



	Plural: Hebrew	Plural: English	Diminutive: Hebrew	Diminutive: English
Step 1	X__=	X__=	X__=	X__=
Step 2	?__	?__	?__	?__

Fig. 2. Findings and stimuli from experiments demonstrating the transfer of phonological principles across modalities. Panel (a) presents results showing English speakers' preference for doubling when forming plurals for novel words and signs. Panel (b) presents results showing English and Hebrew speakers' preference for doubling when forming plurals versus diminutives for signs. The scatter plots present the doubling responses of individual participants, columns indicate the means, and chance level is marked by the dotted line. The tables below each graph illustrate the stimuli from respective forced-choice procedures. Data are from Experiments 1, 2, 5, 6, 10, 11, and 12 in Berent, Bat-El, Brentari, Dupuis, and Vaknin-Nusbaum (2016).

syllables (e.g., *blif*) or worse-formed ones (e.g., *bdif, lbif*). Results showed that ill-formed syllables elicited a stronger hemodynamic response, indicating that their structure was more difficult to compute. These results suggest that speakers disprefer ill-formed syllables even if they have little or no lexical or articulatory experience. It thus appears that syllable hierarchy is governed by abstract phonological principles that are universal, and their precursors are evident at birth.

Amodal Design: Phonology by Mouth and by Hand

If phonological principles are abstract, then they could potentially apply to either speech or sign. And indeed, phonology is not limited to spoken language. Every sign language comprises phonological patterns of meaningless elements. Furthermore, some phonological principles might be shared across modalities (Sandler & Lillo-Martin, 2006).

To illustrate this possibility, consider the restriction on phonological doubling. Doubling refers to the repetition of phonological elements—either full (e.g., *mama*) or partial (e.g., *banana*). Doubling (e.g., *slaflaf*) is systematically avoided in phonology. But when doubling indicates systematic link between form and meaning (e.g., diminutives, as in the Hebrew *klavlav*, "puppy," from *kelev*, "dog"), it is actively promoted. Thus, phonological doubling is avoided, but morphological doubling is preferred.

In a recent set of experiments, my colleagues and I found that people extend these preferences to both speech and signs (Berent, Bat-El, Brentari, Dupuis, & Vaknin-Nusbaum, 2016). To examine doubling preferences in spoken language, we asked English speakers to make forced choices between two novel words—one with doubling (e.g., *slaflaf*) and a no-doubling control (e.g., *slafmak*). In one experiment, people made these choices for meaningless phonological forms (presented either as isolated words or as names for a single object). Results showed that doubling was systematically avoided (see Fig. 2a). In another experiment, participants were first presented with the base *slaf* along with a novel object. They were next shown a set of objects of the same kind and were asked to choose the name for the set (e.g., *slaflaf* vs. *slafmak*). Now that doubling indicated a systematic morphological operation (i.e., plurality), it was consistently preferred. Together, these results demonstrate that people shift their doubling preferences depending on the level of analysis (phonology vs. morphology). Because the stimulus was unchanged, the shift must have reflected abstract principles rather than sensorimotor demands associated with the stimulus itself.

We next asked whether English speakers would extend the same principles to linguistic signs. In these experiments, English speakers who lacked command of any sign language were invited to guess which stimulus formed a better American Sign Language (ASL) sign—a sign with two identical syllables (XX) or two different syllables (XY). Results showed that, when presented with meaningless phonological forms (i.e., doubling was not systematically linked to meaning), people showed a dislike for doubling, akin to the doubling aversion for speech. But once doubling signaled morphological plurality (when the base X was paired with a single object and participants were then asked to name an object set), a significant doubling preference once again emerged. These results show that people extend the same abstract principles to speech and sign.

A final set of experiments showed that speakers' doubling preferences for signs depend on the morphological structure of their spoken language. In these experiments, doubling in signs signaled either plurality (e.g., X = a ball; XX = a set of balls) or diminution (e.g., X = a ball; XY = a small ball). Of interest was whether the interpretation of doubling depended on participants' spoken language—English or Hebrew. English morphology marks plurality, but it does not systematically mark diminution. By contrast, Hebrew morphology marks diminutives by doubling (e.g., *kelev*, "dog," vs. *klavlav*, "puppy"), so doubling invariably indicates semantic attenuation—never augmentation (as required by plurality). If the preference for doubling in signs requires a morphological analysis, then Hebrew speakers should favor doubling in signs when doubling signals diminutives (in line with the morphology of their spoken language), whereas English speakers should show this preference for plurals. Results (see Fig. 2b) were in line with this prediction. Together, these findings suggest that phonological (and morphological) knowledge relies on abstract linguistic principles that apply to both speech and signs.

Translational Implications: The Case of Dyslexia

Beyond its theoretical significance, the structure of phonology also carries translational implications for the host of language disorders that implicate a phonological deficit at their core. Dyslexia presents an instructive case study.

Although dyslexia is defined as a reading disorder, many individuals with dyslexia exhibit subtle impairments to speech perception (e.g., the discrimination of *ba* and *pa*) and the decoding of speech from print (Ramus & Ahissar, 2012). Faced with these facts, many researchers have concluded that dyslexia originates from a phonological deficit. But this conclusion incorrectly equates phonology with speech. As discussed above, phonology is only one of the multiple representations of speech; other (lower) levels include auditory and phonetic forms. Accordingly, difficulties with speech perception could result either from a phonological deficit or from a deficit to those nonphonological sources.

To adjudicate between these possibilities, my colleagues and I compared the state of the phonological and phonetic systems in individuals with dyslexia (Berent, Vaknin-Nusbaum, Balaban, & Galaburda, 2012, 2013; Berent, Zhao, Balaban, & Galaburda, 2016). Results showed various abnormalities in phonetic processing, including the identification of speech sounds and the discrimination of speech from nonspeech. Remarkably, the same individuals showed full sensitivity to various phonological rules. For example, English- and Hebrew-speaking adults with dyslexia were fully sensitive to the syllable hierarchy (Berent et al., 2013; Berent, Zhao, et al., 2016). Put differently, the phonological and phonetic systems dissociate in dyslexia. This dissociation is fully in line with the hypothesis that the phonological system is distinct from lower levels of sensorimotor processing. These results further demonstrate the potential of a linguistically informed approach to illuminate the basis of speech and language disorders.

Summary

This review has examined whether humans are equipped with a specialized mind/brain system for phonology. Specialized biological systems exhibit unique universal designs. To determine whether phonology is a specialized biological system, we have thus investigated (a) whether speakers of different languages converge on shared phonological principles and (b) whether phonological principles are distinct from sensorimotor pressures.

One line of evidence for the dissociation of phonology and the sensorimotor system is presented by their distinct computational properties: Phonological principles are abstract and combinatorial, whereas the sensorimotor system operates by blending. Moreover, speakers of different languages exhibit similar preferences concerning syllables that they have never heard before, and these preferences appear to rely on abstract principles. Further evidence for the abstraction of phonology is presented by (a) the transfer of phonological principles from spoken to sign languages and (b) the dissociation between phonological and phonetic processing in dyslexia. Whether phonological universals indeed exist and whether they are the product of a specialized phonological system remain open questions. Nonetheless, these results illustrate the potential of a linguistically informed approach to elucidate the functional architecture of the human mind and brain and the etiology of language disorders.

Recommended Reading

Archangeli, D., & Langendoen, L. (1997). *Optimality theory*. Oxford, England: Blackwell. Provides a general introduction to phonology.

Berent (2013). (See References). Examines the cognitive architecture of the phonological system and its evolution in ontogeny and phylogeny.

Berwick, Okanoya, Beckers, and Bolhuis (2011). (See References). Provides a general discussion of birdsong structure.

Brentari and Coppola (2013). Provides a discussion of sign language phonology and its spontaneous emergence.

Elman et al. (1996). Provides a critic of domain specificity, in contrast to that of Fodor (1983) and Pinker (1994).

Evans (2014). Provides a modern critic of domain specificity, in line with that of Elman et al. (1996).

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Glossary

Domain-general system. A system of the mind/brain whose operation is not specific to any particular cognitive domain.

Domain-specific system. A system of the mind/brain that is innately designed for the processing of information in a particular domain (e.g., language, vision, number).

Morphemes. Units that pair phonological form and meaning. For example, the word *cans* comprises two morphemes (the base noun *can* and the plural suffix *s*).

Morphology. Our knowledge regarding the links between word forms and meaning. For example, regular English plurals (e.g., *dogs*) are formed by a morphological operation that appends the suffix –*s* to the singular base (e.g., *dog*).

Onset. The consonant or consonant cluster that occurs at the beginning of a syllable (e.g., *bl* in *block*). Onsets that comprise a single consonant are simple; onsets with multiple consonants are complex.

Phonetics. The system responsible for the extraction of discrete phonological elements (e.g., the phonemes /b/ and /p/) from the analog sensory signal (e.g., speech). To use a metaphor, if phonological elements are likened to Lego blocks, then phonetics is the system that extracts blocks from the plastic stuff.

Phonology. Our knowledge concerning the patterning of meaningless linguistic elements—either spoken or signed. For example, English phonology allows speakers to conclude that the meaningless pattern *blin* is a possible word in their language, whereas *lbin* isn't. Similar meaningless patterns also define the structure of manual linguistic signs.

Sonority. A scalar phonological property that correlates with the loudness of consonants; the louder the consonant, the higher its sonority. Least sonorous (softest) are stops (e.g., *b, p*; s = 1); next come nasals (e.g., *m, n*; s = 2), followed by liquids (e.g., *l, r*; s = 3).

Sonority profile (Δs). The sonority profile of a syllable reflects dynamic changes in sonority. For example, the sonority profile of the initial consonant sequence (onset) is obtained by subtracting the sonority of the second consonant from the first. For *bnif*, Δs = 1; for *bdif*, Δs = 0; whereas for *lbif*, Δs = −2.

Syllable (in birdsong). A unit of birdsong that comprises smaller elements, called notes.

Syllable (in human phonology). A meaningless phonological unit that minimally includes a single sonority peak (typically, a vowel).

Syllable hierarchy. A hierarchy of syllables that differ systematically on their grammatical well-formedness and their frequency across languages. One such hierarchy is defined by the sonority profile (Δs) of the onset consonant cluster (e.g., *bn* in *bnif*)—as Δs decreases, the syllable becomes worse formed. Thus, best formed (and most frequent) is *bnif* (Δs = 1), followed by *bdif* (Δs = 0); worse formed (and least frequent) is *lbif* (Δs = −2). Note that this generalization defines the structure of consonant clusters occurring at the onset of the syllable; syllable-final consonants exhibit the opposite preference.

Transcranial magnetic simulation. A non-invasive technique that modulates (either increases or decreases) activation in specific brain regions via electromagnetic induction.

Declaration of Conflicting Interests

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Notes

1. Unlike many who subsequently discussed his work, Fodor himself did not consider these conditions necessary for specialization.
2. In modern phonology, all phonological principles are violable, so languages can differ on the type of syllable they allow. English, for instance, allows *blif* but not *lbif*, whereas both syllables are attested in Russian. Nonetheless, the restrictions on syllable structure are demonstrably active in both languages.
3. We chose a Russian talker because the Russian language allows all these syllable types (e.g., *bnif, bdif, lbif*), so these stimuli could be produced naturally.

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