Title

Phonological Abstraction in The Mental Lexicon

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Phonological Abstractness in the Mental Lexicon

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1 Talking and Listening

When we try to understand how we speak, and how we listen, an unavoidable fact is that we use the same vocabulary items again and again. So, not only are these stored in memory, but they are learned on a language-specific basis. In this way, we directly confront the issue of mental representations of speech; that is, something about how we store, retrieve and remember units of speech. What are these units? What are these mental representations? These questions are central to generative phonology, a fact reflected in the title of a collection of important papers by Morris Halle, a founder of the field: *From Memory to Speech and Back Again* (Halle, 2003).

In this chapter we review some of the most basic — and most fascinating — conclusions and open questions in phonology regarding how abstract these mental representations of speech are. In an era of big data, and data mining, the prevailing attitude in science and scientific observation seems to be to store every last detail, to never assume any detail is irrelevant, no matter how small, because you never know when it may in fact make a difference somewhere. This attitude is also present in the psychology of language, where it has been shown that people are sensitive to astounding details of aspects of speech reflecting people's age, gender, social status, neighborhood, and health (Coleman, 2002; Pierrehumbert, 2002; Johnson, 2006). Pierrehumbert (2016) reviews this literature and highlights some

theoretical accounts.

In the context of this prevailing attitude, the theory of generative phonology makes some surprising claims. First, it claims it is *necessary* to abstract away from much of this detail to explain systematic aspects of the pronunciations of the morphemes, words, and phrases we utter. In other words, while a person is sensitive to subtle phonetic details which are informative about various aspects of a speaker's condition, the theory of generative phonology claims those very same details are *irrelevant* to the very same persons' mental representations of the *pronunciations* of morphemes and words. As such the mental representations of these pronunciations are particular abstractions. We review the arguments for this position in section 3. Section 4 shows how these ideas lead to the *phoneme*, a necessarily abstract category of speech units, which is said to be the fundamental unit out of which the pronunciation of vocabulary items are built.

We then turn to a question posed by Paul Kiparsky: *how abstract is phonology?* (Kiparsky, 1968) — or, more specifically, *how abstract are the mental representations of speech?* A vigorous back and forth debate over this question followed, but now, over fifty years later, there is still no consensus regarding the answer. A basic problem is that some languages present good evidence that morphemes are specified with phonological content that is never realized as such in any surface manifestation of those morphemes. At issue is precisely what kind of evidence justifies such abstract phonological content. In our minds, this question, and others related to it, are particularly important and remain among the most interesting, and understudied, questions in phonology today.

But first, we begin this chapter with some thoughts on the nature of abstraction and idealization.

2 What is abstraction?

The first thing to point out about abstraction is not how odd it is, but how common it is. Orthographic letters are abstractions. The capital letter "A" and the lowercase letter "a" are quite different, and yet at some level of abstraction they are referring to the same thing. Money is an abstraction. Whole numbers and fractions are also abstractions. For example, there is no such thing as "three." There are only examples of collections of three items. Such abstractions are not just taken for granted, but they are valued: the earlier toddlers and young children learn such abstractions, the more we marvel at their intelligence.

A very common approach to problem solving one learns in grade school is shown in the diagram in Figure 1.

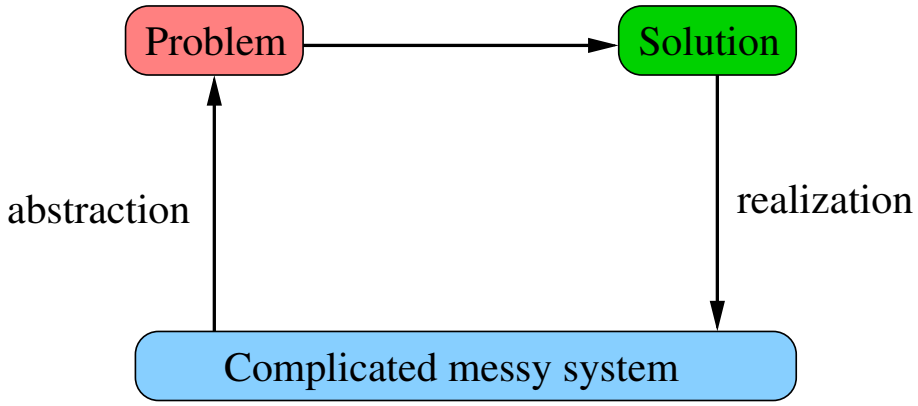

Figure 1: Abstraction, Problem-Solving, and Realization

For example, in an elementary-level math class, students are often given a problem expressed in plain language. Their job is to extract the relevant information, organize it into an equation, solve the equation, and report back the answer. Figure 2 shows a 4th grade math exercise.

Similarly, when responding to challenges that his law of falling bodies did not correspond to the real world, Galileo used an analogy to accounting:

> what happens in the concrete [...] happens in the abstract. It would be novel indeed if computations and ratios made in abstract numbers should not thereafter correspond

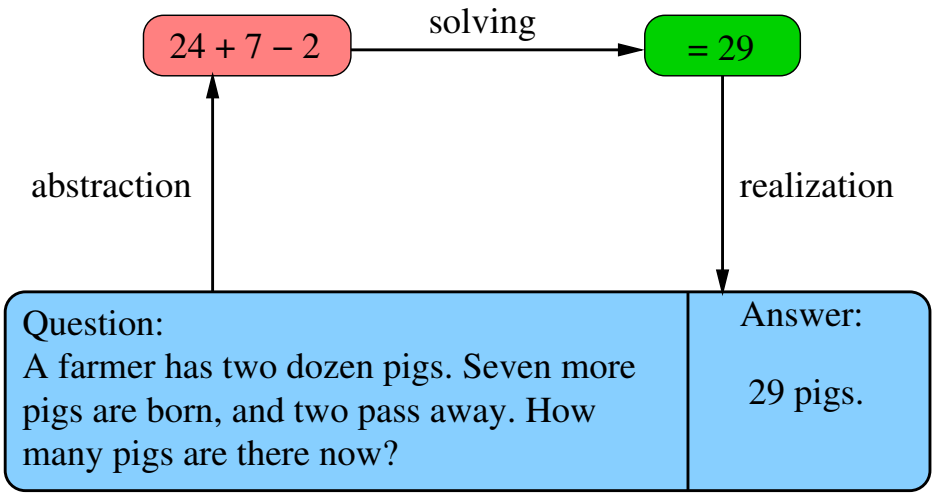

Figure 2: A 4th grade math exercise illustrating the process in Figure 1.

> to concrete gold and silver coins and merchandise [. . .] (quoted in Wootton (2015, pp. 23–24))

Here Galileo mentions an important feature: one can make computations with abstract numbers without directly referencing the particular objects that implement them. Given a proper abstraction, one can make an inference or calculation at the level of numbers with results that then correspond to some specific physical effect or process. This property, that a given abstraction can have many implementations, is known as **multiple realizability** (Bickle, 2020). An abstract object is multiply-realizable by a number of concrete objects. The concrete objects might differ from each other in various ways, but the ways in which they differ are irrelevant to the abstraction. Orthographic letters, and the mental representations of units of speech, are abstract in this way, too.

The second important point about abstraction is that there are degrees of abstraction. Even the question in Figure 2 as written in plain language is abstract since, for example, it uses numbers to explain the situation, and not for instance a photograph of the two dozen pigs and/or video of seven pigs being born and two others dying. Figure 3 illustrates the concept of degrees of abstraction. The only change we would make to it would be to add question marks after each of the subcaptions in the figure. The question is always "Is the

level of abstraction too realistic? too abstract? or just right?"

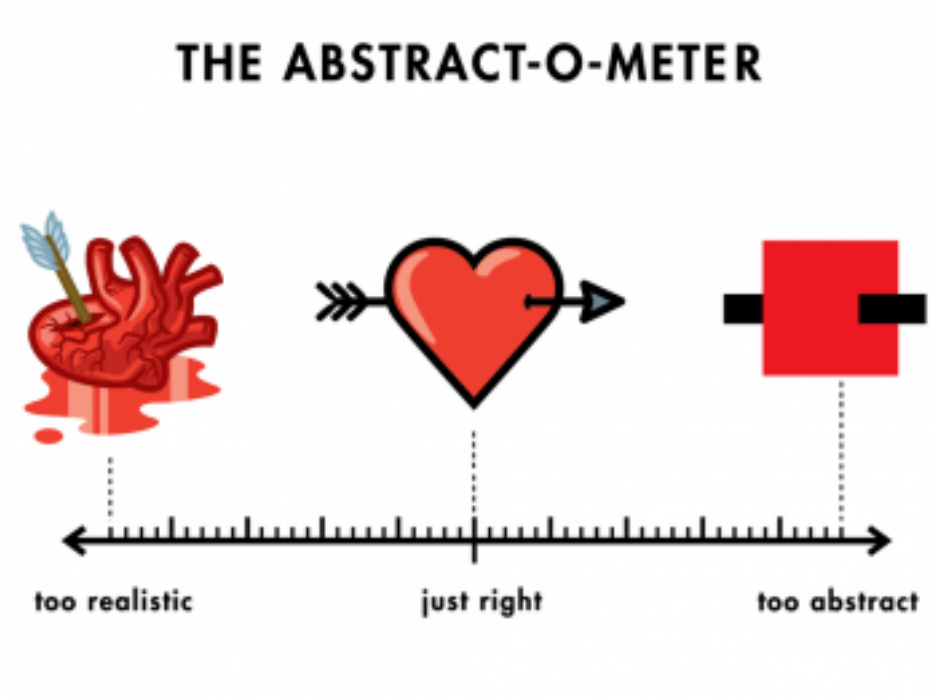

Figure 3: Degrees of Abstraction (from `https://computersciencewiki.org/index.php/Abstraction`).

Answering this question is not easy. It is not at all obvious what the right level of abstraction is. It is appropriate to deliberately consider whether a particular degree of abstraction is appropriate or not. We are in an age of big data and the milieu of the age seems to be to err on the side of "too realistic" and to avoid analyses that are "too abstract." Our own view is that this is shortsighted. Many things were at one time considered to be "too abstract" but are now recognized as being perfectly reasonable and in fact essential and useful.

When one studies the history of mathematics, it is interesting how notions once considered to be "too abstract" were considered crazy or useless. This includes things like the number 0, real numbers, $\sqrt{-1}$, uncountable infinity, number theory, and so on. When Pythagoras and his group realized that $\sqrt{2}$ could not be expressed as a fraction of whole numbers, they called it "irrational," literally "unreasonable." The term sticks today. Cantor went

mad after realizing that infinitely-sized sets had different degrees of cardinality. Today this fact underlies the Church-Turing thesis of computability. The development of the complex numbers caused much costernation in the 17th and 18th centuries but are routinely used today to understand complex physical systems. Developments in number theory in the early part of the 20th century had no purpose other than to satisfy some strange mathematical aesthetic, and now underlie secure cryptographic communications, protecting business operations, journalists, and other vital communications.

In short, we are sympathetic to the view put forth by Cheng (2015, p. 22): "Abstraction can appear to take you further and further away from reality, but really you're getting closer and closer to the heart of the matter".[1]

In this chapter we show that abstractness is a property exploited both by speakers of natural languages and by scientists describing the linguistic knowledge of those speakers.

3 Phonology and the Mental Lexicon

The pronunciation of a word is a sequence of events in time. From the perspective of speech production, these events are defined articulatorily. From the perspective of speech perception, these events can be defined acoustically and perceptually. The International Phonetic Alphabet (IPA) defines categories of speech sounds articulatorily and provides a symbol for each categorized speech sound. For consonants, these symbols specify three aspects of articulation: the place of articulation, the manner of articulation, and the activity of the vocal folds. Symbols representing vowels primarily specify the degree of jaw aperture, how forward the positioning of the root of the tongue is, and any rounding of the lips. For example, the pronunciation of the word 'math' is transcribed in the IPA as [mæθ], as there are three distinct speech sounds in sequence: [m], which is articulated by stopping airflow at the lips but releasing it through the nose, with the vocal folds held together such that

[1] One of the clearest recent expositions on abstractness and its virtues is in Ch. 2 of Cheng's book, *How to Bake* π, which we encourage readers of the present chapter to read.

they vibrate; [æ], which is an open front unrounded vowel; and [θ], which is articulated by constricting but not stopping airflow with the blade of the tongue between the teeth with the vocal folds spread apart. For most speech acts, these articulations are similar across speakers of the same idiolect, despite individual physiological variation.

For a word like 'tune', one transcription of it using the IPA is [tun], often referred to as a *broad transcription*. In contrast, a *narrow transcription* of this word using the IPA is [tʰũːn]. The difference between the broad and narrow transcriptions is the degree of abstraction. Both transcriptions reveal systematic aspects of standard American English speech. However, the broad transcription only includes so-called *constrastive* information and the narrow transcription includes some *non-contrastive* information as well, indicated in this case with various diacritic marks: the aspiration on the [t], indicated with [ʰ], and the nasalization [˜] and extra duration [ː] of the vowel [u]. Both kinds of transcriptions can be used as abstract representations of the pronunciation of this word stored in memory, and one could ask whether the long term memory representation of the pronunciation of the word 'tune' is more like the broad transcription, the narrow transcription, or something else. One can ask if there is only one long-term memory representation of the pronunciation of the word 'tune', or if there are multiple, possibly partially redundant representations. All of these hypotheses are open to study. In the remainder of this chapter, we use broad IPA transcriptions as we discuss representations of the pronunciations of words. The degree of abstractness chosen is not critical, but we settle here to facilitate additional discussion.

With this in mind, we ask the question: what does modern generative phonological theory say about the mental representations of speech? The central empirical fact that informs this question is that, in many languages of the world, morphemes are pronounced in different ways depending on context. To illustrate with an example, Odden (2014) draws attention to the pattern exhibited by the different verb forms in Kerewe shown in Table 1.

There is an interesting difference between the first group of verb forms and the second group of verb forms. In the first group, for example, the pronunciation for the verb stem

Infinitive	*1sg habitual*	*3sg habitual*	*Imperative*	*gloss*
[kupaamba]	[mpaamba]	[apaamba]	[paamba]	'adorn'
[kupaaŋga]	[mpaaŋga]	[apaaŋga]	[paaŋga]	'line up'
[kupima]	[mpima]	[apima]	[pima]	'measure'
[kupuupa]	[mpuupa]	[apuupa]	[puupa]	'be light'
[kupeketʃa]	[mpeketʃa]	[apeketʃa]	[peketʃa]	'make fire w/ stick'
[kupiinda]	[mpiinda]	[apiinda]	[piinda]	'be bent'
[kuhiiga]	[mpiiga]	[ahiiga]	[hiiga]	'hunt'
[kuheeka]	[mpeeka]	[aheeka]	[heeka]	'carry'
[kuhaaŋga]	[mpaaŋga]	[ahaaŋga]	[haaŋga]	'create'
[kuheeba]	[mpeeba]	[aheeba]	[heeba]	'guide'
[kuhiima]	[mpiima]	[ahiima]	[hiima]	'gasp'
[kuhuuha]	[mpuuha]	[ahuuha]	[huuha]	'breathe into'

Table 1: Kerewe verbs, from Odden (2014, pp. 88–89)

'adorn' is consistently [paamba] regardless of whether it is in the infinitival form (prefixed with [ku]), the 1sg habitual form (prefixed with [m]), the 3sg habitual form (prefixed with [a]), or the imperative form (not prefixed). It thus makes sense to assume that /paamba/ represents in a Kerewe speaker's mental lexicon the major features of the pronunciation of the verb stem 'adorn'.[2] However, when the same kind of morphological analysis is applied to the forms of the verb 'hunt' in the second group of verb forms, we find that the verb stem's pronunciation in the 1sg habitual form is [piiga] whereas in the other forms it is [hiiga]. So the question naturally arises, what long-term memory representation of the pronunciation of the verb stem 'hunt' do speakers of Kerewe have?

One possibility is that both /piiga/ and /hiiga/ are stored, along with the knowledge that [piiga] is used in the 1sg habitual form and that [hiiga] is used otherwise. This is fine as far as it goes, but it is of interest that the other verbs in this second group pattern exactly the same way: they begin with [p] in the 1sg habitual form, and with [h] otherwise. Furthermore, there are no verb stems in Kerewe which begin with [h] in the 1sg habitual form. Taken together, these observations suggest there is something *systematic* about the

[2]Here and elsewhere in this chapter we follow traditional phonological notation of transcribing the mental representation of speech between slashes and the actual pronunciaton within square brackets. When the distinction is immaterial, we use italics.

variation in the pronunciation of the various forms of this group of verbs in Kerewe, a systematicity that storage of all pronunciations plus information about their distributions does not readily or insightfully capture.[3]

The methods of modern generative phonology lead analysts to posit that the long-term memory representation of the pronunciation of the verb stem 'hunt' that speakers of Kerewe have is /hiiga/, and that *h* representations are transformed to *p* representations when they immediately follow *m* representations. Consequently, the 1sg habitual form of 'hunt' is [mpiiga] because it derives from /m+hiiga/ by application of this phonological transformation.[4] This phonological analysis explains the systematic variation observed because it predicts that every /h/-initial verb stem ought to be realized as [p]-initial when it follows any prefix ending with *m*, such as the 1sg habitual.

There are two key reasons why the mental representation of 'hunt' cannot instead be /piiga/, with *p* transformed to *h* when it immediately follows not-*m*. First, it is assumed that phonological transformations cannot make direct reference to the negation of a class of speech sounds; in this case, to 'not-*m*'. Second, and more significantly, it has been independently determined that the members of the first group of verb stems in Table 1 all begin with /p/, and yet the putative transformation of *p* to *h* immediately following not-*m* does not apply to those verb forms. Positing that members of the first group of verb stems begin with /p/ and that members of the second group begin with /h/ (transformed to *p* immediately following *m*) succinctly and systematically distinguishes the two groups.

One argument against this position is that there are cases where it does seem like two distinct pronunciations of a morpheme are stored. A well-known example is the nominative suffix in Korean, which has two pronunciations: [ka], which is suffixed onto vowel-final words, and [i], which is suffixed onto consonant-final words. This alternation is phonologically conditioned, but it is nevertheless a stretch of a phonologist's imagination to concoct a

[3]More — and more detailed — arguments against this 'morpheme alternant theory' can be found in Kenstowicz and Kisseberth (1979, pp. 180–196).

[4]The '+' indicates the presumed morphological boundary between the 1sg habitual prefix /m/ and the verb stem /hiiga/.

rule that transforms /ka/ to [i], or /i/ to [ka], or some other machination that relates these two forms of the nominative suffix in some phonological way. Furthermore, there are no other places in the Korean lexicon or language which exemplify any $k \sim \varnothing$ or $i \sim a$ alternation. In other words, a single posited underlying form and rules (whatever they are) would only account for the alternation between [ka] and [i] in the nominative suffix.

So in Korean, the best analysis of the nominative suffix alternation appears to be a long-term memory representation of the pronunciation of the suffix as {/i/, /ka/} with the choice of which one to select being based on the phonological properties of the stem the suffix attaches to. Given that such examples exist in the world's languages, the question is: why don't we just use the same kind of analysis for e.g. Kerewe? The answer is the one given above. The systematicity observed in the realization of Kerewe verb stems points to the straightforward phonological analysis in that case, and the lack of systematicity observed in the realization of the Korean nominative suffix points to the alternant selection analysis in that case. For more discussion of phonologically conditioned allomorphy, see Nevins (2011).

The argument just made is the basic one for the position that morphemes are stored in long-term memory with a single representation, known as the *underlying form*. The fact that the same morpheme can be pronounced in different ways depending on context is due to phonological transformations of this underlying form into its various *surface forms*. The fact that these transformations are systematically applied explains the systematicity in the alternations of the morphemes across the vocabulary of the language.

The phonological analysis in the generative tradition thus comes with two symbiotic parts. The first posits, where systematicity and its explanation demand it, a single mental representation in long-term memory of the pronunciation of a lexical item — that item's underlying form. The second is the transformational part of a phonological grammar which defines how underlying forms are mapped to surface forms, which are more concrete representations of the pronunciation of the lexical item in the particular context in which it is realized.

For example, in the case of Kerewe, the underlying form for 'hunt' is /hiiga/, the underlying form for the 1sg habitual form of 'hunt' is /m+hiiga/, there is a phonological transformation changing *h* to *p* immediately following *m*, and so the surface form in this case is [mpiiga].

Once underlying forms and transformations making them distinct from some of their corresponding surface forms are posited, a natural question arises: *how distinct can underlying forms be from surface forms?* This is the question of abstractness in phonology. We approach this question first from the perspective of two interrelated, fundamental concepts in phonological theory, phonemes and distinctive features, in section 4, setting the stage for discussion of more specific examples of evidence for different types of abstractness in analyses of phonological patterns in section 5.

4 Phonemes and Features

Much of the question of abstractness in phonology concerns the individual units of speech whose concatenation makes up the pronunciation of lexical items. For example, the speech sounds identically transcribed as *k* in the Kerewe verb stems *heeka* 'carry' and *peketʃa* 'make fire with stick' are the same at some level of abstraction; they are just being utilized in different contexts in different lexical items. Precise aspects of the articulation or these two instances of *k* may well exhibit systematic differences, parallel to the way that the (narrowly transcribed) [t^h] in [t^hɪk] 'tick', the [t] in [stɪk] 'stick', and the [ɾ] in [ˈæɾɪk] 'attic' differ systematically in English but are also the same, and at the same level of abstraction as the *k* in Kerewe.

The idea that people's mental lexicons make use of a mental alphabet of abstract speech sounds has a very long tradition in linguistics, dating back at least to Pāṇini's grammar of Sanskrit, likely written in the 6th–5th century BCE.[5] Details of individual theories aside, the speech sounds of this abstract mental alphabet are referred to as *phonemes*.

[5] A much more comprehensive historical context can be gotten from Anderson (1985); see in particular pp. 270–276.

Phonemes are obviously abstractions: they represent groups or categories of speech sounds, abstracting away from many phonetic particulars, such as the systematic and relatively easily perceptible differences between [t^h], [t], and [ɾ] in the English example above. In this section we trace the evidence for the psychological reality of phonemes and highlight two prominent views of phonemes: one as an indivisible alphabetic symbol, and the other as a local confluence of more basic units or properties known as *distinctive features*.

Readers interested in a more comprehensive review and discussion of the phoneme are directed to Dresher (2011), who distinguishes three views of the phoneme as an entity: the phoneme as *physical reality*, the phoneme as *psychological concept*, and the phoneme as *theoretical fiction*. Dresher (2011, p. 245) concludes that "once we abandon empiricist assumptions about science and psychology, there is no obstacle to considering the phoneme to be a psychological entity." This is an important framing, because it means that any linguistic work describing the nature and content of the phoneme is by necessity a statement about mental representation, in much the same way as the concept of underlying forms discussed in section 3. So the question becomes, how much abstraction or idealization is involved in such a psychological entity?

Edward Sapir was the first to present evidence for the psychological reality of phonemes. What is perhaps Sapir's better-known article, "The Psychological Reality of Phonemes" (Sapir, 1933), was preceded by his article in the first issue of the journal *Language*, "Sound Patterns of Language" (Sapir, 1925). Together, these two articles establish the perspective that (1) the phoneme is a psychological unit of speech, and (2) the character of the phoneme requires taking into account how it functions in the larger phonological context of the language; it cannot be understood solely from investigation of the articulatory or acoustic properties of its surface realizations. Sapir (1925) argued that languages with the same surface inventory of speech sounds could be organized differently at the underlying, phonemic level. Sapir (1933) argued that the same phoneme-level organization can explain the behavior of native speakers of a language, whether it be with respect to errors they make in the

perception or production of speech or in terms of the choices they make when devising or using a novel writing system to represent the speech sounds of their language.

Nearly a century later, psychological evidence for phonemes continues to be found and presented in the literature. The first issue of *Language* in 2020, 95 years after the publication of Sapir's (1925) article in the very first issue of the same journal, includes an article by William Labov arguing that the regularity of a sound change in Philadelphia is understandable to the extent that speakers of this dialect of English have an abstract mental representation of the front unrounded mid vowel (Labov, 2020).

Jumping back in time to observations by Bloomfield (1933) and Bloch (1941), among others: English unstressed vowels reduce to schwa [ə] in many contexts, making [ə] an allophone of every English vowel phoneme. Thus we have [ˈfo̲ɹə̲ˌgɹæ̲f] 'photograph', with a primary-stressed [o], an unstressed [ə], and a secondary-stressed [æ], alternating with [fə̲ˈtʰɑ̲gɹə̲ˌfi] 'photography', with primary-stressed [ɑ] flanked by unstressed [ə]s. It follows that phonemic representations of English morphemes must include unreduced vowels only, with reduction to [ə] being due to a phonological transformation, and moreover that the underlying form of many morphemes, such as /fotɑgɹæf/ 'photograph', will not directly correspond to *any* of their complete surface manifestations due to the nature of stress assignment in English.[6]

Phonemic analysis is the set of methods by which a language's underlying inventory of phonemes is induced from the distribution and behavior of its surface speech sounds, which can of course differ from language to language. Borrowing an example from Hayes (2009, pp. 31–34), English and Spanish have a set of surface speech sounds that can be broadly transcribed as [t d ð ɾ],[7] but their distribution and behavior in each language is such that:

[6]Bloch (1941, pp. 281–283) observed that this represents a potential learning challenge, because arriving at the 'right' underlying form for a morpheme requires exposure to a sufficient variety of its surface manifestations.

[7]Narrower differences include the precise tongue tip position for the articulation of [t d] (alveolar in English, dental in Spanish) and the degree of constriction of [ð] (more close in English, more open in Spanish).

- /ɾ/ is a phoneme distinct from /t/ and /d/ in Spanish, but not in English, where [ɾ] is sometimes a surface realization of /t/ (e.g. [bæt] 'bat', [ˈbæɾəˠ] 'batter') and other times a surface realization of /d/ (e.g. [sæd] 'sad', [ˈsæɾəˠ] 'sadder'), and
- /ð/ is a phoneme distinct from /t/ and /d/ in English, but not in Spanish, where [ð] is always a surface realization of /d/ (e.g. [unˈdisko] 'a record', [losᶻˈðiskos] 'the records').

From the same surface inventory of speech sounds [t d ð ɾ], then, we arrive at a different phonemic inventory in each language: /t d ð/ in English and /t d ɾ/ in Spanish, with [ɾ] a conditioned variant of /t d/ in English and [ð] a conditioned variant of /d/ in Spanish.[8]

These examples illustrate the basis of important development in 20th Century linguistics: the idea that the phoneme is not the minimal unit after all, and that instead there are subphonemic units — *distinctive features* — out of which phonemes are built. Generally speaking, distinctive features are used to describe phonologically-relevant phonetic distinctions between speech sounds: those phonetic distinctions that are common to similarly-behaving sounds, and those that differ between the conditioned variants of phonemes. In Spanish, for example, the complementary distribution of [d] and [ð] is matched by complementary distribution of [b] and [β] and of [g] and [ɣ], and the members of each of these pairs are related to each other in precisely the same way: [b d g] are *voiced stops* (vibrating vocal folds and stopping of airflow at three different places of articulation), while [β ð ɣ] are voiced *continuants* (constriction but not stopping of airflow at corresponding places of articulation). In English, the related speech sounds [t d ɾ] are all *coronals* (constriction by the tongue tip/blade), the phonemes /t d/ are both coronal stops, and the conditioned variant [ɾ] is a coronal continuant.

The distinctive feature idea was explored further by the Prague School of phonologists, notably Roman Jakobson and Nikolai Trubetzkoy, for whom *contrast* between phonemes

[8]Whether /d/ or /ð/ is the right representation of this phoneme in Spanish is a matter of some debate. Harris (1969) says /d/, Baković (1994) says /ð/, while Lozano (1979) opts for underspecification of the difference between the two speech sounds.

was a core theoretical premise. Analyzing the nature and systematicity of such contrasts required viewing phonemes as possessing features distinguishing each from the others. The particular features necessary to distinguish one phoneme from others thus describe the content of that phoneme. In this sense,

> [a]ny minimal distinction carried by the message confronts the listener with a two-choice situation. Within a given language each of these oppositions has a specific property which differentiates it from all the others. The listener is obliged to choose either between two polar qualities of the same category [...] or between the presence and absence of a certain quality [...]. The choice between the two opposites may be termed *distinctive feature*. The distinctive features are the ultimate distinctive entities of language since no one of them can be broken down into smaller linguistic units. The distinctive features combined into one simultaneous or [...] concurrent bundle form a *phoneme*. (Jakobson et al., 1952, p. 3)

Phonological features were intended to be the cognitive connection between the articulatory and perceptual speech systems.

> [T]he distinctive features correspond to controls in the central nervous system which are connected in specific ways to the human motor and auditory systems. In speech perception detectors sensitive to the property detectors [...] are activated, and appropriate information is provided to centers corresponding to the distinctive feature[s] [...]. This information is forwarded to higher centers in the nervous system where identification of the utterance takes place. In producing speech, instructions are sent from higher centers in the nervous system to the different feature[s] [...] about the utterance to be produced. The features then activate muscles that produce the states and configurations of different articulators[.] (Halle, 1983, p. 95)

Over a quarter century later, the same idea informs the neurolinguistics and biolinguistics literatures.

> The [...] featurally specified representation constitutes the format that is both the endpoint of perception — but which is also the set of instructions for articulation. (Poeppel and Idsardi, 2011, p. 179)

> Features serve as the cognitive basis of the bi-directional translation between speech production and perception, and are part of the long-term memory representation for the phonological content of morphemes, thus forming a memory-action-perception loop [...] at the lowest conceptual level. (Volenec and Reiss, 2017, p. 270)

Just as a phonemic analysis of a language's phonological patterns reveals its phonemic inventory, so does a featural analysis reveal its distinctive feature inventory. A phoneme consists of an individual combination of distinctive feature values, but there will be some particular distinctive feature value combinations that do not correspond to phonemes in a given language. For example, the phonemic inventory of Russian includes voiceless oral stops /p t k/ and voiced oral stops /b d ɡ/ at the same three places of articulation (labial, coronal, dorsal), but nasal stops /m n/ at only two of these — meaning that the combination of distinctive feature values describing a dorsal nasal /ŋ/ does not correspond to a phoneme in Russian.

A phonemic inventory is often presented as a stand-alone entity in the context of a phonological analysis, but phonologists recognize restrictions on the distributions of individual phonemes (see e.g. Hall 2013). For example, some argue /ŋ/ is a phoneme of English, but it is only found word-finally (e.g. [sɪŋ] 'sing'), before word-level suffixes (e.g. [ˈsɪŋəˠ] 'singer', [ˈsɪŋɪŋ] 'singing'), or when followed by /k/ or /ɡ/ ([sɪŋk] 'sink', [fɪŋgəˠ] 'finger'). Similarly, /ð/ is a phoneme of English, but its distribution is heavily restricted, being found at the beginning of a handful of function words, mostly determiners ([ðɪs, ðæt, ðiz, ðoz, ðɛm, ði, ðaɪ, ðə, ðɛn] 'this, that, these, those, them, thee, thy, the, then'), in a handful of words ending in [ðəˠ] (['ʌðəˠ, 'bɑðəˠ, 'wɛðəˠ, 'fɛðəˠ, 'mʌðəˠ], 'bɹʌðəˠ, 'fɑðəˠ] 'other, bother, weather, feather, mother, brother, father'), and at the end of a handful of verbs, mostly denominal ([bɹið, beɪð, ʃið, ɹaɪð] 'breathe, bathe, sheathe, writhe').

Conditioned variants of phonemes by definition also have restricted distributions. The distinction in Russian between voiced and voiceless obstruents (a class that includes the stops noted above) is found only before sonorants, and is otherwise *neutralized* in agreement with following obstruents (voiced before voiced, voiceless before voiceless) or to voiceless word-finally.

These restrictions on the distributions of phonemes and of their conditioned variants, and those on the recombination of distinctive features mentioned earlier, provide fodder for the kinds of abstract analyses that command particular attention in phonology, to which we now turn.

5 How Abstract are Mental Representations?

The question posed in this section title mainly lurks under the surface of modern debates in phonological theory, such as the extent to which phonology can be reduced to physiological principles governing articulation and perception (Ohala, 1981, 1997; Hale and Reiss, 2000; Hayes et al., 2004; Blevins, 2004; Heinz and Idsardi, 2013; Reiss, 2018). The question was asked more directly by Kiparsky (1968), as directly betrayed by this classic paper's title: *How abstract is phonology?* The paper addresses concerns about early work in generative phonology, which admitted the possibility of many transformations applying in crucial sequence from underlying to surface representations such that the specifications of a given underlying representation could be quite a bit different from those of its eventual surface representation.[9] The concerns were about the possibility of 'excessive abstractness', though different types of abstractness and how one is to measure them with respect to one another were often more matters of opinion than principle. As discussed further below, Kiparsky's proposal was not so much a line drawn in the sand as it was the curtailment of one particular type of abstractness. His and subsequent theoretical proposals have placed limits on the

[9]Or very similar, in some respects, by way of a non-spurious there-and-back-again sequence of transformations known as a *Duke of York derivation* (see Pullum 1976; McCarthy 2003; Baković 2013 for discussion).

possible types of differences that may hold between an underlying representation and its various surface manifestations, but they have not somehow placed limits on the *'distance'* between these representations.

The form of the evidence for a relatively abstract phonological analysis is typically one where what otherwise appears to be the same phoneme exhibits two distinctive forms of behavior, one expected (call this one A) and one unexpected (call this one B). The more strands of evidence of this sort that exist in any given analysis, the more compelling the case for it; Yokuts (Kisseberth, 1969), Nupe (Hyman, 1970), and Dida (Kaye, 1980) are particularly compelling cases. The unexpected behavior of B can be approached in one of two ways, both being abstract in some sense.

One approach is to posit that A and B are indeed phonemically identical, but that there is some abstract non-phonological diacritic marking X, present in forms with B but not in those with A, to which relevant phonological transformations are sensitive. (X may but need not have other functions in the language.) We call this the *abstract diacritic* approach.

Kiparsky refers to the other approach as "the diacritic use of phonological features", and it is instantiated in one of two basic ways. One instantiation is to directly posit that B is a phoneme distinct from A in terms of some feature such that the combination of distinctive features describing B does not surface, either at all or in the phonological contexts or lexical items in question. Relevant phonological transformations sensitive to the A/B distinction apply, and this distinction is subsequently neutralized with A. The other instantiation is to posit that A and B are phonemically identical, but that there is some other phoneme C, co-present with B but not with A, to which relevant phonological transformations are sensitive. C is either subsequently deleted or neutralized with some other phoneme. We call both of these instantiations the *abstract phoneme* approach.

Abstract phonemes can be either absolute or restricted. An *absolutely abstract phoneme* — or an "imaginary segment" (Crothers, 1971) — is a combination of distinctive feature

values posited as a phoneme in some set of morphemes but that is not realized as such in the surface forms of *any morphemes in the language*. An example appears in an analysis of exceptions to vowel harmony in Hungarian (Vago, 1976): some stems with the neutral front vowels [i iː eː] unexpectedly condition backing of suffix vowels, motivating the postulation of abstract back vowel phonemes /ɯ ɯː ʏː/ in these stems that are eventually and uniformly fronted.

A *restrictedly abstract phoneme* (O'Hara, 2017) is a combination of distinctive feature values posited as a phoneme in a restricted set of contexts but that is not realized as such in *any surface contexts corresponding to that set*. An example appears in an analysis of exceptions to vowel coalescence in Mushunguli (Hout, 2017): some stems beginning in the high vowels [i u] unexpectedly block otherwise regular coalescence with preceding /a/, motivating the postulation of glide phonemes /j w/ that respectively never surface before [i u] but that do surface in other contexts. These glides block coalescence and are subsequently deleted just before [i u].

All abstract phoneme analyses crucially rely on the possibility of *opaque interactions* between phonological transformations (Kiparsky, 1973). In each of the examples sketched above, the transformation that voids the representation of its abstract phoneme crucially must not apply before application of the relevant transformation(s) sensitive to the abstract phoneme.[10] In some cases, the abstract phoneme is needed in the representation to prevent the application of an otherwise applicable transformation, as in the case of Mushunguli. These involve the type of opaque interaction known as *counterfeeding*. In other cases, the abstract phoneme is needed in the representation to ensure the application of an otherwise inapplicable transformation, as in the case of Hungarian. These involve the type of opaque interaction known as *counterbleeding*. Abstractness is thus intimately intertwined with opacity: to the extent that a theoretical framework (dis)allows opaque interactions, it (dis)allows

[10]We write 'must not apply before' as opposed to 'must apply after' because these opaque interactions can be had with simultaneous as opposed to ordered application of phonological transformations (Kenstowicz and Kisseberth, 1979; Joshi and Kiparsky, 1979, 2006; Kiparsky, 2015). See also Baković and Blumenfeld (2017) for discussion.

abstract phoneme analyses.

Kiparsky's proposed principle was meant to ensure that every phoneme specified as a particular combination of distinctive features in a given morpheme's underlying form will be realized with that precise set of specifications in at least one surface form of that morpheme.[11] This effectively excludes abstract phoneme analyses such as those sketched above — but in each of these cases the alternative is to rely instead on diacritic marking, which is, as already noted, also a form of abstractness. More recently, O'Hara (2017) specifies a MaxEnt learning model that assigns sufficiently high probability to a restrictedly abstract phoneme analysis (based on a case in Klamath), and significantly lower probability to both absolutely abstract phoneme and abstract diacritic alternatives. It is thus reasonably clear that a hypothetical abstract-o-meter (recall Figure 3) would place absolutely abstract phonemes closer to the 'too abstract' end of the spectrum than restrictedly abstract phonemes, but where abstract diacritics fall on that spectrum is a largely unresolved matter. We must thus conclude here that "a phonological analysis, independently of its 'degree' of abstractness, is (only) as adequate as the motivation and evidence that can be produced in favor of it and against substantive alternatives" (Baković, 2009, p. 183).

This section and the last focused on the issue of phonological abstractness in the mental lexicon at the level of the phoneme and of the distinctive feature. This is primarily because most relevant research has been focused here, with the possible exception of the syllable (Goldsmith, 2011; Strother-Garcia, 2019). However, other representational levels and systems also have been argued to play a role in the mental representations of words, notably tonal representations (Yip, 2002; Jardine, 2016) and metrical stress (Hayes, 1995; van der Hulst, 2013). These representations have also been the subject of intense study, including the psycholinguistic and neurolinguistic literature, to which we turn in the next section.

[11] We put aside the precise formulation of Kiparsky's principle, as well as of its ensuing revisions (Mascaró, 1976; Kiparsky, 1982, 1993), focusing instead on its intended function.

6 Types of Evidence

The preceding sections discussed the perspective of phonological abstractness using structural linguistic arguments from the typology of spoken language. However, it is often claimed that structural arguments are far from a definitive proof, constituting one type of evidence. This is especially true for the psychological reality of these abstract forms. Ohala (1974) makes this point:

> It seems to me that the important question should not be whether phonology is abstract or concrete, but rather what evidence there is for the psychological reality of a particular posited underlying form. If our aim is simply a descriptive one, then of course abstract forms can be posited without any further justification than the fact that they make it easier to state certain regularities. However, if we are interested in reflecting the competence of a native speaker, then we must provide evidence that what we are claiming as part of a speaker's knowledge is indeed such.

What other types of evidence are there? This section describes various other types of evidence bearing on the question of abstractness. The first type of evidence comes from expanding the typology to consider non-spoken language, that is, signed and tactile language. This evidence is still structural, but provides an important window into the lexicon. How dependent is the long-term memory representation of a word on the physical system which externalizes it? At the same time, Ohala and many others take behavioral and psychological tests as providing additional necessary, if not sufficient, evidence for the reality of these forms. Recent advances in neuroimaging and increasing ease of use allow for intricate looks into the biological underpinnings of phonological representations, combined with computational models and simulations. However, literature in all these topics is vast, especially with regard to experimental work. Here we provide a sample of work that bears on the questions described earlier.

6.1 Evidence from Signed and Tactile Phonology

An important source of evidence for the existence and nature of phonological abstraction comes from languages without a spoken modality - namely, signed and tactile languages. Sign languages arise spontaneously in deaf communities, are acquired during childhood through normal exposure without instruction, and exhibit all of the facets and complexity found in spoken languages (see Sandler and Lillo-Martin (2006) for a groundbreaking overview). However, if human language evolved without respect to modality, we should find hearing communities that just happen to use sign language instead of spoken language, and we do not. Sign languages are thus "an adaptation of existing physical and cognitive systems for the purpose of communication among people for whom the auditory channel is not available" (Sandler, 1993).

Sign languages offer, as Sandler (1993) puts it, "a unique natural laboratory for testing theories of linguistic universals and of cognitive organization." They give insight into the contents of phonological form, and conditions on which aspects of grammar are amodal and which are tied to the modality. They also offer unique opportunities to study the emergence of phonology under various conditions: where home-signers (Goldin-Meadow, 2005) are congregated and a sign language emerges among themselves, as in Nicaragua (Senghas et al., 2004); and where a localized hereditary deaf population lives among hearers who also sign, as in Bali (Marsaja, 2008) or in a Bedouin group in Israel (Sandler et al., 2005).

One crucial contribution of non-spoken phonology is that it switches the issue of "how abstract is phonology?" to "where does abstraction lie, and to what extent is it independent of the modality?" There are generally two directions answers can take. To the extent that a given phonological form or constraint is present across modalities, one may make the case that it is truly abstract, in the sense that it exists without regard to the articulatory system which realizes it. On the other hand, to the extent that a given form or constraint differs, one can ascribe that difference to the modality, to the nature of the articulatory

system. In this way, non-spoken phonology provides nuance into the relationship between the pressures of abstraction and the pressures of realization in the mental lexicon.

Up until 1960, sign languages were rarely considered fully-fledged natural languages possessing morpho-syntactic or phonological structure (see van, to appear for the history of sign phonology). Recognition of phonological compositionality came from the groundbreaking work of Stokoe (1960). His proposed division of signs into meaningless chunks showed sign languages display both morpho-syntactic and phonological levels, a "duality of patterning" or "double articulation" which had long been considered unique properties of spoken languages (Martinet, 1960; Hockett, 1960).

Stokoe's phonological system contained abstractions for what the separate parts of the sign: the handshape, the movement of the hand, and the location in front of or on the body. Stokoe insisted that the study of sign language form should not be seen through the prism of spoken language phonology, coining the term 'chereme' from the Greek root *cher* meaning 'hand', in contrast to 'phoneme'. While Stokoe's division of the form of signs was phonetic, designed as a compositional system of phonetic transcription that would replace holistic drawings, he also regarded the symbols as representations of the discrete units that characterize the signs.

Much work on the psychological reality of phonological abstractions in sign came from the Salk Institute (see Klima and Bellugi 1979 for an accessible overview, and Emmorey 2001 for more recent developments). They showed experimentally that percepts of signs in short-term memory are compositional. Studying production errors or 'slips of the hands', they argued for the compositionality in the articulatory phase. Using American and Japanese Sign Language, they showed that ASL signers make judgments about what they considered well-formed or ill-formed. These judgements presuppose knowledge of how smaller units can be combined, knowledge that is captured in phonotactic constraints on the basic units as well as their permissible combinations. As van notes, Klima and Bellugi (1979)'s accessibility and cognitive scope convinced many linguists and non-linguists that sign languages are

'real' languages and that sign linguistics is a proper subdiscipline in the field in ways Stokoe was unable to.

While Stokoe's work stressed the simultaneity of the units in a sign, later researchers (Liddell and Johnson, 1989; Liddell, 1984; Newkirk, 1981; Supalla and Newport, 1978) demonstrated the necessity of referencing the beginning and end points of the movement of signs, for example for inflectional purposes where the referents are marked by discrete locations, or to express phonological processes involving a switch in the beginning and end point of the movement (see Sandler 1989 and van der Hulst 1993 for discussion).

These considerations resulted in models containing abstract timing units, forming a temporal skeleton to which the features of the sign associate in a many-to-one fashion (often called autosegmental in linguistics (Goldsmith, 1976a). Most researchers (Liddell, 1984; Liddell and Johnson, 1989; Sandler, 1989, 1993; Perlmutter, 1993; Brentari, 1998) proposed an abstract sequence that temporally represented both initial and final location, as well as an intermediary movement unit.

The notion of simultaneous and compositional structure in a sign, as well as sequential structure, leaves a big question: how modality-dependent are these properties? Languages in both modalities have sequential and simultaneous structure, but there are striking differences in the degree and centrality of such structure. Spoken languages vary in syllable structure, word length, and stress patterns among syllables. Sign languages appear limited in all these aspects. They are overwhelmingly monosyllabic, have no clusters, and show extremely simple stress patterns, due to few polysyllabic words apart from fully reduplicated forms (Wilbur, 2011).

Additionally, the structural organization in signed or spoken language has a direct effect on the phonology. Strikingly few phonological rules that are not morphosyntactically triggered have been discovered in sign languages, mainly due to sign's lack of sequential structure. Significant sequential structure in sign mainly appears under morphosyntactic operations that concatenate morphemes and words (affixation, compounding, and cliticization)

(Aronoff et al., 2005). Predictably, when this occurs, a smorgasbord of phonology arises.

In general, sequential affixation is rare across sign languages (Sandler, 1996; Aronoff et al., 2005), and sign exhibits a strong tendency to express concatenative morphology through compounding (Meir, 2012). Aronoff et al. (2005) show that affixation usually results from grammaticalization of free words, via a series of diachronic changes concerning phonological and semantic factors. They cite the relative youth of sign languages as causing their lack of affixes compared with verbal languages. No known sign languages are over 300 years old, with some like Nicaraguan Sign Language, as young as 40 (Woll et al., 2001).

The lack of sequential structure in sign languages does not imply structural simplicity, however. Sign languages routinely employ nonconcatenative morphology (Emmorey, 2001; Meier, 2002), incorporating morphological material simultaneously in the phonology with restricted sequential form. Of course, simultaneous phonological structure exists in all languages, but differ across modalities in the amount. Very few sign features actually become sequenced, while in spoken language features are overwhelmingly sequenced, rarely simultaneous. Comparing hand configuration and place autosegments to autosegments in spoken language shows further differences. Unlike spoken autosegments for tone or harmony patterns, which typically consist of one or two features, the hand configuration autosegment in sign languages is extremely complex, containing almost half of sign features organized in an intricate feature geometry (van der Hulst, 1995; Sandler, 1996).

In sum, the phonological module may leverage the representational abilities of the particular articulatory/perceptual system. van der Hulst and van der Kooij (2018) cite Brentari (2002) and Emmorey (2001) that visual perception of signs (even with sequential properties) is more "instantaneous" than auditory speech perception, and adapt Goldsmith (1976b)'s division of phonology in terms of the notions of "vertical and horizontal slicing of the signal". They state:

> an incoming speech signal is first spliced into vertical slices, which gives rise to a linear sequence of segments. Horizontal slicing then partitions segments into co-temporal

feature classes and features. In the perception of sign language, however, the horizontal slicing takes precedence, which gives rise to the simultaneous class nodes that we call handshape, movement, and place. Then, a subsequent vertical slicing of each of these can give rise to a linear organization.

Of course, the phonetics and phonology of sign language differ in many ways. Lillo-Martin (1997) cites Blakemore (1974)'s result that exposure to vertical and horizontal lines in the environment affects development of feline visual perception, and asks "why shouldn't exposure to the special acoustic properties of the modality affect perception, especially auditory perception?" Sandler and Lillo-Martin (2006) note that unlike spoken syllables in many languages, sign language syllables prohibit location clusters comparable to consonant clusters, or diphthong-like movement clusters, and there must be a movement between locations due to the physiology of the system. Additionally, sign syllables do not have onset-rhyme asymmetries, which affects syllable structure and stress assignment, they typically align intonation, conveyed by facial expression, with phonological/intonational phrases, not syllables inside those phrases, where spoken languages usually do (Nespor and Sandler, 1999). The similarities and differences in phonological abstraction across modalities means signed languages will have an important role as evidence. This holds equally true for language expressed by the DeafBlind through the tactile modality, often called tactile or pro-tactile sign languages (see Edwards (2014) for a recent phonological analysis).

6.2 Psycholinguistic and neurolinguistic evidence

As mentioned, behavioral testing has long been argued as necessary evidence for the mental reality of phonological abstraction, in addition to typological evidence. The introduction and improvement of neuroimaging methods enabled correlations between behavioral tasks and gross neural excitation levels associated with them. In addition, recent simulation tools allow for modeling of phonological representations in an idealized *in silico* setting.

Here we overview several results via behavioral and neural methods bearing on phonological organization of the lexicon by its salient features into abstract phonemes, as well as work on the temporal abstraction of speech.

One salient question concerns experimental evidence for abstract phonemic and featural representations of words. For example, In Russian, the sounds [d] and [t], which featurally differ in voicing, are contrastive, members of different phonemes. In Korean, these sounds do not contrast and are members of a single phoneme. Kazanina et al. (2006) used the neuroimaging method of magnetoencephalography (MEG), which tracks the timecourse of gross, large-scale neural activity, to show that Russian and Korean speakers react differently to these sounds. The Russian speakers separated the sounds into two categories corresponding to /t/ and /d/. On the other hand, the Korean speakers did not separate the sounds, again corresponding to the analysis of a single underlying phoneme. from this result, the authors conclude that both phonetic and abstract phonemic analyses necessarily shape the perceptual analysis of speech sounds.

There is much evidence supporting a vast neuronal ensemble for phonological representations in speech production and perception (see Eickhoff et al. (2009) and Jueptner and Krukenberg (2001) for an extensive overview). In particular, various portions of the superior temporal sulcus are suggested to encode the phonological representations discussed in this chapter. Scharinger et al. (2011) used a combination of MEG imaging and statistical modeling to map the entire vowel space of a language (Turkish) onto three-dimensional cortical space, organized by lateral-medial, anterior–posterior, and inferior-superior axes. Their statistical model comparisons showed that, while cortical vowel maps do reflect acoustic properties of the speech signal, articulator-based and featural speech sound information "warps the acoustic space toward linguistically relevant categories".

Scharinger et al. (2012) used MEG to localize three vowel feature variables (height, frontness and roundness) to the superior temporal gyrus. Mesgarani et al. (2014) used cortical electrode placement to show that the Superior Temporal Sulcus encodes a 'manner

of articulation' parameter of speech sounds. Intriguingly, different electrodes responded selectively to stops, sibilant fricatives, low back vowels, high front vowels and a palatal glide, and nasals, respectively. Bouchard et al. (2013) showed similar results, that the Superior Temporal Gyrus encodes a 'place of articulation' parameter, confirming labial, coronal and dorsal place features, across various manner classifications. These results match with Hickok and Poeppel (2007)'s hypothesis that "the crucial portion of the STS that is involved in phonological-level processes is bounded anteriorly by the most anterolateral aspect of Heschl's gyrus and posteriorly by the posterior-most extent of the Sylvian fissure".

Additionally, recent experimental evidence using aphasic patients even supports the existence of abstract phonological rules in processing. Linguistic analysis posits that the English words *pit* and *spit* both contain the segment /p/ in their underlying representations. In the surface representation *pit*, with the /p/ on word-initial position, aspirates to get [p^h] and *spit* (preceded by /s/) does not, to get [p]. Buchwald and Miozzo (2011) constructed an experiment using the productions of two aphasic patients who were unable to produce an /s/ in relevant consonant clusters like /sp/ or /st/, and compared them with correctly produced consonants. They wanted to test whether an aphasic would aspirate the /p/, (marking phonological fricative-deletion), or not (the fricative deleted *after* successful application of the phonological rule).

To analyze it, they compared the voice-onset-time (VOT) of the two patients on the two instances. VOT provides an acoustic measure of the relative aspiration of the consonant by seeing how much the following voicing is delayed. One patient had a long VOT ([p^h]) while the other had a short VOT ([p]), confirming the divide between two distinct levels of phonological and phonetic influences in processing. Follow-up work by Buchwald and Miozzo (2012) showed similar results for nasal consonants which deleted in clusters like /sn/ and /sm/. The conclusion to be drawn from these studies points to abstraction in the units being processed, mentally divorced from their phonetic realization but ultimately driving it.

Apart from the biological underpinmnings of the atomic representations characterizing speech units, there is additionally much work focused on the biological underpinnings of temporal abstractions in speech. Specifically, much of this work focuses on the insula, basal ganglia, and cerebellum, where temporal information is speculated to be filtered in a cortical-subcortical loop for the purposes of motor planning (Eickhoff et al., 2009). In this process, motor sequence plans are filtered through through basal ganglia, while the cerebellum converts the sequences into fluent, temporally distributed articulations. Ackermann et al. (2007) underpin this by describing drastic negative effects on speech production consistent with damage to the cerebellum.

While neuroimaging methods brought many advantages, they simultaneously introduced a uniquely thorny issue to phonological abstraction, which Poeppel (2012) divides into the "Maps Problem" and the "Mapping Problem". The Maps Problem concerns descriptive analysis of the behavioral and neural underpinnings of mental representations, say the effects and brain areas associated with a particular phonological phenomenon. The Mapping Problem concerns how to take a particular mental representation, perhaps known to correlate with some behavioral entity or brain network, and mechanistically connect it to neuronal function. Neither the maps problem nor the mapping problem have easy answers (Buzsaki, 2019), and decades of work have led to many open and nuanced questions.

Attempting to address the Mapping Problem, some work seeks a somewhat more explanatory approach to the forces underlying the temporal segmentation of the signal produced and perceived. One emerging insight is that the perceptual system divides an incoming auditory stream into two distinct time widows (Giraud and Poeppel, 2012; Chait et al., 2015). What phonological entities do they map to? As Poeppel and Idsardi (2011) put it, there are:

> Two critically important windows that appear instantiated in spoken languages: segments and syllables. Temporal coordination of distinctive features overlapping for relatively brief amounts of time (10–80 ms) comprise segments; longer coordinated

> movements (100–500 ms) constitute syllabic prosodies. (Poeppel and Idsardi, 2011, 182)

A more fundamental question concerns the neural mechanism which drives these windows and their coordination. Oscillatory activity within and between neural populations has been posited (Giraud and Poeppel, 2012). Neural populations which comprise a certain type of neuron may show a stable neural oscillation at certain frequency bands which varies depending on their excitatory and inhibitory properties (see (Buzsaki, 2006) for an accessible overview). Evidence suggests that pyramidal interneuron gamma oscillations, as well as theta oscillations, comprise the segmental vs. syllabic time distinction. These two oscillations funnel an incoming speech signal into time windows of different sizes, computationally represented by the waveform of the population activity.

In silico modeling work reveals another interesting property. While these oscillations do track the signal, a crucial feature is that rhythms of distinct frequencies show specific coupling properties, termed cross-frequency coupling (Hyafil et al., 2015b). Briefly, this means that the stable oscillatory populations innervate each other, allowing different timescales to track one another, effectively parsing a temporally complex signal efficiently. Specifically for speech perception, Hyafil et al. (2015a) showed that when a network showing gamma oscillations coupled to a network showing theta osciallations, it was able to effectively segment a corpus of phonological words much better than a network where this coupling was absent.

These results reflect an explosion of work using neurolinguistic and psycholinguistic tests to describe the sort of representations speakers have. The intersection of experimental results with theory promises many new insights into the mental content of the lexicon. For a further dicussion on the particular biological substrate underlying phonological abstraction, and how they impact the phonetics-phonology interface, see Volenec and Reiss (2017).

7 Conclusion

In this chapter, we have endeavored to motivate and review a central idea of modern generative phonology that the fundamental representational units of words in languages are abstract and psychologically real. In particular the systematic patterning of the pronunciation of morphemes motivates an abstract mental representation of a morpheme's pronunciation. These underlying forms are largely regarded as sequences of phonemes, which are themselves abstractions, and which are organized along featural dimensions. These abstract mental representations find support not only from the patterning in morpho-phonological paradigms, but also from language change, from sign language linguistics, and from psycholinguistic and neurolinguistic study.

There are many open and fascinating questions regarding the nature of abstract mental representations of words. Many are among the most basic and fundamental. How abstract can they be? How are they learned? How are they realized in the brain? The fact that we simultaneously know both so much and so little about phonological abstractness in the mental lexicon sends a clear message that this will continue to be a fertile and exciting area of research for many years to come.

To conclude this chapter, we can do no better than to repeat the concluding sentences of Labov (2020, pp. 57, emphasis added): "We have a common ground in our understanding of what it means to know a language. It involves knowing a vast number of particular things. *But at bottom it is reaching down to something very deep, very abstract, and very satisfying.*"

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