The Initial and Final States: Theoretical Implications and Experimental Explorations of Richness of the Base

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In this chapter we present the initial stages of work that attempts to assess the 'psychological reality' of one of the more subtle grammatical principles of Optimality Theory ('OT'; Prince and Smolensky 1993), *Richness of the Base*. Within the OT competence theory, we develop several of this principle's empirical predictions concerning the grammar's final state (Section 1) and initial state (Section 2). We also formulate linking hypotheses which allow these predictions concerning competence to yield predictions addressing performance. We then report and discuss the results of experimental work testing these performance predictions with respect to linguistic processing in infants (Section 3) and adults (Section 4) .

1. Introduction

Optimality Theory (henceforth, 'OT') is a highly output-oriented grammatical theory. The strongest hypothesis is that *all* systematic, language-particular patterns are the result of output constraints — that there is no other locus from which such patterns can derive. In particular, the *input* is not such a locus. Thus, for example, the fact that English words never begin with the velar nasal ŋ cannot derive from a restriction on the English lexicon barring ŋ-initial morphemes. Rather, it must be the case that the English grammar *forces* all its outputs to obey the prohibition on initial ŋ. This requirement amounts to a counterfactual: *even if there were* an ŋ-initial lexical entry in English, providing an ŋ-initial *input*, the corresponding *output* of the English grammar would *not* be ŋ-initial. Thus, the absence of ŋ-initial words in English must be explained within OT by a grammar — a ranking of constraints — with the property that *no matter what the input*, the *output* of the grammar will not be ŋ-initial. That is, the OT analysis of English must consider a set of inputs to the grammar — the *base* — that is as *rich* as possible: the base includes all universally-possible inputs, including those that are ŋ-initial, those that contain clicks, those that consist of 17 consecutive consonants, etc.

This principle — *Richness of the Base* — means that it is not sufficient that the ranking constituting the English grammar derive the correct outputs from inputs drawn from a putative English lexicon of underlying forms. In addition, the grammar must also ensure that any hypothetical input at all, even one that violates the systematic patterns of English, produces an output that obeys these patterns.

This constitutes the first 'prediction' of Richness of the Base relevant here: the final ranking of an English learner must filter out initial ŋ's as well as, say, consonant clusters that are not legal in English. Thus, for example, when subject to the English constraint ranking, the input /ktobi/ must be mapped to an output such as [kətobi] which lacks the English-illegal onset [kt].

This prediction resides in the OT competence theory: it is a claim about an abstract input-output mapping. In order to use this prediction to assess the 'psychological reality' of Richness of the Base, we need a working hypothesis linking competence to performance. For example: if auditorily presented with [ktobi] — produced fluently by a Polish speaker, for example — and asked to employ this 'place name' fluently in a sentence, adult native monolingual English speakers will produce [kətobi] or some other form respecting English phonotactic patterns. We seek experimental confirmation of this prediction in Section 4 below. Clearly, a naturalistic approximation to this situation occurs in loan words, and the broad empirical generalization is that indeed foreign words are adapted to conform to native patterns. However, this adaptation is often only partial: loanwords frequently contain structures illegal in the borrowing language. The experimental results we report below also display this incomplete nativization as well, with outputs exhibiting deviations from English with interesting regularities. In Section 4 we will attempt an extension of Richness of the Base that recognizes particular propensities for partial nativization as an integral part of the final state of a native grammar.

The second prediction we exploit from Richness of the Base is more subtle, and concerns not the final but the *initial* state of the grammar. Section 2 develops a learnability argument leading to this prediction, which is simply stated: in the initial state, markedness constraints must dominate faithfulness constraints — otherwise the final state demanded by Richness of the Base could not be achieved in certain problematic cases. The assumption here is that OT grammars are comprised of only two types of constraints: faithfulness constraints, which compare the input and output and demand that they be equal, and markedness constraints, which examine only the output and penalize universally dispreferred or *marked* structures. We operate within this core structure of OT, with an eye to future research addressing richer versions of OT.

Like the derivation of the prediction MARKEDNESS ≫ FAITHFULNESS concerning the initial state, the linking hypothesis connecting this prediction to performance is somewhat complex: we take it up in Section 3. The result is an experimental paradigm designed to test whether infants behave in accordance with the 'MARKEDNESS dominates FAITHFULNESS' prediction. The outcomes of such experiments are also presented in Section 3.

2. Learnability and the initial state

How does the adult language-specific grammar — constraint ranking — come about? There are two aspects of this grammar to consider: the origin of the constraints themselves, and the determination of their relative ranking. Since the ranking is language-particular, it must be learned; we turn to this matter shortly. But since the constraints themselves are universal, it is not necessarily the case that they are learned from experience: it is logically possible that they are somehow innately specified, and OT makes no commitment on this issue. The research summarized in this section extracts a theoretical prediction from the hypothesis that knowledge of universal constraints in OT is innate; the research summarized in the next section attempts to put this prediction to an experimental test.

According to the learning theory for OT proposed in Tesar and Smolensky 1993, 1998a, b, 2000, the language learner re-ranks constraints in the face of learning data. When the learner's current grammar declares that the optimal output for a word is an erroneous pronunciation, constraints are minimally demoted so that the correct pronunciation is declared optimal by the revised grammar. The learning algorithm for a stochastic version of OT proposed in Boersma 1998 performs more gradual re-ranking, but it is also driven by the errors made by the learner's current grammar.

2.1. The initial state

What is the initial ranking of constraints, prior to the re-ranking induced by the data of the language to be learned? Adopting the working hypothesis that the universal OT constraints are innate and thus present in the initial state, and elaborating an argument originally from Prince 1993, Smolensky 1996a developed a learnability argument showing that as a class, *markedness constraints must outrank faithfulness constraints in the initial state*, or certain languages would not be learnable. This characterization of the initial ranking is consistent with a body of work analyzing data from child phonology within the OT framework (Demuth 1995; Gnanadesikan 1995; Levelt 1995; Levelt and Van de Vijver 1998; Pater and Paradis 1996). Broadly speaking, with MARKEDNESS dominating FAITHFULNESS in the initial ranking, the child's productions will contain only unmarked forms: violations of markedness constraints can only be optimal if higher-ranked faithfulness constraints require them, and in this initial state there *are no* higher-ranked faithfulness constraints.

Smolensky 1996b exhibited a perhaps surprising consequence of the assumption that in the initial state markedness constraints are present and dominate faithfulness constraints: this assumption can broadly explain the discrepancy observed in language learners' early production and comprehension abilities. In particular, perceptual capacities that infants display in speech processing contrasts with the inaccuracies that are apparent in their speech production. On the surface, the skill that infants show in comprehension appears to demand that faithfulness constraints be highly ranked, whereas their difficulties in producing speech seem to require that faithfulness constraints be low-ranked. However, Smolensky 1996b argued that what distinguishes production from comprehension is only which structures compete: in production, it is structures sharing the same underlying form, whereas in comprehension, it is structures sharing the same surface form. Once this difference in competition is taken into account, a single ranking — with markedness dominating faithfulness — accounts both for highly unfaithful child production and relatively faithful child comprehension.

We now quickly sketch the learnability argument showing that markedness must out-rank faithfulness initially, illustrating with the example of word-initial ŋ. The question facing the learner here is, what is the correct ranking of the relevant markedness and faithfulness constraints? The markedness constraint is violated by ŋ-initial words; for expository purposes we'll take it to be a constraint against syllable-initial ŋ, and simply call it $M_ŋ$. The relevant faithfulness constraints, which we'll call $F_ŋ$, require that an underlying initial ŋ be faithfully mapped to an initial ŋ in the output. Again, the learner's problem is to determine the relative ranking of $M_ŋ$ and $F_ŋ$.

There are three cases to consider. The first is the easiest, the case illustrated by Vietnamese. Here, some words of the language are pronounced with an initial ŋ in violation of $M_ŋ$. This violation must be forced by a higher-ranking constraint $\mathbb{C}$: $\mathbb{C} \gg M_ŋ$. $\mathbb{C}$ cannot be a markedness constraint: there is no evidence for a universal constraint *favoring* initial ŋ. So $\mathbb{C}$ must be a faithfulness constraint, $F_ŋ$. Thus the presence of ŋ-initial words in this type of language immediately informs the learner that the ranking must be $F_ŋ \gg M_ŋ$. Only under this ranking can an ŋ-initial underlying lexical form actually be pronounced with an initial ŋ. This first case will be called that of *a marked inventory*: the language's inventory of allowed sound structures includes the marked element in question — initial ŋ.

In the remaining two cases, the target ranking is the reverse: $M_ŋ \gg F_ŋ$; these are the cases of *unmarked inventories*. One such case is English, but first we take up the easier case, a hypothetical language we will call English′. English′ contains words like *sing* taking a suffix *-er* to form *singer*. The pronunciations of these two forms in English′ are [sɪŋ] and [sɪ.nɚ] (the period marking a syllable boundary): *sing* is pronounced as in real English, with a ŋ in the syllable coda, but in the pronunciation of *singer,* the nasal is pronounced *n* (as in *sinner*) — because it is now in syllable-initial (onset) position. The English′ pronunciation of *singer* violates the faithfulness constraint $F_ŋ$: the underlying form has a velar nasal while the pronounced form has a coronal nasal. This alternation of a sound between ŋ and *n* tells the child learning English′ that in this language, $F_ŋ$ is lower-ranked than the markedness constraint $M_ŋ$ that prohibits ŋ in onset position. Thus, when a language exhibits alternations of this sort, there is explicit evidence available to the child for the language-particular ranking M ≫ F; this case will be called *an unmarked inventory with alternation.*

But such evidence is not always present. The third case — *an unmarked inventory without alternation* — is illustrated by real English: there is no alternation between ŋ and *n* like that found in English′. Nonetheless, the adult speaker of English must, according to Richness of the Base, rank $M_ŋ \gg F_ŋ$. Since the lexicon of English only places ŋ where it can be syllabified faithfully into the coda, the pronunciation of English words never forces the child to choose between satisfying $M_ŋ$ and satisfying $F_ŋ$: by faithfully pronouncing each underlying ŋ in coda position, *both* $M_ŋ$ and $F_ŋ$ are always satisfied. Regardless of how $M_ŋ$ and $F_ŋ$ may be ranked, the learner will make no errors in pronunciation. Therefore, there will be no evidence of the sort used in the learning algorithm to drive constraint re-ranking. Thus if the learner's constraints are to end up — as Richness of the Base requires — with $M_ŋ \gg F_ŋ$, then these constraints *must start off with this ranking*.

Because this same argument can apply to any pair of potentially-conflicting markedness and faithfulness constraints, the conclusion is quite general: in the initial state, markedness constraints must out-rank faithfulness constraints. Only if the language provides overt evidence contradicting this ranking — the case of a marked inventory — will the reverse ranking come to be posited by the learner.

It is worth noting that what is crucial to the learnability argument is that the M-constraint is *contrast neutralizing* and the F-constraint is *contrast inducing*. The force of M is to restrict the output to the unmarked pole of a dimension of possible variation (e.g., to prevent ŋ-initial words rather than to allow words to be either ŋ-initial or not). The force of F is to require that input differences along this dimension be maintained in the output. So the argument's conclusion might be generally stated that neutralization-inducing constraints must dominate contrast-inducing constraints. Thus it is not actually critical to any of the analyses in this paper whether the phonological phenomenon in question is literally a contest between markedness and faithfulness; "M" and "F" should be taken to refer to the relevant contrast-suppressing and -inducing constraints, whatever their formal character. Thus the conclusion of the learnability argument can in fact be stated in rather theory-neutral terms: in the initial state, the grammar favors neutralizations to the unmarked, and only under pressure of observed marked forms does the grammar change to allow marked structures to surface.

As pointed out recently in Hayes 1999b and Prince and Tesar 1999, the pressure that Richness of the Base imposes for MARKEDNESS ≫ FAITHFULNESS is not limited to the initial state. Through interaction with other constraints, re-ranking that occurs during learning can disturb the initial ranking M ≫ F even in a language lacking marked structures, where this ranking must prevail in the end. These authors propose various mechanisms by which the pressure towards MARKEDNESS $\gg$ FAITHFULNESS can be continually imposed by a learning algorithm, reinstating this aspect of the initial state, except where this pressure is overcome by positive evidence that F $\gg$ M — evidence provided by the presence of marked structures in the target language.

Opposing the line of argument we have just summarized is another view. From the perspective of a developmental psychologist, one might have had an entirely different expectation: that, at the outset, faithfulness constraints should dominate markedness constraints (see also Hale and Reiss 1997). According to this alternative point of view, the simplest assumption that an infant might make is that surface forms faithfully mirror their underlying structure. Only in the face of evidence to the contrary would the learner assume that there is a more complicated relationship between surface forms and their underlying representations. The assumption that surface forms faithfully mirror underlying forms amounts to the assumption that faithfulness constraints outrank markedness constraints; this would then be the initial state as infants begin to acquire a native language. In this alternative theory, inaccuracies in the earliest productions of words would be ascribed not to grammar, but to difficulties that infants have in coordinating the actions of the articulators.

As a new source of evidence complementing these theoretical arguments concerning the character of the initial state, we have conducted experimental studies to evaluate the relative ranking of MARKEDNESS and FAITHFULNESS in the earliest grammars.

2.2. Nasal Place Assimilation

To date our experiments addressing the relative rankings of MARKEDNESS and FAITHFULNESS in the initial state have addressed a single phonological phenomenon, nasal place assimilation. For now, we will assume that nasal place assimilation is driven by a markedness constraint requiring that every nasal that is followed by a consonant must have the same place of articulation as that consonant; we'll call this constraint '$M_{NasalPl}$' or simply 'M_{NP}'. This markedness constraint potentially conflicts with the faithfulness constraints F_{NP} requiring that the place of articulation of a consonant in the input be preserved in the output. At issue will be the relative ranking of M_{NP} and F_{NP}.

Since the experiments we report here involve English-learning infants, it is relevant to consider the status of nasal place assimilation in English, which is somewhat complex. Within a single morpheme, it is almost always respected; for example, we have words like *bend*, *bump*, and *bank* [bæŋk], but no words like hypothetical *bemd*, *bunp*, or *bamk*. However, when a nasal at the end of one morpheme contacts a consonant at the beginning of a following morpheme, two outcomes are possible, depending on whether the morpheme boundary is the 'inner' type characteristic of Level 1 affixation, or the 'outer' type of Level 2. For the inner type, the nasal behaves as if it were in the same morpheme as the following consonant: it assimilates. An example of this type is the prefix *in-*, meaning 'not,' as in *inaudible* and *inexpensive*. The nasal consonant of this prefix is pronounced [n] before coronal stops such as [t,d] (*intolerable, indefinite*), but the same input is pronounced [m] in cases where the consonant immediately following the prefix is a labial stop, /p, b/: *imperfect, imbalance*.[1] While an affix of the first, inner type will alternate, exhibiting assimilation, an affix of the second type will not; for example we get *input* and *incoming* with a different morpheme *in-* (meaning 'directed inward' rather than 'not').

Thus the situation confronting the learner of nasal place assimilation in English is in fact a composite of the three cases illustrated above for word-initial ŋ. Considering only simple, mono-morphemic words, English clusters are assimilated, i.e., unmarked with respect to M_{NP}: English has an unmarked inventory without alternations. This is the hard case for learning, where the initial ranking must rank M_{NP} above F_{NP} in order for the language to be learnable. For morphologically complex words with inner, Level 1, affixation, clusters are still unmarked: here, English has an unmarked inventory *with* alternations, as exhibited by *in-*, 'not.' Finally, for morphologically complex words with Level 2 affixation, English does allow unassimilated clusters violating M_{NP}, so now the inventory appears to be marked.

This heterogeneous pattern is of course quite familiar in morphophonology, where, to grossly oversimplify, morpheme junctions at an inner level look like morpheme-internal environments, whereas junctions at an outer level look like the simple concatenation of separate words with little or no influence on one another. Although there are several theoretical proposals for handling this general pattern within OT and other phonological frameworks, we will adopt here a highly simplified approach adequate to our limited needs. We will assume that the markedness constraint M_{NP} requires that a nasal consonant have the same place of articulation as a following consonant if these two consonants are in the same *stem*. On this simplified view, inner, Level 1 morpheme junctions lie within the stem, while more superficial, Level 2 junctions lie outside the stem. Thus in *imperfect* the (Level 1) prefix *in-* 'not' falls within the same stem as the root *perfect*, so M_{NP} applies, requiring assimilation. In *input*, however, the (Level 2) prefix *in-* 'directed inward' falls outside the stem containing the root *put*, so M_{NP} does not apply, just as it fails to apply between the two words in the compound *pinpoint* or the two words in the phrase *in petroleum*.

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[1] This morpheme *in-* 'not' fails to assimilate to other following consonants, however, as in *incompetent, ingratitude, informal,* and *involuntary*.

On this analysis, the adult English ranking is $M_{NP} \gg F_{NP}$. There is evidence in the language for this ranking from alternations, but these are highly limited, applying to *in-* 'not' (before labial stops only) and perhaps also to *con-* 'together' (*contemporary*, *compatriot*, *congruence*). It seems reasonable to assume that children cannot exploit this evidence during their first two years, the period of time we examine in the experiments discussed below. So for all intents and purposes, for infants, English nasal assimilation presents the difficult case of an unmarked inventory without alternations — the case for which learnability requires that the initial ranking be MARKEDNESS ≫ FAITHFULNESS. Furthermore, at the age of the youngest children we tested (4.5 months), the literature shows no evidence of the acquisition of language-particular phonotactics (Jusczyk et al. 1993; Jusczyk et al. 1994; Mattys & Jusczyk in press). Thus it is unlikely that any behavior we see in these infants is the result of statistical analysis of English consonant clusters. Any evidence we find that these youngest infants rank MARKEDNESS above FAITHFULNESS would seem to support the nativist learnability argument that this is knowledge encoded in the initial state.

Thus we ask the experimental question: do infants show evidence of the ranking MARKEDNESS ≫ FAITHFULNESS? Focusing on nasal place assimilation, our goal then is to determine whether the youngest English-learners give evidence of observing each type of constraint, and if so, to determine how they rank these two types of constraints with respect to one another.

3. Experimental explorations of the initial state

Section 2 argued that under the nativist hypothesis, a principle fundamental to Optimality Theory, Richness of the Base, entails that in order for languages with unmarked inventories to be learnable, the initial state must be characterized by the schematic ranking MARKEDNESS ≫ FAITHFULNESS. In this section we undertake experimental assessment of this conclusion.

3.1. Experimental methods, hypotheses, and predictions

The work discussed here attempts to assess the hypotheses stated in (1).

(1) **The central grammatical hypotheses (initial state)**

Insight into infants' processing of linguistic input can be gained from the assumptions that, in the infants' grammars:

a. MARKEDNESS constraints are present;

b. FAITHFULNESS constraints are present;

c. MARKEDNESS ≫ FAITHFULNESS.

The technique we employ for observing the linguistic processing of infants is the Headturn Preference Procedure, a computer-automated method used extensively in infant speech research (Jusczyk, 1998; Kemler Nelson et al., 1995). The dependent variable is the listening time to two types of spoken stimuli designed to differ significantly only along the linguistic dimension of interest — the independent variable. In this procedure, each infant sits on a caregiver's lap in a chair in the center of a three-sided enclosure. A test trial begins with the flashing of a light on the center panel. When the infant fixates the center light, it is extinguished, and a light on one of the side panels begins to flash. When the infant makes a head turn of at least 30 degrees in the direction of the flashing light, the experimenter initiates a speech sample from the loudspeaker on the same side as the light and begins recording the infant's looking time by pressing a button on the response box. If the infant turns away from the loudspeaker by 30 degrees for less than 2 consecutive seconds, and then reorients in the appropriate direction, the trial continues, but the time spent looking away from the loudspeaker is eliminated from the total orientation time on that particular trial (the experimenter presses another button on the response box to stop the timer). If the infant looks away for more than 2 consecutive seconds, the trial is terminated. Both the experimenter and the caregiver wear sound-insulated headphones and listen to loud masking music to prevent them from hearing the stimulus materials throughout the duration of the experiment.

To link OT principles concerning the competence grammar to the performance of infants, we adopt the working hypothesis given in (2).

(2) **Linking hypotheses, initial state: Higher Harmony ⇒ longer listening time**

a. Infants will attend longer to stimuli that conform better to their current grammar, all else equal.

b. Phonologically unrelated stimuli presented as isolated words 'conform to a grammar' if they are each a possible output of the grammar.

Relative version: Given two such stimuli A and B, A 'conforms better' to a grammar if, treated as isolated outputs and evaluated by the grammar, A has higher Harmony than B. Underlying forms for these outputs are assumed to be chosen to maximize Harmony (as in the lexicon optimization of Prince and Smolensky 1993: Ch. 9 or the robust interpretive parsing of Smolensky 1996b and Tesar and Smolensky 1996, 1998b, 2000).

c. Phonologically related stimuli presented in a potentially grammatically-related configuration 'conform to a grammar' if they are in fact so related by the grammar. In particular, consider a set of spoken items presented as a list of triads consisting of three prosodic words of the form

X … Y … XY′

where XY′ is a concatenation of X and Y in which some sound changes may have possibly occurred (e.g., *on…pa…ompa*). Such a triad 'conforms to a grammar' if there is a choice of inputs /x/ and /y/ such that X, Y, and XY′ are respectively the output of the grammar for the three inputs /x/, /y/, and /xy/, in which /xy/ is literally the concatenation of x and y (possibly separated by a morphological boundary). (Thus, depending on the ranking of FAITHFULNESS in the grammar, the conforming XY′ may be a faithful concatenation of X and Y, or an unfaithful concatenation reflecting phonology.)

Relative version: One set of such stimuli A 'conforms better' to a grammar than another set B if A has higher Harmony according to the grammar. The inputs /x/ and /y/ are presumed chosen to maximize Harmony. (Thus *on…pa…ompa* conforms better to a grammar than does *on…pa…onpa* if the grammar assigns higher Harmony to the mapping /onpa/ → *ompa* than it does to the input-output mapping /onpa/ → *onpa*.)

Hypothesis (2b) suffices for evaluation of the hypothesis (1a) that MARKEDNESS constraints are evidenced in the initial state, because MARKEDNESS constraints involve only outputs. The more complex hypothesis (2c) is necessary, however, for assessing FAITHFULNESS and its ranking relative to MARKEDNESS, since inputs as well as outputs of the grammar must be involved. Use of triad stimuli of the form described in (2c) will be referred to as *the X/Y/XY paradigm*.

The work reported in this section are the initial results of a general research program with a wide range of potential applications within grammatical theory. If the proposed Linking Hypotheses (2) — including the X/Y/XY paradigm — bears up under experimental investigation, listening times can be used to investigate many aspects of the grammars of infants. The initial work reported here involves two dimensions of phonological markedness: syllable structure and nasal place assimilation. The corresponding markedness constraints are respectively ONSET/NOCODA and $M_{NasalPl}$, a constraint (introduced in Section 2.2) requiring that the place of articulation of a nasal consonant agree with that of a following consonant.

With respect to syllable structure, we examine a prediction of the Basic C/V Syllable Theory (Prince and Smolensky 1993: Ch. 6): a single intervocalic consonant will universally be parsed into the onset of the following syllable rather than the coda of the preceding syllable. That is, ···VCV··· will always be parsed ···V.CV··· rather than ···VC.V···, where the period marks the syllable boundary. Thus, all else equal, stimuli with the syllable structure ···V.CV··· (such as *ba.di to.ma …*) will conform better to any grammar than those with the structure ···VC.V··· (*bad.i tom.a …*). The reason is as follows. These forms may well violate many markedness consonants — e.g., *toma* violates a constraint prohibiting nasals — but the two matched lists will fare equally well with respect to all constraints except those sensitive to the only difference between the lists, the location of the syllable boundary. And here, both the constraints ONSET ('syllables have onsets') and NOCODA ('syllables do not have codas') are violated by all the forms in the second list and satisfied by all those in the first. Regardless of where these markedness constraints may be ranked in the infant's current grammar, this entails that the first list is more harmonic than the second, and by hypothesis (2b), infants are thus predicted to attend longer to the first list — if ONSET or NOCODA is indeed present in their grammars.

The case of syllable structure was chosen for the initial study in part because the competing alternatives — different syllabifications (e.g. *to.ma* vs. *tom.a*) — are equally faithful to any underlying form.[2] There can therefore be no question of conflict between the markedness constraints ONSET/NOCODA and faithfulness constraints. This allows for a relatively simple experiment, but does not allow us to test the hypothesis concerning the relative ranking in the

[2] We are assuming here that syllabification is not present in underlying forms. This is commonly assumed to account for the strong cross-linguistic generalization that syllable structure is not lexically contrastive. If syllable structure were present in underlying forms, the predictions stated in the text would still follow, but now because of the ranking structure of the initial state: faithfulness to underlying syllable structure would be dominated by markedness. See the discussion of nasal assimilation below for an experimental approach to testing such a ranking.

initial state of MARKEDNESS and FAITHFULNESS. For this purpose, we turned to a different markedness constraint, $M_{NasalPl}$: satisfying this constraint can require changing the place of articulation of a consonant, violating FAITHFULNESS and thereby setting up a conflict of the desired type.

The experimental study of $M_{NasalPl}$ tests all three hypotheses in (1). First, to test the hypothesis that FAITHFULNESS is present in the infants' grammars and relevant to their behavior in the way hypothesized in (2c), we compare a list of items of the form *om…pa…ompa in…du…indu …* with a matched list of items of the form *om…pa…indu in…du…ompa …*.[3] The lists are designed to fare equally well on all constraints except FAITHFULNESS, which is satisfied in the first list and violated in the second. In particular, note that the lists are constructed so that the XY forms do not violate $M_{NasalPl}$: the final nasal in X always agrees in place with the initial stop in Y. Thus if FAITHFULNESS is present in the infants' grammars and relevant to their behavior in the way hypothesized in (2c), infants should attend longer to lists of the first — faithful — type.

Next, to test whether M_{NP} is in fact present in infants' grammars, we compare lists such as *ompa…indu…* with matched lists *o**md**u…i**np**a…*. The first list satisfies M_{NP} while the second list violates it, and the matching of syllables employed in the two lists means that the two lists fare equally with respect to other constraints. Thus if M_{NP} is present in the initial state then, according to (2b), we predict infants will attend longer to the first type of list.

For direct comparison with the faithfulness experiment, it is actually preferable to design the markedness experiment using lists of triads comparable to those used for studying faithfulness. The first type of list includes triads of the form *om…pa…ompa in…du…indu …* while the second type of list is a matched list of items of the form *in…pa…i**np**a om…du…o**md**u …* . Both lists satisfy FAITHFULNESS because each 'XY' bisyllable is a faithful concatenation of the 'X' and 'Y' monosyllables. But the consonants coming into contact in XY were selected so that nasal place assimilation was satisfied in the first list and violated in the second. Again, we predict from (2c) that infants will attend longer to the first type of list. This is the paradigm actually employed in the experiments described below.

Finally, to test whether MARKEDNESS $\gg$ FAITHFULNESS, we must pit F_{NP} against M_{NP} . Now the first list consists of triads of the form *o**n**…pa…o**m**pa* while the second list contains matched

[3] There were 6 lists of each of the two types in each experiment. The X items had the form VC or CVC, with the initial C an obstruent and the final C one of the nasals *n*, *m*, or *ŋ*; in each list of 8 triads, all X forms had the same nasal; . The Y items had the form CV with C a voiced or unvoiced obstruent and V a vowel occurring word-finally in English. X, Y, and XY' were each naturally produced (by a female native-speaker of English) as a single prosodic word; XY' was produced with initial stress and was not an English word. Triads were separated by 1 sec. and items within each triad were separated by 0.5 sec. The total duration of each list was approximately 25 sec.

items *on…pa…**onpa***. The first list violates F_{NP} but satisfies M_{NP} , and the reverse is true of the second list. The prediction from the Richness of the Base argument in Section 2 is that infants will attend longer to lists of the first type.

Clearly, if the overall research program enabled by the linking hypothesis (2) is viable, experiments of this general sort can be used to address virtually any putative markedness constraint. The approach may even extend to syntax in older children.

3.2. Experimental results: Youngest infants

In determining the age groups to test, we took into consideration experimental results showing that although 9-month-old infants show significant listening preferences for sound patterns that observe the phonetics and phonotactics of English, 6-month-olds do not (Jusczyk et al., 1999; Jusczyk et al., 1993b; 1994; Mattys & Jusczyk, in press). We thus felt it important to test infants no older than 6 months in order to better access initial state, prior to acquisition of significant language-particular knowledge of phonology. The youngest age at which infants have sufficient head and neck control to be tested in the Headturn Preference Procedure is about 4.5-months of age.

The experimental results are summarized in the table (3). Each row corresponds to a single experiment. The column labeled 'MARKEDNESS' indicates whether a given experiment addressed markedness of syllable structure or nasal place of articulation. The ages of infants participating in these experiments are indicated as well: 6 and 4.5 months, respectively. In each experiment, we tested the prediction that infants will attend longer to stimuli with greater Harmony, according to the hypothesized initial grammar. In the experiments labeled 'Markedness' in the 'Constraints' column, the stimuli presented differed only in that the forms with lower Harmony violated the markedness constraint(s) in question ("*M"), while the forms with higher Harmony satisfied the markedness constraint(s) ("TM"). In the 'Faithfulness' experiment, the higher-Harmony stimuli satisfied FAITHFULNESS ("TF") while the lower-Harmony stimuli did not ("*F"). In the 'Markedness *vs.* Faithfulness' experiment, the higher-Harmony triads respected MARKEDNESS but violated FAITHFULNESS, while the reverse was true of the lower-Harmony triads. In all other respects, the two types of stimuli were matched in each experiment.

The infants' listening times to the two types of stimuli presented in each experiment are shown in the columns headed 'Higher Harmony' and 'Lower Harmony'. The mean times are shown in boldface, with the standard deviation (SD) and standard error (SE) shown beneath. The difference in listening times for each experiment is assessed by several measures in the final column. The proportion of infants preferring the higher-Harmony stimuli are shown as a fraction with denominator 20 or 16, depending upon whether the data from 20 or 16 infants were used in the experiment. In boldface, the *p*-value of the significance of the difference in mean listening times is shown, according to a paired t test; t values are shown beneath the *p* value.

(3) **Results of experiments addressing the initial state**

	MARKEDNESS	Age (mo)	Constraints	Higher Harmony	Lower Harmony	Difference
				Example	*Example*	Proportion
				Mean Time	**Mean Time**	***p***
				SD / SE (sec)	SD / SE (sec)	*t*
1	ONSET/	6	Markedness	*V . CV*	*VC . V*	14/20
	NOCODA			**10.99**	**9.35**	**.007**
				2.77 / 0.62	2.98 / 0.67	2.996
2	ONSET/	6	Markedness	*CV*	*VC*	14/20
	NOCODA			**10.63**	**9.50**	**.017**
				1.64 / 0.37	1.94 / 0.43	2.63
3	$M_{NASALPL}$	4.5[4]	Faithfulness	*m…po…mpo* TM TF	*m…po…**uŋkɚ*** TM *F	11/16
				15.36	**12.31**	**.006**
				3.89 / 0.97	4.55 / 1.14	3.22
4	$M_{NASALPL}$	4.5	Markedness	*m…po…mpo* TM TF	*m…po…**mpo*** *M TF	11/16
				15.23	**12.73**	**.044**
				4.49 / 1.12	4.80 / 1.20	2.21
5	$M_{NASALPL}$	4.5	Markedness *vs.* Faithfulness	***m**…po…mpo* TM *F	*m…po…**mpo*** *M TF	12/16
				16.75	**14.01**	**.001**
				4.58 / 1.14	4.01 / 1.00	4.21

As shown in (3), the results of Experiment 1 provide evidence that at 6 months infants' grammars include a markedness constraint on syllable structure (either ONSET or NOCODA). Since natural production of the marked syllable structure VC.V is problematic, these stimuli were created by splicing together two separately-recorded syllables. The forms V.CV were also produced by splicing, in order to minimize differences other than syllable structure between the two types of stimuli. As a check on the results of Experiment 1, in Experiment 2 we tested infants' preference between lists of simple CV or of VC forms; these stimuli involved no splicing, although it is no longer as obvious that they equally well satisfy FAITHFULNESS.

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[4] In each of experiments 3–5, sixteen infants (7 males, 9 females), from monolingual English-speaking homes, were tested. The average age of the infants for each experiment fell between 4 months, 16 days and 4 months, 20 days, with ages of individual infants ranging from 4 months, 2 days to 5 months, 8 days. Additional infants (six for experiments 3 and 4, 14 for experiment 5) were tested but not included for reasons of excessive fussiness or crying, failing to orient properly to the test apparatus, experimenter error, or parental interference.

Nonetheless, hypothesis (2b) implies that infants should attend longer to the CV forms than the matched VC forms, since the latter but not the former violate ONSET/NOCODA, while the lists fare equally well with respect to markedness constraints evaluating individual segments. The results shown in (3) confirm the presence of syllable markedness constraints in the grammar of 6-month old infants.

The table further displays the results of Experiments 3 and 4, which provide evidence for the presence of FAITHFULNESS and MARKEDNESS with respect to nasal place, respectively. The relative ranking of these constraints was examined in Experiment 5, which provides evidence confirming the nativist learnability argument's prediction that MARKEDNESS $\gg$ FAITHFULNESS in the grammars of 4.5-month-old infants, the youngest age at which this method can be employed.

3.3. MARKEDNESS and FAITHFULNESS in older infants

A complete presentation of Experiments 3–5 is provided in Jusczyk, Smolensky and Allocco 2000, which also presents seven other experiments. These additional experiments examine nasal place markedness in infants at ages 10, 15, and 20 months. Faithfulness experiments at 10 months confirms the presence of FAITHFULNESS as assessed in the X/Y/XY paradigm, as Experiment 3 above did at 4.5 months. Markedness experiments at 10 and 15 months confirm the presence of $M_{NasalPl}$, as Experiment 4 above did at 4.5 months. The results of the markedness *vs.* faithfulness experiments are more complex. At 10 months, infants show the same result as the 4.5-month olds did in Experiment 5 above: they favor markedness over faithfulness. At 15 months, however, infants show no preference: there is no significant difference between listening times for the two types of stimuli. This experiment was repeated with a different set of 16 15-month-olds, , with precisely the same results. But this state of indeterminate ranking is short-lived. By 20 months, infants return to a clear preference for forms obeying MARKEDNESS at the expense of FAITHFULNESS

What factors are responsible for the absence of any clear ranking of these markedness and faithfulness constraints in 15-month-olds? The fact that two separate groups of infants at this age displayed exactly the same pattern of results indicates that the absence of any consistent ranking of these constraints should be taken seriously. D.A. Dinnsen (personal communication, November, 1998) has suggested a possible explanation for the uncertainty in the ranking at 15 months. In particular, it is at this age that infants show the first signs of learning about morphology in their comprehension of language. For example, Shady (1996) found that neither 12- nor 14-month-old English-learning infants showed significant listening preferences for passages with function words (functor morphemes) in the proper position (natural passages) over passages with function words in improper positions (unnatural passages). However, by 16 months, English-learners are sensitive to the phonetic and distributional properties of function words and listen longer to the natural passages. Similarly, Santelmann and Jusczyk (1998) explored English-learners' sensitivity to the relationship between the auxiliary verb *is* and the verb ending *-ing*. The *-ing* morpheme is one of the earliest acquired morphemes in children's productions of English (Brown, 1973; de Villiers & de Villiers, 1973). Santelmann and Jusczyk found that sensitivity to the basic dependency between the function morpheme *is* and the morpheme *–ing* develops between 15- and 18-months of age. Together, these two studies provide evidence that, beginning at approximately 15 months of age, infants are becoming sensitive to the presence of morphemes in the speech around them.

As L. Benua (personal communication, September, 2000) has pointed out to us, the beginnings of morphology pose difficulties for the child's analysis of nasal assimilation in English. Presented with a single-syllable item like *im* in a stimulus triad of the experiment, 15-month infants may now explore the new possibility that this is a prefix, combining with the following root *po* to form a morphologically-complex word *impo*. Now under this analysis, it is unclear whether a prefix-final nasal should assimilate to a following consonant: the evidence available from English is mixed. As we have seen, an 'inner,' Level 1, affix like *in-* 'not' will assimilate; an 'outer,' Level 2, affix like *in-* 'directed inward' will not. Until the child's morphology becomes sophisticated enough to sort out such subtleties, the evidence will provide conflicting information about whether it is markedness or faithfulness that should dominate here. The result might well be indefiniteness of ranking of the sort exhibited by the 15-month-olds in our study.

By 20 months it may be that children are no longer treating the hypothetical forms in the experiment as novel affixes. Perhaps their receptive lexicons are now substantial enough that the complete absence of recognizable lexical items suggests to them that, while the sound patterns they are hearing are highly English-like, these are not actually English lexical items. Thus perhaps the 20-month-olds are not attempting lexical and morphological analysis, just as an adult presumably would not. The forms are being treated as morphologically simple items, subject to the basic patterns of English phonology, which, as we have seen, demand that nasals assimilate. The constraints that are being applied to the experimental stimuli are the most basic ones, where nasal place markedness dominates faithfulness.

3.4. Extensions

We have discussed initial work in an experimental research program that attempts to rather directly observe the presence and ranking of grammatical constraints in infants too young to be producing any linguistic utterances. If this research program proves successful, it may become possible for such experimental observation to directly inform theory development, even with respect to some of the most theoretically intricate issues in linguistic theory.

Take nasal place assimilation, for example. It can be exploited to examine a deep theoretical question concerning OT: must the type of optimization used in OT to date be modified to allow constraints to be highly selective in the forms that they compare? In recent work, Wilson 2000 proposes such a fundamental modification of the theory in order to address what he argues to be a fundamental problem in standard OT. While the problem is much more general, it is nicely illustrated by nasal place assimilation. (Here we apply Wilson's general approach to the particular case of nasal assimilation; this is not a case Wilson treats explicitly.) It appears to be a strong empirical generalization that when a nasal comes in contact with a following consonant with a different place of articulation, if place assimilation occurs, *it must be the nasal that assimilates*. Within standard OT, an output constraint like M_{NasalPl} that requires a nasal consonant N to agree in place with a following consonant C *can* be satisfied by changing the place of C, and, as shown in a number of such cases in Wilson 2000, this entails that in the typology predicted by standard OT, there are languages in which it is C not N that assimilates under certain general conditions. In Wilson's proposed modification of OT, the markedness constraint M_{NasalPl} is replaced with a different type of constraint which we'll call ${}^{\rightarrow}M_{\text{NasalPl}}$. Now M_{NasalPl} asserts that a form in which a nasal fails to agree in place with a following consonant is less harmonic than *any* form lacking such an agreement failure. But ${}^{\rightarrow}M_{\text{NasalPl}}$ is a *targeted constraint*: it asserts **only** that a form *S* in which a nasal fails to agree in place with a following consonant is less harmonic than the single form *S*′ which is exactly like *S* except that the nasal's place has changed to agree with that of the following consonant.

Targeted constraints solve this and many other important problems for standard OT. But the formal definition of optimization required in the new theory — called TCOT ('TC' for 'targeted constraints') — must be made significantly more complex in order to deal with the new possibility that constraints can be targeted, because such constraints refuse to assert a Harmony relationship between all but a small set of closely-related pairs of forms (like *S* and *S*′).

A new source of evidence that a move from OT to the more formally-complex TCOT is empirically warranted might be provided by experiments of the sort discussed above. According to standard OT, triads like *on…pa…onda* should satisfy M_{NasalPl} and thus be preferred to their faithful counterparts *on…pa…onpa*. But according to TCOT, the opposite is the case. In TCOT, being unfaithful to the place of a nasal N in order to achieve agreement with a following consonant C will raise Harmony when markedness outranks faithfulness. But unfaithfulness to the place of *C* cannot raise Harmony: the agreeing form is *not* declared more Harmonic by the *targeted* constraint ${}^{\rightarrow}M_{\text{NasalPl}}$ — it is merely unfaithful. The studies reported here are neutral concerning the difference between OT and TCOT here: since the triads used in the experiment always altered the place of the nasal, both OT and TCOT agree that the resulting unfaithfulness will increase Harmony when markedness outranks faithfulness. Thus empirical light of a new sort might be directed towards fundamental theoretical questions in phonology by further experiments examining unfaithfulness in the post-nasal consonant, and potentially many other theoretically important contexts as well.

4. Experimental explorations of the final state

In Section 3, we discussed experimental evidence suggesting that, at the earliest time we can test them (4.5 months), infants possess markedness and faithfulness constraints, and rank them MARKEDNESS $\gg$ FAITHFULNESS, as predicted for the initial state by Richness of the Base in a nativist interpretation of OT. We now turn to experimental exploration of the final state. In Section 4.1 we consider theoretical implications for Richness of the Base of partial nativization of loanwords; this leads to the concept of *hidden rankings* and an extended formulation of Richness of the Base itself. In Section 4.2 we formulate a hypothesis linking Extended Richness of the Base to phonological performance, and present the design of our primary experimental condition. The experimental results are presented in Section 4.3; they reveal *hidden strata* among the onset clusters illegal in English. In Section 4.4 we undertake an analysis of the experimental results, introducing the crucial notion of local conjunction of constraints. In Section 4.5 we discuss the other experimental conditions we examined, and their implications for our proposed analysis. Finally we briefly consider alternative possible types of explanations of the experimental findings in Section 4.6 , and, in Section 4.7, possible explanations for the origin of hidden rankings.

As explained in Section 1, a prediction concerning the final state of the grammar follows immediately from Richness of the Base, and might even be taken as definitive of it: the constraint ranking of an adult who has mastered English always outputs a form consistent with the general patterns of English, regardless of the input given to the grammar. To probe this aspect of the final state, we wish to induce adult English speakers to give as inputs to their phonological grammars underlying forms that, if faithfully parsed, would be illegal in English. Under such conditions, if Richness of the Base is correct, the grammar must 'repair' these 'defects', producing an English-legal output.

4.1. Covert grammars

The actual situation must, however, be more complex. We know that when foreign words are borrowed into a language in which they would be illegal, many types of defects are repaired, but often some types of defects are systematically left untouched (e.g., Kiparsky 1968, Saciuk 1969, Holden 1976, Yip 1993, Itô and Mester 1995b). It is as though the final grammar does not treat all illegal structures equally: some it simply will not tolerate, others it will let slide. As a case in point, consider the well-studied case of Japanese, where, roughly speaking, the established lexicon provides a kind of archeological slice through time, in which forms that were borrowed at different points in time display different regularities. Itô and Mester 1995a, 1995b, 1999 present an extensive OT analysis which allows us to state this precisely; this has been the point of departure for further work in OT (e.g., Davidson and Noyer 1996, Fukazawa 1998; Fukazawa, Kitahara and Ota 1998, Katayama 1998).

The truly native or Yamato vocabulary of Japanese can be characterized by a certain constraint ranking which sharply divides all forms into the legal and the illegal. But among forms borrowed from Chinese, some of the constraints observed by all Yamato forms are seen to be imposed on the foreign forms, while others are not. Itô and Mester exploit the markedness/faithfulness structure of OT to provide an elegant formal analysis of this mixed situation. According to their analysis, among all the constraints obeyed by Yamato forms, some have stronger force than others: they are higher ranked. Schematically:

(4) $M_1 \gg M_2 \gg F \gg M_3$

where

(5) Constraints relevant to Japanese lexical stratification

a. M_1 No voiced geminates.

b. M_2 No unvoiced obstruents following a nasal.

c. F Voicing of input segments must be preserved in the output — IDENT([voice])

d. M_3 NOCODA

According to this ranking, in native words, the markedness constraint M_3 can be violated, but both M_1 and M_2 must be respected because they dominate a relevant faithfulness constraint F. In the Yamato lexicon, there is no evidence for the relative ranking of M_1 and M_2; their relative ranking might just as well be reversed:

(6) $M_2 \gg M_1 \gg F \gg M_3$

Alternatively, we could say that the Yamato lexicon provides evidence only for the partial ranking:

(7) $\{M_1, M_2\} \gg F \gg M_3$ — base form of grammar

But in processing a Chinese loan input, suppose some faithfulness constraints are allowed to move up in rank:

(8) $M_1 \gg M_2 \gg F \gg M_3$

This means that the Chinese borrowings will be 'repaired' to satisfy M_1, but violations of M_2 will now be tolerated. Such is actually the case in Sino-Japanese forms with the constraints in (5).

We propose to explore what we believe to be a new interpretation of this state of affairs: at the time when the Chinese forms were being borrowed, the base adult Japanese grammar actually was (4). The ranking $M_1 \gg M_2$ was a *hidden ranking*: there was no evidence for it in the Japanese lexicon at that time. The forms violating M_1 and those violating M_2 define two *hidden strata* of Japanese, a covert distinction among Japanese-illegal forms.

Suppose furthermore that at the time of borrowing, the ranking of F was somewhat variable: it was a *floating constraint* (Reynolds 1994, Zubritskaya 1994, 1997, Nagy and Reynolds 1997, Anttila 1998, Boersma 1998; Boersma and Hayes 1999, Legendre, Hagstrom, Todorova and Vainikka 2000):

(9) $M_1 \underset{F}{\underline{\gg M_2 \quad}} \gg M_3$ — covert form of grammar

Each time a form is pronounced, the position of a floating constraint is fixed somewhere in its range. Thus, rather than the ranking (4), sometimes the following ranking will apply:

(10) $M_1 \gg F \gg M_2 \gg M_3$

When F occupies the lowest ranking in its range, we will say it is in its *base position*, and the resulting grammar we'll call the *base ranking*, (4). In both of the total rankings generated by the floating constraint — (4) and (9) — M_1 will be respected in all outputs; but M_2 will be respected only by the outputs of the base grammar. Suppose we assume, as a mutual constraint between the lexicon and the grammar, that a native vocabulary item must be assigned a consistent pronunciation by the grammar: that is, the output must be the same for both rankings (4) and (9). The native forms, then, must all obey M_2. The result is that, considering only these native lexical forms, there is now no evidence for the true full ranking (9) — only for the partial ranking (7).

But the non-native inputs provided by Chinese allow us to see the hidden rankings in the final state. Suppose that, perhaps with the commitment of additional cognitive resources, the ranking of F can sometimes be pushed by the speaker up to its elevated position. This allows for a more faithful pronunciation of the foreign input, although not generally a fully faithful pronunciation, as there remain markedness constraints like M_1 which are still higher-ranked than elevated F. The result is that the foreign input will be partially nativized. And the character of the partial nativization in the output provides information about the adult Japanese grammar that could not be extracted by considering native forms alone: it shows that the grammar possesses the hidden rankings in (9), and that the description in (7) is inaccurate.

Over time, the incorporation of a large number of borrowed Chinese forms into the Japanese lexicon presumably led to the establishment of a standardized elevated 'docking' position for F, with the now-partially-nativized Sino-Japanese lexical items marked in the lexicon as forming a distinct 'stratum' corresponding to this elevated FAITHFULNESS position. At this point, learning Japanese includes learning the different positions for F, so no special cognitive effort is involved in employing the Sino-Japanese vocabulary.

The ultimate fate of loanwords in a language is not our direct concern here. What is relevant to our discussion is only the initial point in the borrowing process, a point at which a foreign input is being processed by a grammar that was learned in a linguistic environment in which such forms were absent. Our interest in this arises because of its potential to reveal the structure of the final state of a native grammar.

The above considerations lead to the following extension of Richness of the Base to grammars with floating FAITHFULNESS.

(11) **Extended Richness of the Base**

a. The final state of the grammar is in general a partial ranking containing floating faithfulness constraints.

b. The location of a faithfulness constraint within its range is probabilistic. For any given input, this range of total rankings yields a set of outputs (possibly a singleton); the probability of each output in this set equals the probability of the collection of all total rankings yielding that output.

c. Marginally, this may lead to variation in the surface forms of the language.

d. Abstracting away from surface variation, the core generalizations exhibited in the (non-varying) surface forms of a language arise because its lexical items are subject to the meta-constraint that their outputs must be constant over the grammar, that is, constant over the floating range of faithfulness constraints. Underlying forms are otherwise unconstrained.

e. Thus for a native input, the output of the grammar is non-variable, and therefore equal to the single output of the base grammar (with faithfulness constraints at the bottom of their floating range). For native inputs, only the base grammar need be considered; floating can be ignored.

f. Inputs that are *not* drawn from the native lexicon will in general yield variable outputs; with FAITHFULNESS elevated from the base grammar, outputs of non-native inputs will in general violate the surface generalizations of the language.

g. It follows that the base grammar satisfies standard Richness of the Base: it generates only outputs respecting the surface generalizations of the language, given any input whatever.

An argument for the crucial final point (11g) goes as follows. Suppose there were some possible input *I* which the base grammar mapped to an output *O* that violated a surface generalization. This would arise because the relevant markedness constraints were outranked by relevant faithfulness constraints in their base position. But then *I* would also yield *O* with FAITHFULNESS elevated from its base position. Thus *I* would yield *O* consistently across the full grammar with floating constraints, so *I* would be a potential underlying form. Since there are no other constraints on underlying forms, there is nothing to bar such an *I* from the lexicon, thereby destroying the observed surface generalization.[5] Therefore such an *I* cannot exist.

An important feature of Extended Richness of the Base (11) is that it subsumes previous work in OT under standard Richness of the Base: this work is now taken to be the study of base grammars, which are determined by the inventory of native forms. The consequences of floating FAITHFULNESS only arise when analyzing the partial nativization evident in actual outputs from non-native inputs need to be analyzed, or the residue of such partial nativization in borrowing-induced lexical strata. It is precisely for such analysis that floating FAITHFULNESS has been previously invoked.

Knowing the articulated depiction of the final ranking provided in the covert form displayed in (10) — rather than the less informative base form illustrated in (7) — is important not just for precisely accounting for the partial nativization of foreign words, but also for second language acquisition. It is commonly assumed in the L2 literature that for adults learning a second language, the initial state for L2 acquisition is the final state of L1 (Broselow and Finer 1991, Archibald 1993, Broselow and Park 1995, Pater 1997, Broselow, Chen and Wang 1998, Hancin-Bhatt and Bhatt 1998). But the unarticulated base form of the grammar of L1 is generally silent on distinctions that are important in L2. For inputs from the L1 vocabulary, the base form suffices to determine the optimal output, but for the foreign inputs of L2, other rankings can be crucial. And in order to account for early L2 productions and the influence of L1 on the initial course of L2 acquisition, the ability of L1 speakers to elevate faithfulness constraints in the face of foreign inputs needs to be precisely specified, as it is in the covert form of the ranking.

Because ultimate application to L2 was a primary motivation for the work reported below, the phonological domain we chose to explore in our experimental work was one that has received considerable prior attention in the L2 literature: consonant clusters. Previous work has focused on cases in which L2 is English, and L1 is a language with an inventory of clusters that is impoverished relative to English (Broselow 1983, Anderson 1987, Tropf 1987, Broselow and

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[5] This abbreviated argument assumes a simplified situation like that discussed above, in which a single faithfulness constraint is floating. An argument considering the fully general case with multiple faithfulness constraints that may change their relative ranking by floating is beyond the scope of the present discussion.

Finer 1991, Eckman and Iverson 1993, Archibald 1998, Carlisle 1998, Hancin-Bhatt and Bhatt 1998). Due to constraints on the availability of experimental participants, we chose English for L1, and tested the production of clusters that are illegal in English. As a convenient way to get a large number of fluently produced English-illegal clusters, we used a Polish speaker to generate the experimental stimuli. While our results have implications for English-speaking learners of Polish, that is not the topic of this research. Rather, our goal is to examine the consonant-cluster component of the final state of the English grammar.

4.2. Experimental design

In the experimental work we now summarize, our goal is to determine the degree to which phonological theory in OT can contribute an understanding of performance. To this end we adopt the following strong working hypothesis linking competence and performance, with the intention of backing off from this hypothesis only as compelled by the performance data.

(12) **Linking hypotheses, final state: probability of production = probability of grammar output**

a. In the face of non-native inputs, speakers can, when sufficient cognitive resources are allocated, elevate a faithfulness constraint from its base position to a higher position within its floating range. Increasing the probability of greater deviation from the base position requires allocating greater cognitive resources at the time of production.

b. Given a non-native form to pronounce, the probability that a speaker will actually produce a given output is the probability assigned to that output by the grammar, where the input to the grammar is the underlying form faithful to the given form. This assumes the speaker has sufficient cognitive resources to enable the form to be correctly perceived and retained in memory until the time of production.

In Section 4.6, we return to examine this hypothesis in light of our experimental results; for now we simply adopt it in order to see how much insight into performance can be directly provided by grammatical theory.

A task that makes available ample cognitive resources is simple repetition of a foreign form. This is the condition under which FAITHFULNESS can best be elevated, sometimes resulting in quite faithful rendering of forms that violate multiple surface generalizations of the native language. We will discuss experimental results concerning the repetition task in Section 4.5. Our primary concern however is to design an experimental condition that best reveals the base grammar of the language, which, according to Richness of the Base, forces any input to meet the surface generalizations of English.

In our experimental design, 16 monolingual adult native English speakers were asked to produce forms with initial clusters illegal in English. The procedure is schematically shown in (13). (For full details, see Davidson In Press)

(13) Experimental procedure

TIME	1200ms	500ms	2400ms	3200ms
COURSE		pause		
VISUAL	vzety		Can you tell me if the Vzety castle is open….	*(visual timer)*
AURAL/ SPOKEN	[vzɛti]			"Can you tell me if the Vzety castle is open…"

The target item — *vzety* in the diagram (12) — was presented both in both aural and written form; the orthography was English-like (not IPA or Polish). The written forms were intended to decrease the probability of misperception of the consonants in the cluster; it is likely that the combined aural and visual presentation also produced a stronger representation in memory, decreasing the probability of memory errors. Speakers were asked to produce the target item in the middle of a carrier sentence that was presented visually; this was intended to increase the probability that the 'normal' English grammar was employed during production of the target item. Two further aspects of the design were also intended to minimize deviations from English. During production, the written form of the sentence was not available, so speakers could not simply read the target item; they had to generate it, along with the rest of the sentence, from a memorial representation. Further, a visual timer provided pressure for a slightly speeded response, again with the intention of minimizing opportunities for shifting out of the English grammar. Finally, to further discourage speakers — at a conscious level — from deviating from 'normal' English in order to produce the foreign item, speakers were told to imagine themselves as American spies in a foreign country. They were told that in order to avoid raising suspicion, they were to act as a "typical American tourist": if they were too accurate with their pronunciations of the foreign words, they would be uncovered as an American spy.

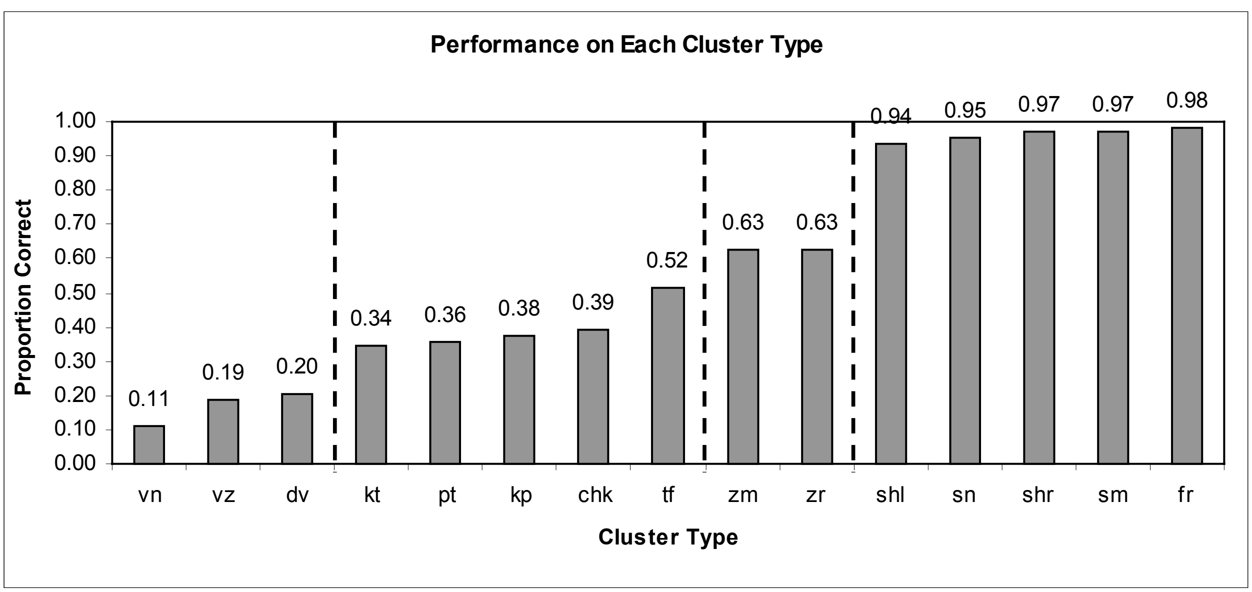
In the terms of the linking hypothesis (12) above, the experiment was designed to strike a delicate balance with respect to the cognitive resources available to the speakers at the time they produced the target item. Combined visual and aural presentation of the target item was intended to provide a representation of the target that was accurate and robust, so the demands of the task would not be so great as to induce errors in what we analyze as the *input* to the grammar. The other factors were intended to make the task sufficiently demanding at production time that there would not be ample resources available to elevate faithfulness constraints. Below we will compare the performance in this experimental condition with other conditions that presumably lead to a greater allocation of cognitive resources to elevating FAITHFULNESS; we will see that the propensity to nativize the input then reduces substantially.

The particular initial consonant clusters employed in the experimental materials were chosen to meet several criteria: they must be present in Polish; they must be absent in English but involve no non-English segments; they must be sufficiently few to enable all trials of the experiment to be completed in a sufficiently short time; they should vary along multiple phonetic dimensions and sample clusters with varying sonority distances. The last criterion reflects a hypothesis discussed below that a substantial factor in performance on a target cluster is whether English permits the sonority distance between its segments. The experimental materials had 15 clusters, each used as the onset of four different bisyllabic pseudo-Polish words; there were 30 carrier sentences, each used twice.

4.3. Experimental results

The results of the experiment are displayed in (14), which also shows the particular target clusters employed. Plotted is the mean proportion correct over all speakers and all tokens of a given cluster.

(14) Experimental results



The clusters fall into four rather distinct groups. Performance is above 90% on all English-legal clusters, assuming *šl* to be legal at least in the East Coast American dialect predominating in our experimental participants. Performance drops to 63% for what we will call the 'Easy' non-English clusters, *zm* and *zr*. Performance drops again to 34–39% for the 'Intermediate' clusters *kt, pt, kp, čk*. The cluster *tf* falls halfway between the Intermediate and Easy clusters; it is convenient for analysis to group it with the Intermediate clusters, which can then be characterized as the voiceless-stop-initial clusters. (Obviously, more extensive and systematic follow-up experiments will be needed for a more definitive classification of clusters of this type.) Finally, dropping to 11–19% correct, we find the 'Difficult' clusters *vn, vz* and *dv*.

While the labels 'Easy/Intermediate/Difficult' are transparent, it should be emphasized that the dependent measure in the experiment is *accuracy*, not *difficulty* per se.

Pairwise comparison of performance on individual clusters shows statistical justification for the post-hoc three-way grouping of the English-illegal clusters. In (15) we summarize the significance levels of performance differences, taking $p < 0.1$ as our criterion. The greyed cells correspond to comparisons of clusters in the same class; these should not be significantly different, and they are not. The white cells correspond to comparisons of clusters in different classes; these should show significant differences, and they do. The only exceptions are indicated by the numbers in (15), which give p levels too high to satisfy the criterion. We have only listed one cluster in the English-legal class, since all these clusters behave alike statistically.

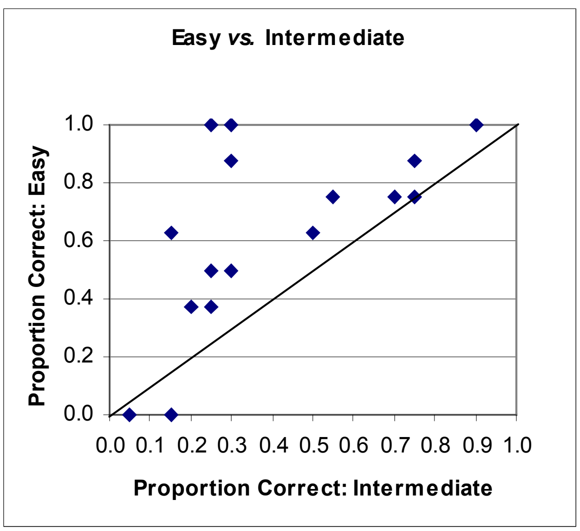
(15) Pairwise cluster differences (where not indicated otherwise, white: $p < 0.1$; grey: $p \geq 0.1$)

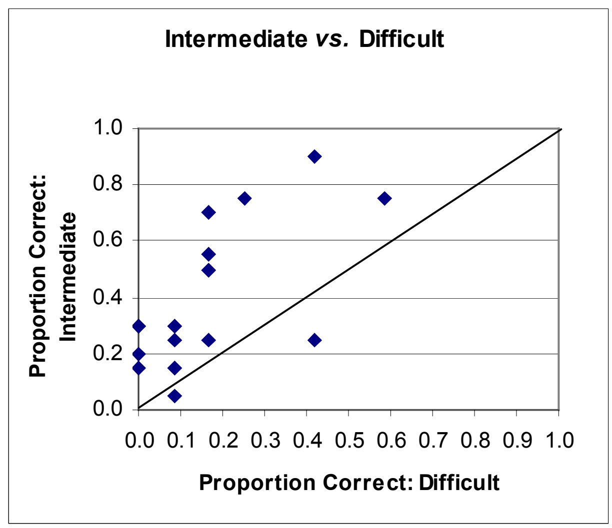
		zr	zm	tf	čk	kp	pt	kt	dv	vz	vn
	fr										
	zr			.23							
Easy	zm			.23							
	tf				.17	.12					
	čk										
	kp										
Intermediate	pt										
	kt								.12		
	dv										
	vz										
Difficult	vn										

At the boundary between the Intermediate and Difficult classes, the comparison *kt* vs. *dv* barely fails the criterion of significance, with $p < 0.12$. The other exceptions all involve *tf*; it fails to be significantly different from both members of the Easy class (*zr*, *zm*); while significantly different from the two members of the Intermediate class on which performance was worst (*pt* and *kt*), it fails to be significantly different from the other two (although with *kp* it is close). (While there may be some indication here that *tf* is better classified as Easy, we will await more significant results before complicating the analysis proposed below in order to account for such a classification.[6])

As a final, within-speaker means for confirming our grouping of clusters, we test the following prediction implicit in the grouping: each subject should produce more correct forms for clusters of the Easy class than for clusters of the Intermediate class, and similarly more for the Intermediate than for the Difficult class. In the scatter plots shown in (16), each point represents the performance of a single speaker. In the first plot, proportion correct on Easy clusters is plotted on the y-axis, while Intermediate cluster performance is plotted on the x-axis. All points are predicted to lie above the principal diagonal ($y = x$), i.e., in the upper left triangle. This prediction is confirmed, with only two speakers failing to meet it. The significance of this result is $p < .002$. Exactly the same result holds in the Intermediate/Difficult comparison shown in the second scatter plot.

(16) Performance comparisons between accuracy classes



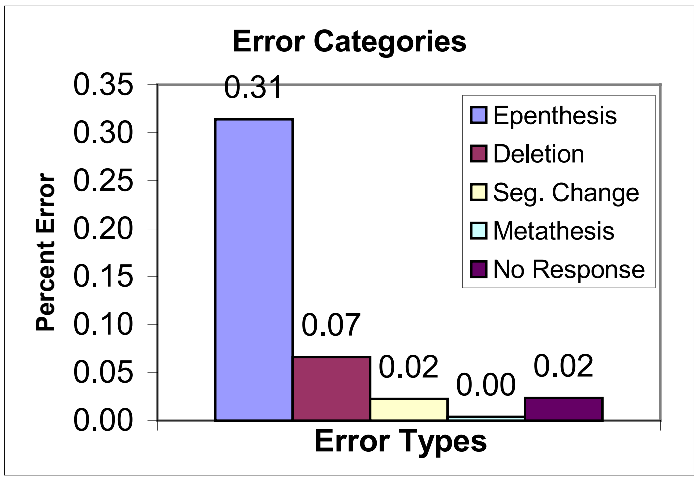


[6] A natural direction for refining the analysis would be to consider *tf* to occupy its own stratum between Easy and Intermediate, and analyze it by extending the hierarchy proposed below for consonant release: $*S_{\bar{A}} \gg *C_C$ (22)-(23). Introducing a new constraint in this family, ranked above the other two, $*S_{[-cont]}$: A stop must not release into a non-continuant, would distinguish *tf*, which satisfies the new constraint, from the Intermediate clusters, which violate it. (Although the status of the affricate in *čk* is a complexity we systematically ignore here, simply treating it like a stop.)

The experimental results seem to suggest that the grammar of English initial clusters contains 'hidden strata' among the illegal forms, each group of clusters defining a stratum. Inputs with clusters of the Easy stratum are most likely to produce faithful, English-illegal outputs, with no nativization. Inputs with clusters in the Intermediate and Difficult strata are successively less likely to surface faithfully, i.e., more likely to undergo nativization.

The 'repairs' performed when English-illegal inputs failed to surface faithfully were overwhelmingly epenthesis, as shown in (17).

(17) Error types



4.4. Analysis

We now examine whether phonological theory can shed light on the hidden strata revealed by the experiment. One hypothesis already proposed in the literature, which in fact guided the selection of the clusters used, is that sonority distance should play a primary role. English allows some clusters with a sonority distance of 1 (e.g., *sn*) but none with sonority distance 0 (e.g, **pk*). This hypothesis predicts then that the class of English-illegal clusters with a legal sonority distance (1 or more) should be produced more accurately than the class of clusters with the illegal sonority distance 0. As shown in (18), however, this is not the case.

(18) Sonority distance *vs.* cluster accuracy

sonority	Difficult			Intermediate					Easy	
distance	*vn*	*vz*	*dv*	*kt*	*kp*	*pt*	*čk*	*tf*	*zm*	*zr*
0		•		•	•	•	•			
≥ 1	•		•					•	•	•

In (18) the clusters are listed in order of increasing proportion correct; there is little correlation between this and the distinction between sonority distances. The lack of performance difference between the two sonority-distance categories was evident in a one-way repeated measures Analysis of Variance (ANOVA) across the mean proportion correct for each category; among English-illegal clusters, there was no significant effect either by subjects [$F_1(1,15)=2.65$, $p > .12$] or by items [$F_2(1,38)=1.75$, $p > .19$]. (There was of course a very significant effect of the English-legal *vs.* English-illegal factor among the clusters with non-zero sonority distance; $p < .0001$ by both subjects and items.)

Given that sonority distance appears to distinguish clusters too coarsely, we turn to a more fine-grained analysis in terms of phonological features, many of which provide the substrate for sonority conditions on onset well-formedness. Can the markedness of different feature combinations, suitably formalized, account for the hidden strata? The table in (19) is suggestive.

(19) Featural analysis of clusters (S=stop; F=fricative; A=approximant; Ā=non-approximant)

English Legal Clusters	(voiceless S)A—*pl, pr, tr, kl, kr*	
	(voiceless **F**)A—*fl, fr, sl, šl, šr*	
	(voiceless, coronal **F**)Ā —*sm, sn, šn, šm, sv, sf*	
	(**voiced** S)A— *bl, br, dr, gl, gr*	
English Illegal Clusters (from experiment)	(**voiced**, coronal **F**)A—*zr*	Easy
	(**voiced**, coronal **F**)Ā —*zm*	
	(voiceless, coronal S̚)Ā—*tf, čk*	Intermediate
	(voiceless, ***non-coronal*** S̚)Ā—*kt, kp, pt*	
	(**voiced**, coronal S̚)Ā—*dv*	Difficult
	(**voiced**, ***non-coronal*** **F**)Ā—*vn, vz*	

What the table shows is that as the clusters get worse, as measured by performance in the experiment, they also get more and more *marked*. In (19), marked feature values along various dimensions have been highlighted; the basic markedness constraints involved are given in (20). The markedness of [+voice] for obstruents is indicated by highlighting this feature in boldface; the markedness of non-coronal place, by bold italics. The markedness of [+continuant] for obstruents (or perhaps for onsets) is indicated by boldface on F = fricative. And underlining highlights the markedness of a stop followed by a non-approximant (Ā): in this environment, the stop is marked because it is unreleased, as indicated in (19) by S̚. We return to this dimension of markedness in a moment.

(20) Segmental markedness constraints

a. *F   *[+continuant, –sonorant]   No fricatives.

b. *VOL$_{-\text{SON}}$ *[+voice, –sonorant]   No voiced obstruents.

c. *$\overline{\text{COR}}$ *PL/{[labial], [dorsal]}   No non-coronal place.

What (19) suggests is that, if the compounding of markedness with decreasing accuracy can be properly formalized, it should allow an explanation of the hidden strata. But the strong interaction of markedness dimensions evidenced here requires a new technical device that allows a special type of inventory: one that excludes only the 'worst of the worst' (Prince and Smolensky 1993:180). As a simple example, consider the interaction of voicing and continuancy, both of which are marked in obstruents. As the initial member of a cluster, a voiced obstruent is marked — but it is nonetheless included in the inventory of English clusters (e.g., *bl*). Similarly, a continuant obstruent (fricative) is marked — but as an initial consonant it is allowed in the English cluster inventory (e.g., *fl*). But an initial obstruent that is *both* voiced *and* continuant — the worst of the worst — is excluded from the inventory (e.g., **vl*). Such an inventory — one that excludes only the worst of the worst — cannot be achieved by simply ranking the relevant faithfulness constraints with the relevant markedness constraints *F and *VOL$_{-\text{SON}}$. For allowing any fricatives at all requires that *F be outranked by all relevant faithfulness constraints (e.g., MAX); otherwise, optimal outputs would be unfaithful to avoid violating *F. The same must be true of *VOL$_{-\text{SON}}$ since voiced obstruents are allowed in the inventory. But now it must follow that the inventory also contains obstruents that are *both* continuant and voiced — voiced fricatives —because all relevant faithfulness constraints must outrank both *F and *VOL$_{-\text{SON}}$.

Not only are inventories that bar only the worst of the worst common, they are, it would seem, a type of inventory for which OT ought to provide a natural account, since they are readily understood in terms of barring sufficiently marked elements. (More formally, these inventories have the central OT property of *harmonic completeness* — they are, in fact, necessary in general to fill out OT typologies sufficiently to achieve *Strong Harmonic Completeness*; Prince and Smolensky 1993:187.) A simple, general means for admitting worst-of-the-worst inventories in OT was first proposed in Smolensky 1993, developed in Smolensky 1995, and applied in Smolensky 1997 to a complex problem in tongue-root vowel harmony which displays considerable formal similarity to the problem posed here by cluster inventories. The proposal is that, in addition to domination, constraints in OT interact via *the local conjunction operator*, &. We illustrate with the current example in tableau (21). *F & *VOL$_{-\text{SON}}$ is a constraint violated by a segment that is *both* a fricative *and* a voiced obstruent. This constraint makes it possible to strengthen the interaction between *F and *VOL$_{-\text{SON}}$ beyond that which arises by mere domination; it now becomes possible for OT to yield the desired inventory banning only the worst of the worst. In addition to the rankings discussed above, which admit into the inventories obstruents that are either continuant or voiced but not both, we add the local conjunction *F & *VOL$_{SON}$ to the grammar, ranking it above all relevant faithfulness constraints. Now, while the markedness incurred by either *F or *VOL$_{SON}$ alone is *not* sufficient to render an unfaithful output optimal, the markedness incurred by both together *is*. (The individual violations of the basic constraints *F and *VOL$_{SON}$ are marked by '✪' when they combine to trigger a violation of their conjunction *F & *VOL$_{SON}$. We consider here only the special case of a cluster-initial consonant; how this restriction is achieved in the actual proposed analysis — via further local conjunction — will be evident shortly.)

(21) Local conjunction enables inventories that ban only the worst of the worst

	*F & *VOL$_{SON}$	MAX	*F	*VOL$_{SON}$
/blik/				
Λ **b**lik				*
lik		*!		
/flik/				
Λ **f**lik			*	
lik		*!		
/vlik/				
vlik	*!		✪	✪
Λ lik		*		

In general, the conjunction of a constraint $\mathbb{C}_1$ with another constraint $\mathbb{C}_2$ local to a domain type $\mathcal{D}$, written $\mathbb{C}_1 \&_{\mathcal{D}} \mathbb{C}_2$, is a new constraint that is violated iff there is both a violation of $\mathbb{C}_1$ and a violation of $\mathbb{C}_2$ within a single domain of type $\mathcal{D}$. The relevant domain is frequently the segment, as it is in the analysis we propose here.[7]

Before showing how local conjunction provides the necessary means of combining markedness dimensions to account for the hidden strata in the English cluster grammar, we return to a dimension of markedness particular to the cluster environment, one involving consonant release.

According to Steriade 1993, a plain, released stop is a plosive (total absence of oral airflow) followed by an approximant (maximum degree of oral aperture): a liquid, glide or vowel. In English onsets, stops can only appear before approximants: unreleased stops are prohibited. In

[7] Local conjunction has been employed for a variety of purposes in OT phonology and syntax; see (refs).

medial and final positions, on the other hand, this prohibition does not hold (*apt*, *aptitude*). The following constraint expresses the markedness of a stop that is followed by a non-approximant:

(22) $*\mathrm{S}_{\bar{\mathrm{A}}}$ A stop must release into an approximant in onsets (no S before Ā)

$*\mathrm{S}_{\bar{\mathrm{A}}}$ is related to the following constraint, which prefers CV syllables.

(23) $*\mathrm{C}_{\mathrm{C}}$ A consonant must release into a vowel in onsets (no C before C).

Any violation of $*\mathrm{S}_{\bar{\mathrm{A}}}$ — a stop followed by a non-approximant, hence non-vowel — will entail a violation of $*\mathrm{C}_{\mathrm{C}}$. Hence $*\mathrm{S}_{\bar{\mathrm{A}}}$ is in a Pāṇinian relation with the more general constraint $*\mathrm{C}_{\mathrm{C}}$. And so, by Pāṇini's Theorem, in order for $*\mathrm{S}_{\bar{\mathrm{A}}}$ to be active, it must be ranked above $*\mathrm{C}_{\mathrm{C}}$ (Prince and Smolensky 1993:82). That SĀ clusters are banned in English, but not all clusters are, is due to the existence of a relevant faithfulness constraint ranked between the two constraints $*\mathrm{S}_{\bar{\mathrm{A}}}$ and $*\mathrm{C}_{\mathrm{C}}$: this admits into the inventory FĀ and SA clusters (which both satisfy $*\mathrm{S}_{\bar{\mathrm{A}}}$), but bars SĀ clusters. For concreteness of exposition, we will assume that the specific faithfulness constraint relevant here is DEP, since epenthesis was the most common simplification strategy employed in the experiment. Since there were few errors of deletion or segment change, MAX and IDENT evidently out-rank DEP.

With these tools in place, a ranking can be posited to account for the hidden strata in the English grammar. In (24), the table (19) has been expanded to show the constraint violations of legal English clusters and the illegal clusters used in the experiment. Going down the table, the final column shows the local conjunctions which render each class of clusters more marked than those appearing higher in the table; the violations of the individual constraints in these conjunctions are marked with '✪', as in (21).

The interpretation of this table (24) may be illustrated as follows. The clusters *zr, zm* are more marked than legal English clusters because the initial segment is the locus of *three* simultaneous constraint violations: $*\mathrm{VOL}_{\text{-SON}}$, *F, and $*\mathrm{C}_{\mathrm{C}}$; the three marks '✪' incurred by the initial *z* in these clusters entail violation of the local conjunction $*\mathrm{VOL}_{\text{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$. Note that violating any *two* of these constraints in the same segment does *not* generate sufficient markedness to result in exclusion from English. Violating *F and $*\mathrm{C}_{\mathrm{C}}$ in the same segment is permitted, as in the cluster *fl*; violating $*\mathrm{VOL}_{\text{-SON}}$ and $*\mathrm{C}_{\mathrm{C}}$ is likewise acceptable (*bl*). And violation of both $*\mathrm{VOL}_{\text{-SON}}$ and *F occurs in every single voiced fricative (*z*).

Note that all clusters violate $*\mathrm{C}_{\mathrm{C}}$, which functions like the *COMPLEX of Prince and Smolensky 1993, except that it explicitly localizes its violation to the initial C of a CC cluster. Thus, to violate a *local* conjunction $\mathbb{C}$ & $*\mathrm{C}_{\mathrm{C}}$, the violation of $\mathbb{C}$ must occur in the *initial* segment of a CC cluster (or, more generally, in a C that is not the final segment of a cluster.)

(24) Decreasing accuracy with increasing markedness (constraints unranked)

			$*\mathrm{S}_{\bar{\mathrm{A}}}$	$*\mathrm{C}_{\mathrm{C}}$	$*\mathrm{VOL}_{\mathrm{-SON}}$	*F	$*\overline{\mathrm{COR}}$	Crucial violated constraints
English	(−voi S)A	*tr, pl, pr, kl, kr*		*			(*)	
	(−voi **F**)A	*sl, šl, šr, fl, fr*		*		*	(*)	
	(−voi, cor **F**)Ā	*sm, sn, šn, šm, sv, sf*		*		*		
	(**+voi** S)A	*dr, bl, br, gl, gr*		*	*		(*)	
Easy	(**+voi**, cor **F**)C	*zr, zm*		✪	✪	✪		$*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$
Inter.	(−voi, cor <u>S)Ā</u>	*tf, čk*	✪	*				$*\mathrm{S}_{\bar{\mathrm{A}}}$
	(−voi, ***¬cor*** <u>S)Ā</u>	*kt, kp, pt*	✪	*			*	
Diff.	(**+voi**, cor <u>S)Ā</u>	*dv*	✪	*	✪			$*\mathrm{VOL}_{\mathrm{-SON}}$ & $*\mathrm{S}_{\bar{\mathrm{A}}}$
	(**+voi**, ***¬cor*** **F**)Ā	*vn, vz*		✪	✪	✪	✪	$*\overline{\mathrm{COR}}$ & $*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$

To take one more example from table (24): like the Easy clusters, the Difficult clusters *vn, vz* also violate the third-order conjunction [$*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$]. In addition, however, the initial consonant *v* has marked place, i.e., it violates $*\overline{\mathrm{COR}}$. Thus the increased markedness of these Difficult clusters is registered by their violation of the fourth-order conjunction $*\overline{\mathrm{COR}}$ & [$*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$].

It is clear in (24) that constraint ranking plays an important role in distinguishing the hidden strata. The cluster *tf*, like many English legal clusters, violates only two of the listed constraints, yet it is in the Intermediate stratum, while the cluster *zr*, violating three constraints, falls in the Easy stratum. Unlike *zr*, the cluster *tf* violates $*\mathrm{S}_{\bar{\mathrm{A}}}$, a constraint that is unviolated among the English-legal clusters. The high rank of $*\mathrm{S}_{\bar{\mathrm{A}}}$ is responsible for its strong impact, single-handedly separating the Easy clusters (which satisfy it) from the Intermediate cluster, which do not.

The formal definition of each conjunctive constraint in (24) follows automatically from the general definition of constraint conjunction, together with the substantive definitions of the basic constraints that are conjoined, given above in (20), (22), and (23). It is useful, however, to provide an English paraphrase of the *effect* of these conjunctions; this is given in (25).

(25) Exegesis of local conjunctions (within onset clusters)

a. $*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$ Violated by a voiced fricative before any C.

b. $*\overline{\mathrm{COR}}$ & $*\mathrm{VOL}_{\mathrm{-SON}}$ & *F & $*\mathrm{C}_{\mathrm{C}}$ Violated by a non-coronal voiced fricative before any C.

c. $*\mathrm{VOL}_{\mathrm{-SON}}$ & $*\mathrm{S}_{\bar{\mathrm{A}}}$ Violated by a voiced stop before an obstruent or nasal.

The ranking implicit in the table (24) is made explicit in (26). The floating range of DEP is indicated, with four positions indicated by the circled digits. The base position ❶ defines the base grammar of English, which admits only those clusters appearing in English lexical items. Elevating DEP to the next-higher position ② now adds to the inventory the group of Easy clusters. Elevating DEP still further, to position ③ and then to ④, incrementally adds the Intermediate and then the Difficult clusters.

(26) English grammar, showing hidden constraint rankings and hidden cluster strata

*VOL$_{\text{-SON}}$ & *S$_{\bar{\text{A}}}$

*$\overline{\text{COR}}$ & *VOL$_{\text{-SON}}$ & *F & *C$_{\text{C}}$ ≫ *S$_{\bar{\text{A}}}$ ≫ *VOL$_{\text{-SON}}$ & *F & *C$_{\text{C}}$ ≫ *C$_{\text{C}}$ ···

④ ③ ② ❶ DEP

Diff.	Interm.	Easy	English
dv *vn,vz* +	*kt,kp,pt,* *čk,tf* +	*zm,zr* +	*šr,šl,sm,* *sn,fr*

To explicitly relate this grammar to the dependent variable observed in the experiment, proportion correct, first consider the simplest assumption, 'uniform floating' (Anttila 1998). On this assumption, all positions ❶ – ④ are visited with equal probability under the conditions of the experiment. The predicted values for percent correct production in the four strata are given in (27). For a cluster in the Difficult stratum (last row) to be correctly produced, DEP must float to its highest position (④), which, under the uniform floating hypothesis, occurs on 25% of productions. For the Intermediate stratum, floating to ④ entails correct production, but so does floating to ③. Thus the predicted percent correct production is now 50%. And so forth up to the English-legal stratum, where correct production is predicted to occur 100% of the time.

(27) Proportion correct across hidden strata

	EXPERIMENT	THEORY	*Uniform Floating*		*Empirically Fit Floating*	
Cluster Stratum	Observed Correct	FAITH Position	Visitation Probability	Predicted Correct	Visitation Probability	Predicted Correct
šr,šl,sm,sn,fr	96%	❶	25%	100%	33%	96%
zm,zr	63%	②	25%	75%	23%	63%
kt,kp,pt,čk,tf	40%	③	25%	50%	24%	40%
dv,vn,vz	16%	④	25%	25%	16%	16%

It is important that the theory correctly accounts for the qualitative ordering of the strata, regardless of the quantitative assumptions concerning the probability of DEP floating to each of the four positions. Each position that yields correct production in one stratum *s* also yields correct production in the strata listed above *s* in (27). Thus, whatever the quantitative value of the probabilities of visiting different positions, the predicted percent correct will increase up the table. (This would even be true if the probability were greatest for ④ and least for ❶.)

Using the observed percent correct values, it is easy to fit the data with assumed values for the visitation probabilities, as shown in the portion of the table in (27) headed 'Empirically Fit Floating.' Thus the experimental results suggest that the probability of elevating DEP to different positions decreases as the degree of elevation increases; most probable is the base position ❶ (33%), least probable the highest position ④ (16%).

The values for visitation probabilities in (27) are fit to average accuracy values over all subjects. The scatter plots in (16) — with a separate point for each speaker — show considerable variance across speakers. On the analysis we are proposing, this variance may be attributed to differences across speakers and trials of the effectiveness of cognitive resources allocated to the elevation of FAITHFULNESS. The relative rankings of markedness constraints, however, are what define the hidden strata, and the evidence is consistent with a common underlying hidden ranking of MARKEDNESS across speakers. While one speaker might be unusually successful at elevating FAITHFULNESS, a shared hidden MARKEDNESS ranking entails that, no matter how good that speaker's performance may be on Difficult clusters, that same speaker's performance on Intermediate clusters must be better, and on Easy clusters, better still. Averaging within speakers over the clusters defining each hidden stratum, (16) shows that this prediction is borne out to a striking degree, holding for all but two of sixteen speakers.

4.5. Other experimental conditions

As explained in Section 4.2, the experimental condition we have discussed so far was designed to minimize the cognitive resources allocated to elevating FAITHFULNESS in response to a clearly foreign input, without overly taxing the resources required to accurately perceive and recall that input. According to the Linking Hypothesis (12), if greater resources are made available, the probability of elevating FAITH should increase, predicting higher proportions of faithful pronunciations.

The same speakers who participated in the experimental condition reported above also participated in two other conditions. The first of these — the 'Foreign Condition' — is just like the one reported above, except that the instructions were different (the stimuli were identical). Now speakers were asked to imagine themselves as tourists traveling in a foreign country. While they did not know the language of this country, they would find themselves having to ask natives for directions to different places, or how to buy different products. They could assume that the natives spoke some English, but they were warned to pronounce the foreign word as carefully as possible, since if they did not, the natives might misunderstand them.

The intention in this manipulation was to probe the conscious, meta-linguistic component of the task. In the condition reported above — the 'English condition' — speakers were discouraged at a conscious level from making special efforts to faithfully pronounce the foreign words; in the Foreign condition, speakers were explicitly encouraged to make such efforts.

In the third, 'Repetition,' condition, subjects heard two repetitions of one token of a word and were then asked to repeat it. The English-like orthographic representation of the word was available throughout the trial, during both perception and production of the word. The same pseudo-Polish words were used as in the other two conditions.

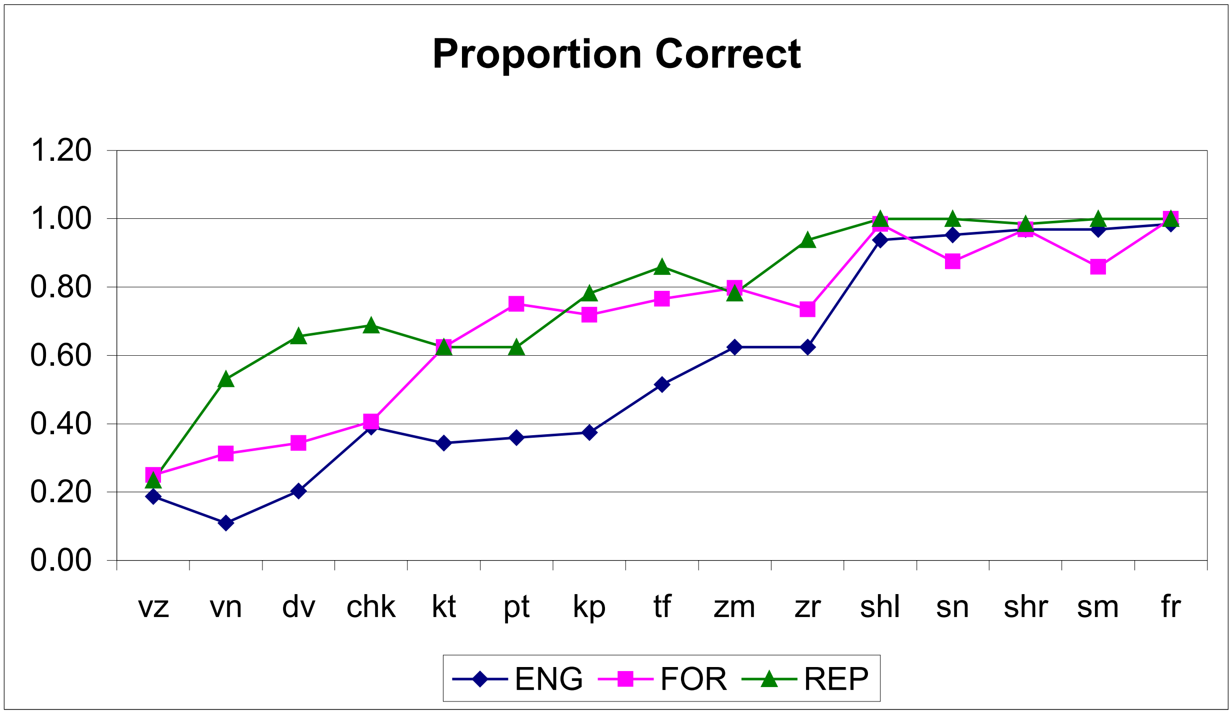
We assume that, in the terms of the Linking Hypothesis (12), the cognitive resources available for elevating FAITH are greatest in the Repetition Condition, least in the English Condition, and intermediate in the Foreign Condition. Accordingly, this hypothesis predicts that the proportion of faithful productions should increase from the English to the Foreign and again to the Repetition Condition. More specifically, the prediction is that the same hidden strata should be evident in all three conditions: these strata are defined by the relative rankings of markedness constraints, which are unaffected by the across-condition manipulations.

The experimental results are shown in the graph (28).As the graph shows, there is a very strong correlation between the performance ordering of clusters across the three conditions. In fact, the rank correlations between the English and Repetition conditions is 0.97, that between the English and Foreign conditions is 0.91, and between the Foreign and Repetition is 0.89 (all $p < .001$).

There is some evidence for discrete strata in the Foreign Condition, and while these correlate with those of the English Condition, the boundaries of the Intermediate stratum seem to shift: *čk* approaches the Difficult group while the others approach the Easy group. Evidence for strata in the Repetition condition is even murkier, perhaps because a ceiling effect is starting to set in: as performance starts to approach 100%, there is less variation across the majority of clusters and so achieving statistically significant differences requires more experimental power. We leave detailed investigation of such questions to future experiments which will aim to provide that power.

As far as the manipulation concerning instructions are concerned, there is little evidence that conscious attempts to "sound American" vs. "sound foreign" affect the relative accuracy of the clusters, although the proportion of faithful utterances increases for nearly all clusters. The only exceptions are *sn*, *sm* where speakers displayed a tendency to produce *šn*, *šm*.

(28) Experimental results: English, Foreign, and Repetition Conditions



4.6. Alternative hypotheses

In this section we briefly consider several alternative approaches to explaining the experimental findings.

4.6.1. Final grammar = base grammar

In our basic hypothesis (11), we have assumed that the final state of the grammar includes floating FAITHFULNESS, with the lowest positions of faithfulness constraints defining the base grammar. The native lexicon is constrained to yield consistent outputs from the full grammar, and as a consequence floating FAITHFULNESS has no effect on the outputs from native inputs. With non-native inputs, however, we can see the effects of floating FAITHFULNESS, thus revealing the full final grammar, including covert rankings.

An obvious alternative is to simply assume that the final state of the grammar is the base grammar, with no floating FAITHFULNESS (leaving aside the flotation responsible for variation in native outputs, which we have been neglecting in our general discussion). Faced with a non-native input, the speakers in our experiment simply depart from their final English grammar, "artificially" elevating FAITHFULNESS in way that is driven by the particular demands of the arguably artificial tasks we ask them to perform.

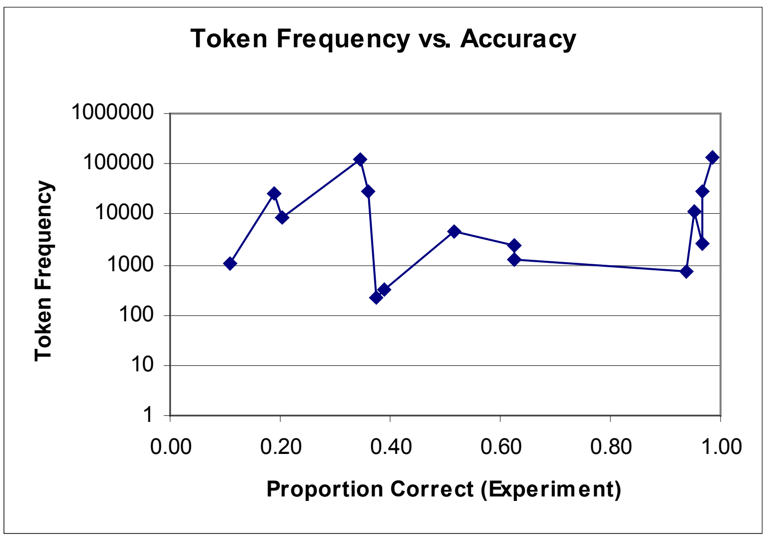
The differences between this interpretation and the one presented in (11) are subtle, and we take no strong stance. We presented (11) as our initial hypothesis because it is the grammatically strongest one, in the sense of making the grammar responsible for explaining the greatest range of data. It appears necessary for OT grammars to admit floating constraints in order to deal with multiple types of variation: synchronic adult variation in phonology (Nagy and Reynolds 1997, Anttila 1998) and syntax/semantics (Anttila and Fong 2000), diachronic variation (Zubritskaya 1997, Anttila and Young-mee to appear), variation in child language (Legendre, Hagstrom, Todorova and Vainikka 2000) and (under our interpretation here) variation across lexical strata (Itô and Mester 1995b, etc.). With this mechanism already introduced within grammatical theory, the grammatically strongest hypothesis would appear to be that it accounts for any other type of variation. The type of variation observed in our speakers' productions appears to be one for which the floating constraint mechanism provides insight. If the adult speakers' grammar encodes their knowledge of phonology, part of that knowledge — according to Richness of the Base — concerns the pronunciations of non-native inputs, and, as far as we have been able to determine experimentally, that part of their knowledge of phonology can be usefully formalized with floating constraints.

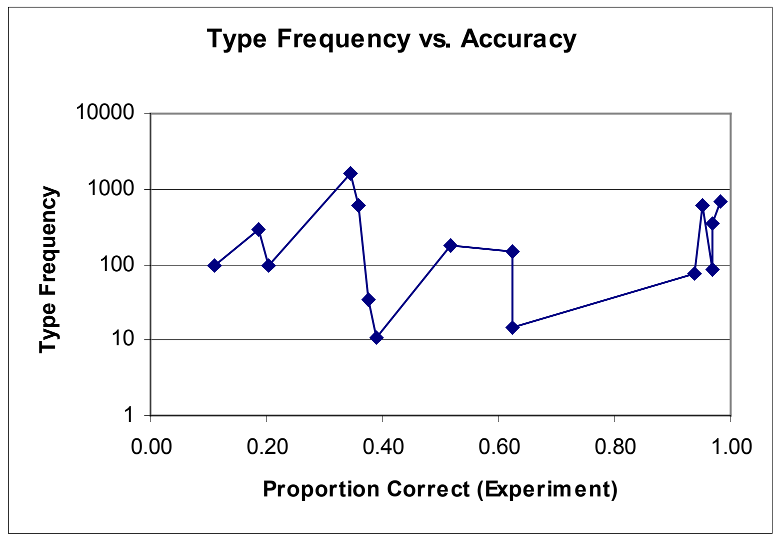
4.6.2. Statistics

In the previous subsection we considered backing off — very slightly — from the point of view we have pushed, that the grammar should encode the knowledge speakers display in these experiments. On the slightly grammatically weakened view of Section 4.6.1, as on the view we have favored, covert rankings of markedness constraints are responsible for the relative accuracy of non-native clusters; but the FAITHFULNESS elevation necessary to account for non-English outputs is not seen as part of the final state per se. A much more severe weakening of the grammatical perspective would in addition deny that covert MARKEDNESS rankings are responsible for relative accuracy — that relative accuracy is not a consequence of the grammar which, say, treats all non-native forms equally. Instead, explanation of relative accuracy might be sought in the statistics of English, with greater frequency predicting greater accuracy. Of course, in onset position, the frequency of the non-English clusters is nominally zero, by definition. But one might look to the relative frequency of hetero-syllabic and coda clusters for explanation.

A frequency count from the CELEX 2 Lexical Database is not encouraging for the statistical perspective, however.[8] As shown in (29), whereas a statistical explanation would require that accuracy is a monotonically increasing function of frequency, there is in fact essentially no correlation between the orders of relative accuracy and relative frequency, whether of tokens or types. The rank correlation coefficients between frequency and accuracy in the experiment is only 0.14 ($p < 0.3$) for tokens, for 0.06 ($p < 0.4$) for types. The poor rank correlation between frequency and accuracy is also shown in (30). In (30a), the clusters are listed from lowest to highest accuracy in the experiment, with boldface marking the Difficult stratum, bold italics marking the Intermediate stratum, italics marking the Easy stratum, and regular typeface indicating English-legal clusters. In (30b–c), the clusters are listed in order of increasing token and type frequencies.

(29) Statistical status of relative cluster accuracy





(30) Orderings of clusters by frequency and accuracy

a. Accuracy ordering (experiment) : **vn vz dv** ***kt pt kp čk tf*** *zm zr* šl sn šr sm fr

b. Token frequency ordering: ***kp čk*** šl **vn** *zr zm* šr ***tf*** **dv** sn **vz** sm ***pt kt*** fr

c. Type frequency ordering: ***čk*** *zr* ***kp*** šl šr **vn dv** *zm* ***tf*** **vz** sm sn ***pt*** fr ***kt***

Of course it is impossible to prove the impossibility of a statistical account, given the potential infinity of statistics that might be computed. For example, it is possible that an extremely careful analysis of casual and fast speech would reveal that vowel deletion yields onset clusters that are nominally illegal in English, with statistical distributions that might mirror the accuracy data. We return to this avenue shortly.

[8] We are extremely grateful to Matt Goldrick for his assistance with these counts.

4.6.3. Phonetic unfaithfulness

In order to maximize the explanatory burden on phonology, we have hypothesized that when a speaker utters *kətobi* for /ktobi/, the schwa results from epenthesis in the phonology. Alternatively, one might hypothesize that phonology proper outputs a faithful *ktobi*, but that our speakers' phonetic systems, unpracticed with *kt* clusters, often fail to provide a faithful rendering of that cluster, with mistiming of gestures leading to the intrusion of a reduced vowel.

Such an alternative is not readily distinguished from our phonological hypothesis, but in future work we hope to investigate one potential avenue. If a fundamental distinction between phonology and phonetics concerns the discreteness of the former relative to the latter, then phonological epenthesis might be distinguished from phonetic 'epenthesis' by the distribution of phonetic characteristics of the schwa: perhaps a fleshed-out version of the phonetic vs. phonological epenthesis hypotheses would predict that, say, the duration of the schwa should be distributed with a mode at 0 msec if the epenthesis results from articulatory mistiming, but with a nonzero mode if the epenthesis is phonological. Detailed phonetic analysis of this issue must await future research. Such analysis is also needed to examine the related hypothesis that the higher error rate induced by voicing (e.g., Difficult *dv* vs. Intermediate *tf*) reflects voicing during articulatory mistiming, acoustically detectable as a vowel, even though the degree of mistiming is identical to that in the corresponding unvoiced cluster. This phonetic hypothesis needs to be contrasted with the hypothesis that the environment of two voiced obstruents leads to phonological epenthesis while the corresponding unvoiced environment does not.

4.7. Origin of hidden rankings

We have attempted to contrast explanations of relative cluster accuracy based on phonological, statistical, and phonetic distinctions. A fundamental challenge in this regard is the fundamental connectedness of these factors. Phonological markedness constraints can often be seen as the grammaticization of articulatory difficulty (e.g., Archangeli and Pulleyblank 1994, Jun 1995, Steriade 1997, Boersma 1998, Kirchner 1998, Hayes 1999a), so distinctions based on articulatory difficulty in a phonetic explanation will necessarily correlate with distinctions based on markedness in a phonological explanation. If the speakers' grammars contain constraints militating against marked structures, all else equal, the frequency with which structures surface should be inversely correlated with their markedness. Further, if grammars include floating constraints with probabilistic positions, grammatical structure manifests itself in the statistics of output distributions, as we saw in (27).

This tight coupling of phonology, phonetics, and surface statistics is at play not only the final, adult state, but also the learning process. As a final issue, we briefly consider how the covert rankings could be learned. The case of interest is when there are few non-native forms in the learner's environment, so sufficient direct evidence of the sort elicited in the experiment is not available.

Future research will assess the degree to which the covert rankings uncovered in the experiment reflect universal markedness tendencies. Such tendencies would raise the possibility of nativist grammatical explanations of covert rankings, encoded perhaps in the initial state. And these tendencies might well reflect factors of articulatory difficulty.

How might language-particular covert rankings be learned? One possibility, first suggested to us by Rochelle Newman (personal communication 1999), is that the frequency with which an 'illegal' onset cluster arises in rapid speech might reflect its hidden stratum. As mentioned above, if empirically substantiated, this might suggest a statistical mode of explanation, or perhaps a phonetic one (Kohler 1990).

But a grammatical line of explanation might also be developed by extending our Linking Hypothesis (12). In this extension, the degree of elevation of a constraint ℂ from its base position determines the extent of reduction for rapid speech. The constraint ℂ is however not the faithfulness constraint DEP-V, but a conceptually-related markedness constraint in the family *STRUC banning structure (Prince and Smolensky 1993). Epenthesis of schwa into a cluster creates additional structure, in particular, a weak syllable (an open syllable headed by a reduced vowel, perhaps one problematic for metrical foot parsing). Let us call the *STRUC constraint violated by such syllables *σ̆.

(31) *σ̆ No weak syllables (*STRUC family)

Replacing DEP-V by *σ above does not affect the analysis, since for the inputs of interest, which possess an initial CC cluster, the two constraints are violated by the same candidates. But if we turn to reduction of native forms in rapid speech, what is at issue is not whether to epenthesize a reduced vowel, but whether to delete one, and here *σ̆ is no longer equivalent to DEP-V.

In its base position, *σ̆ must be dominated by MAX-V so that the base English grammar retains weak syllables; this is illustrated in tableau (32), which shows a range of relevant hypothetical inputs. The base grammar allows the initial, weak vowel in inputs like /C_1IC_2ant/ to surface faithfully, for any pair of consonants C_1 and C_2. This grammar also allows the initial cluster *pl* to surface faithfully, but not the illegal clusters *pt* (Intermediate stratum) and *dv* (Difficult stratum); as in the analysis above, these clusters are broken up by epenthesis. In this tableau the unfaithful candidates are in italics, and a preceding '*' marks faithful candidates that are non-optimal; these flag the clusters banned by this ranking. Weak vowels in candidates are marked V̆ to distinguish them from other vowels, marked V́. The subhierarchy of markedness constraints *VOL$_{SON}$ & *S$_{Ā}$ ≫ *S$_{Ā}$ ≫ *C$_{C}$ constitute the hidden rankings proposed above which separate the hidden strata occupied by the clusters *dv*, *pt*, and *pl*.

(32) Exposing covert rankings 1: English Base Grammar

	*VOL$_{SON}$ & *S$_{Ā}$	*S$_{Ā}$	MAX-V	*σ̆	DEP-V	*C$_{C}$
/pɪlant/						
☞ pɪ̆lánt				*		
plánt			*!			*
/plant/						
☞ plant						*
pə̆lánt				*!	*	
/pɪtant/						
☞ pɪ̆tánt				*		
ptánt		*!	*			
/ptant/						
* ptánt		*!				
☞ *pə̆tánt*				*	*	
/dɪvant/						
☞ dɪ̆vánt				*		
dvánt	*!		*			
/dvant/						
* dvánt	*!					
☞ *də̆vánt*				*	*	

Now elevating *σ̆ just above MAX-V enables some weak vowels to be deleted for rapid speech. Such deletion typically creates clusters, and these are subject to the hierarchy of constraints with the covert rankings in question. With minimal elevation of *σ̆, deletion of weak vowels occurs if this creates an English-legal cluster, but is blocked if an illegal cluster would result. This is illustrated in tableau (33).

When the ranks of the constraints violated by illegal clusters are infiltrated by floating *σ̆, their relative rankings are exposed. Tableau (34) illustrates a degree of elevation in which *σ̆ is still ranked below the constraints violated by clusters in the Difficult stratum, but above those violated by clusters of the Intermediate stratum. Now weak vowels delete when this creates a cluster that is either English-legal (*pl*), or within the first two (Easy; Intermediate: *pt*) hidden strata of the illegal clusters. Weak vowel deletion is however blocked when an illegal cluster in the third (Difficult, *dv*) hidden stratum would result.

(33) Exposing covert rankings 2: Rapid Speech Grammar, English-legal clusters only

		*VOL$_{-SON}$ & *S$_{\bar{A}}$	*S$_{\bar{A}}$	***σ̆**	MAX-V	DEP-V	*C$_{C}$
/pɪlant/							
*	pɪ̆lánt			*!			
☞	*plánt*				*		*
/plant/							
☞	plant						*
	pə̆lánt			*!		*	
/pɪtant/							
☞	pɪ̆tánt			*			
	ptánt		*!		*		
/ptant/							
*	ptánt		*!				
☞	*pə̆tánt*			*		*	

(34) Exposing covert rankings 3: Rapid Speech Grammar, English+Easy+Intermediate Clusters

		*VOL$_{-SON}$ & *S$_{\bar{A}}$	***σ̆**	*S$_{\bar{A}}$	MAX-V	DEP-V	*C$_{C}$
/pɪlant/							
*	pɪ̆lánt		*!				
☞	*plánt*				*!		*
/plant/							
☞	plant						*
	pə̆lánt		*!			*	
/pɪtant/							
*	pɪ̆tánt		*!				
☞	*ptánt*			*	*		
/ptant/							
☞	ptánt			*			
	pə̆tánt		*!			*	
/dɪvant/							
☞	dɪ̆vánt		*				
	dvánt	*!			*		
/dvant/							
*	dvánt	*!					
☞	*də̆vánt*		*			*	

Just as in the analysis of the experimental results developed above, floating *σ̆ exposes the hidden strata by rendering reduction increasingly less probable as the resulting clusters enter hidden strata increasingly more distant from base English.

We hasten to reiterate that it remains for future research to evaluate the empirical soundness of any line of explanation based in rapid speech. Our intent here is only to suggest that, while such an explanation might invite an agrammatic, simply-statistical interpretation, it appears that there is in fact at least one grammatical approach that may offer a unified explanation of the patterns exhibited in rapid speech and in the pronunciation of non-native inputs.

5. A final word from our sponsor

In this work we have attempted to formulate working hypotheses that place the greatest demands on phonological theory to explain phonological performance. The theory is asked to produce a prediction about the phonological knowledge initially present in infants, and it does so with the help of a nativist hypothesis: universal constraints are present and ranked broadly as MARKEDNESS ≫ FAITHFULNESS. The theory is next asked to predict the phonologically-relevant behavior of infants, and it does so, with the help of a linking hypothesis that one of the few reliably measurable behaviors of infants, orientation time, will positively correlate with the degree to which phonological stimuli conform to their knowledge — their phonological grammars. The theory is finally asked to characterize the expected behavior of adults producing forms that violate their phonological knowledge, and it does so with the help of the previously developed notion of probabilistically floating constraints. When experiments are conducted to test all these theoretical predictions, we find that the theory does indeed allow the experimental data to be put into sharp focus. We have identified several respects in which the current state of the experimental program needs strengthening in future work. The experiments reported here are literally the first we have conducted. Our hope is only to have made the case that such a program of research — directly confronting OT phonological theory with performance data — is one worth pursuing further. We hope also to have shown how Richness of the Base — a subtle, inherently counterfactual principle of OT which might have been thought to have only abstruse theoretical import — may in fact have a surprisingly important role to play in the explanation of human linguistic performance.

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