On the role of substance, locality, and amount of exposure in the acquisition of morphophonemic alternations

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Abstract

We discuss what factors influence the acquisition of morphophonemic alternations. What mechanisms are available to the learner; what is the basis for grammatical generalizations? Using the Artificial Language Paradigm we compared the acquisition of three alternations differing in phonetic substance, locality, and amount of exposure: one alternation was substantively based and structurally local, another one was structurally local but not substantively based, and the last alternation was neither substantively based nor structurally local. Within each alternation we exposed the experimental groups to a greater or smaller number of instances. Results show a clear advantage for the substantively based alternation during acquisition. In addition, the local dependency has an advantage over the non-local one and alternations that are presented frequently have an advantage over those that are presented infrequently. We show that all three factors influence the acquisition of morphophonemic alternations, but they do so to a different degree. Phonetic substance causes the strongest boost in the acquisition process and builds on locality, which also plays a role, and amount of exposure influences the acquisition process independent of the nature of the alternation. We argue that acquisition models should take the interaction of these factors into account.

1. Introduction

This paper deals with three factors and their relative importance during the acquisition of morphophonemic alternations. To acquire the full phonological system of her native language, a child needs to acquire three main components of phonological knowledge (Hayes 2004; Prince and Tesar 2004). First, the child needs to learn which lexically conditioned and contextually conditioned variants are part of her language. Second, she needs to learn the phonotactics of her language – which sounds may occur where. Third, she needs to learn about alternations – context dependent realizations of a phoneme or a morpheme. The acquisition of contrasts (Levelt 1994; Werker and Tees 2002; Peperkamp 2003) and phonotactics (Fikkert

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1994; Jusczyk 1997) has been the focus of research in phonological acquisition; children acquire this knowledge mainly during their first three years of life. Since knowledge of both is required for the acquisition of alternations and they are a considerable step in phonological acquisition, alternations are acquired relatively late and subject to errors (Berko-Gleason 1958; Hayes 2004; Kerkhoff 2007). Yet little is known about the mechanisms at work during the acquisition of alternations. To what extent do lexical factors determine the acquisition, and what are the contributions of phonetic and structural factors in addition to frequency? Children need to learn that morphemes may differ depending on phonological contexts. Alternations can be shaped by phonology, as for example, the English plural suffix, which is /ɪz/ after stems that end in sibilants, /s/ after stems that end in voiceless obstruents, and /z/ after all other stems (Berko-Gleason 1958). Alternations can also be a remnant of diachronic phonology, as for instance, Umlaut in German, in which some stems with back vowels in the singular have a front vowel in the plural (Wiese 1996). It is a fact, however, that the acquisition of morphophonology is a difficult step for the child, and it is therefore worth thinking about factors that support it. We will discuss three such supporting factors, namely phonetic substance, locality, and frequency (amount of exposure).

A growing body of literature provides evidence for the positive influence of phonetic substance on morphophonemic acquisition. An alternation that facilitates either perception or production is learned with more ease than an alternation that does not (Wilson 2006; Redford 2008; van de Vijver and Baer-Henney 2011). Locality is another factor that plays a role in the acquisition of alternations. Dependencies between adjacent elements – local dependencies – are learned easily (Saffran, Aslin, and Newport 1996), and so are local ones where there is a dependency between two elements that are not adjacent on the phonetic surface but on an abstract, representational level (Newport and Aslin 2004). Nevertheless, there must be limitations to a computational learning mechanism in terms of how much material it will evaluate: the more elements it takes into account, the more computational effort that must be expended. The resulting hypothesis would be: the nearer, the easier. A local dependency is learned more easily than a non-local one. The other supporting factor is frequency of occurrence: the more often a child is exposed to an alternation, the more easily it is learned. Exemplar-based theories emphasize the influence of this factor, sometimes assuming that type and token frequency of an alternation is the sole key to its acquisition (Bybee 2001).

We investigated the influence of the three factors with the Artificial Language Paradigm (ALP). We created an artificial language containing certain alternations that varied across experimental groups in terms of substance, locality, and amount of exposure. First, adult participants were exposed to the artificial language, and then – using new material – we tested to what extent the alternation had been acquired. We found a clear effect of substance coupled with locality and a smaller effect of locality alone, and we found that an alternation which is neither substantively based nor structurally local was not learned at all. An alternation grounded in phonetics is learned more easily than an alternation that is not grounded in phonetics. Initially substance boosts the acquisition process. Locality is also important: a local alternation is learned better than a non-local one. We also found a significant effect of amount of exposure, but it is much smaller than the effect of substance and locality. In fact, amount of exposure plays a role if and only if the alternation is substantively based and/or local. We want to argue for the relative importance of each of these factors.

2. Theoretical background

A morpheme alternates if it has different forms in different contexts (Hayes 2009). The Turkish plural suffix, for example, is /lɛr/ after words with a front vowel, such as /inɛk/ 'cow', and is /lɑr/ after words with a back vowel such as /kɑplɑn/ 'tiger', see (1).

(1) a. /inɛk/ + /lɛr/
b. /kɑplɑn/ + /lɑr/

In order to be competent speakers of Turkish, native speakers need to know which suffix is attached to which stem and furthermore, when they are confronted with a new word, they need to know how to form its plural. In our paper we want to discuss three factors that play a role in learning alternations: substance, locality, and amount of exposure. Although it has been found that children start early with the acquisition of alternations (Fikkert and Freitas 2006), there is a great deal of evidence that children have problems with alternations up to the age of 7 (Berko-Gleason 1958; Hayes 2004; Kerkhoff 2007).

Alternations are often the consequence of trying to comply with the phonotactics of the language. The mechanisms underlying the acquisition of alternations are still not fully understood and they are debated in the literature (Hayes 2004). Research with children suggests that the acquisition of alternations is influenced by lexical as well as phonetic factors (Fikkert and Freitas 2006; Peperkamp, Le Calvez, Nadal, and Dupoux 2006). Kerkhoff (2007) presents a first comprehensive investigation of the acquisition of the Dutch voicing alternation. A syllable-final voiceless obstruent in the singular of a noun may correspond in the plural to a voiced obstruent (/bɛt/ ~ /bɛdən/ 'bed – beds') or to a voiceless obstruent (/pɛt/ ~ /pɛtən/ 'cap – caps'). She shows that children prefer non-alternating forms, and, therefore, tend to make voicing errors (/bɛt/ ~ */bɛtən/). Kerkhoff asked children to produce plural forms for novel singular words such as /kɛt/, expecting them to produce the plural form either as /kɛdən/ or /kɛtən/. Her results show that alternations are produced variably within a phonological environment. Kerkhoff found that children rely on lexical information, and she assumes that this is the reason for the relatively late acquisition of this alternation. In a recent study, van de Vijver and Baer-Henney (2011) researched the acquisition of German vowel and voicing alternations which occur with equal frequency in the children's input but are acquired along two different paths of acquisition: the acquisition of the alternations seems to depend on their different status in terms of phonetic grounding. Both alternations are part of the singular–plural paradigm. In fact, since a great deal of additional knowledge is necessary for the acquisition of alternations, such as semantic and morphological aspects of alternating words, it is such a difficult step that children often avoid alternations initially (Kerkhoff 2007; van de Vijver and Baer-Henney 2010).

As acquiring morphophonemic alternations is difficult, it is assumed that there are supporting factors. For the acquisition of contrasts, Peperkamp, Le Calvez, Nadal, and Dupoux (2006) showed that a child needs to learn which of the contrasts are truly allophonic and which ones only look like they are allophonic. To do this the child needs linguistic filters in addition to information about the amount of exposure. It is likely, but as yet not investigated, that such a strategy would also work for alternations: a speaker needs linguistic and statistical information. There is currently a debate on biases that possibly guide the acquisition of alternations. However, there is no work that investigates the interaction of several factors. What is the relative contribution of each factor? The next sections introduce the three factors, substance, locality, and amount of exposure, and we briefly present what they contribute to phonological acquisition.

2.1. *Substance*

One factor on which speakers may rely in order to learn alternations is phonetic substance. In the words given in example (1) above the vowels in /inɛk/ are produced in the front of the mouth and the vowels in /kɑplɑn/ are produced in the back of the mouth. This phonetic fact can be translated in terms of the phonological feature [back]: front vowels are [−back] and back vowels are [+back]. Speakers of Turkish may arrive at the generalization that the vowel of the suffix has the same feature specification for the feature [back] as the stem. This agreement in vowel features, which is known as vowel harmony, may facilitate speech perception as under harmony a vowel feature extends over the whole word (Kaun 2004). In addition, vowel harmony can be seen as a production phenomenon resulting from the coarticulatory assimilation between two vowels (Ohala 1994). Speakers could use this substantively based knowledge to arrive at the following generalization: for ease of perception and production, all vowels in the prosodic word have the same value for [back].

Substance, the phonetic grounding of an alternation, is a factor that has recently come to the fore in research on phonology. In language processing (Kager and Shatzman 2007; Zuraw 2007; Coetzee 2008; Zhang and Lai 2010) and language acquisition (Wilson 2006; van de Vijver and Baer-Henney 2011), the speaker or learner seems to benefit from phonetically based patterns. Coetzee and Kager and Shatzman have both shown that speakers who are presented with artificial items are sensitive to their gradient well-formedness. They differentiate between grammatical and ungrammatical forms they have never heard before and rate them on a continuum. They prefer forms with phonetically grounded sound patterns over forms with sound patterns that are to a lesser degree or not phonetically grounded. Thus Coetzee (2008) shows that although /stVt/ is a possible word of English, there is a perceptual bias against it when it is compared to other non-words which have the form /stVk/ and /stVp/: Coetzee's participants prefer the non-homorganic form of /stVk/ or /stVp/ over /stVt/. Wilson (2006) showed explicitly that phonetic factors such as ease of perception and ease of production serve as a bias in learning. He taught groups of adult participants various alternations that differed with respect to their phonetic grounding. One group was exposed to a velar palatalization rule before /i/ (/kinə/ → /tʃinə/), and the other group was exposed to a velar palatalization rule before /e/ (/kenə/ → /tʃenə/). Fronting of the velars makes their articulation more similar to that of palatoalveolar affricates; velar stops and palatoalveolar affricates are not only articulatorily but also acoustically and perceptually similar before front vowels. Hence, velar palatalization before a *more* front vowel like /i/ is more substantively based and favored over velar palatalization before a *less* front vowel like /e/. Wilson then showed that the groups of learners generalized the pattern asymmetrically. Participants generalized from a less substantively based condition (velar palatalization before /e/) in the training to a more substantively based one (velar palatalization before /i/). In contrast, another group did not generalize from the more substantively based condition to the less substantively based one.

There is also evidence for substantive bias from L1 acquisition. Van de Vijver and Baer-Henney (2011) compared the acquisition of two alternations in the German singular–plural paradigm. The first alternation is a voicing alternation in which a stem that ends in a voiceless obstruent may alternate with a voiced one if it appears between sonorants due to suffixation, and the second alternation is a vowel alternation in which a back stem vowel may alternate with a front vowel. The voicing alternation is phonetically grounded (Westbury and Keating 1986), but the vowel alternation is not. It turns out that the voicing alternation has a clear advantage during acquisition as compared to the vowel alternation.

Variation at fine level of phonetic detail can be argued to be highly relevant to perception (Hawkins and Smith 2001), yet experimentally appears to be ignored by speakers (Mitterer and Ernestus 2008) in a range of tasks. Certainly, phonological generalizations of the traditional type which form the topic here certainly have to be abstracted away from variation in fine phonetic detail, despite ultimately being grounded in natural and phonetically grounded patterns, which is a problem beyond the scope of this paper.

Given the evidence reviewed here, it seems to be very probable that phonetic substance is a factor that can influence language acquisition. Yet at the same time, there is evidence that substance is not all speakers rely on. Hayes, Zuraw, Siptár, and Londe (2009) found that a language can have processes that are not substantively based and yet such processes are learned. In Hungarian, for example, words that end in bilabial stops favor suffixes with front vowels. Even though this generalization cannot be reduced to phonetics – it does not obviously facilitate production or perception – speakers are aware of it and extend it to new words.

2.2. *Locality*

Another factor that may influence the acquisition of alternations is locality in phonological structure. Alternations can be described as dependencies between a trigger and a target. If the triggering element fulfills a certain condition, then the target element is changed. In German the velar fricative has two allophones, palatal [ç] and dorsal [x] (Wiese 1996). If the target fricative is preceded by a [−back] vowel, it is realized as a palatal fricative, otherwise as a dorsal fricative. In this case, trigger and target are adjacent in the string. Such alternations are easy to learn since the string that needs to be considered to formulate the generalization is small; it consists of two adjacent segments. There are, however, also alternations that involve segments that are not string-adjacent. In Arabic, for example, there are restrictions on which consonants can appear in succession in the root (McCarthy 1979). Frisch, Pierrehumbert, and Broe (2004), for instance, show that the first two consonants in the root may not be the same. Vowel harmony can, likewise, be understood as a co-occurrence restriction on vowels. Again, this suggests that these vowels are adjacent at an abstract representational level (Kaun 2004; Finley 2009). In general, then, a segmental element of one type (C, V) can intervene between segmental elements of the other type (V, C), but nevertheless, the latter may still take part in an alternation ensuring agreement among features. Phonological theories in which each feature occupies its own tier in phonological representation have been proposed to resolve the apparent non-local nature of many phonotactic patterns and alternations that are difficult to explain in a strictly linear theory of phonology (Leben 1973; Goldsmith 1976; McCarthy 1979).

Phonological structure also helps in learning by restricting the search space that the learner must consider in acquiring an alternation. The greater the distance between the trigger and the target, the greater the computational cost of arriving at the correct generalization. Previous research has shown that 8-month-old children, older children, and adults are able to compute transitional probabilities of adjacent segments and that they use this for segmentation of the continuous speech stream into smaller units (Saffran, Aslin, and Newport 1996; Saffran, Newport, Aslin, Tunick, and Barrueco 1997). However, dependencies do not only hold between surface adjacent elements, but also between elements that are not adjacent at the surface, and the computational mechanism should be capable of dealing with this. One possibility is that the learning mechanism is restricted to learn only local dependencies – surface or tier adjacent dependencies (Gafos 1998). For phonotactic learning, Newport and Aslin (2004) have shown that non-local dependencies such as between non-adjacent syllables are not learned. We think that learners may constrain the possible computations to local dependencies or treat them preferentially as compared to non-local ones. In other words, there is a focus on local dependencies.

2.3. *Amount of exposure*

Speakers may also rely on amount of exposure – frequency – as another factor in learning about alternations. Turkish speakers, for example, could use the fact that all words with front vowels are pluralized with the suffix /lɛr/ and all words with back vowels are pluralized with the suffix /lɑr/. On the basis of the co-occurrence frequencies of words and suffixes, native speakers could arrive at the generalization that since all words that have front vowels select /lɛr/ as the plural suffix and all words with back vowels select /lɑr/, a new word that is more like /inɛk/ will select /lɛr/ and a new word that is more like /kɑplɑn/ will select /lɑr/. Now the more the learner is exposed to an alternation, the easier it is to acquire. This is in line with a usage-based account (Bybee 2001). The strong claim is that grammar emerges from and is completely determined by language use.

For the acquisition of alternating suffixes, frequency effects might work as follows. The learner would store all instances of words available to her in some network. In language acquisition it is likely that a suffix – a part of the word – has a higher type frequency than the part that corresponds to the stem. Thus, the suffix becomes more accessible and is the subject of further analyses. If frequency were the only factor influencing acquisition, then two alternating forms of a suffix that occur with the same frequency are predicted to be acquired in a similar way. No matter what the phonological shape of the alternants is or the nature of the rule that governs their distribution, they would be acquired with the same ease. Recent research has shown, however, that the frequency of surface segments alone might not be sufficient as a basis for learning phonotactic generalizations (Berent, Steriade, Lennertz, and Vaknin 2007; Daland, Hayes, Garellek, White, Davis, and Normann 2011). For example, Peperkamp et al. (2006) test an algorithm that learns an allophonic system on the basis of exposure to a sample of word forms. In Western Dutch the segment /l/ is realized without velarization before vowels and with velarization after vowels. The variants are said to be in complementary distribution; before vowels the velarized [ɫ] is never found and after vowels the non-velarized [l] is never found. The algorithm proposed by Peperkamp et al. takes phonetic similarity into account and learns to predict which sounds are true allophones and which sounds are spurious allophones. However, if the algorithm only takes occurrence into account and not phonetic similarity (Austin 1957), it will also find spurious allophones. To consider another example, the segment /h/ occurs before vowels and never after vowels in German, and the segment /ŋ/ always occurs after vowels and never before vowels. With no information about phonetic similarity, the algorithm would wrongly classify these sounds as contextual variants of one another.

We have now presented the theoretical background that motivates our experimental investigation of phonological learning using the ALP. We formulate the following predictions: if there is an influence of substance on learning, there should be an advantage for a substantively based alternation as compared to an alternation that is not substantively based. Specifically, if two groups of participants are exposed to two alternations – one that is substantively based and one that is not – the group exposed to the substantively based alternation should generalize the pattern to new items to a greater extent than the group exposed to the alternation that is not substantively based. Similarly, if there is an influence of locality, there should be an advantage for a local alternation as compared to a non-local alternation such that for two groups of participants exposed to two alternations – a local one and a non-local one – the group exposed to the local alternation should generalize the pattern to new items to a greater extent than the group exposed to the non-local alternation. And further, if there is an influence of amount of exposure, there should be an advantage for an alternation that occurs more frequently as compared to an alternation that occurs less frequently such that for two groups of participants exposed to two alternations – one that occurs more frequently and one that occurs less frequently – the group exposed to the frequently occurring alternation should generalize the pattern to new items to a greater extent than the group exposed to the infrequently occurring alternation. By comparing the differences in all cases and using a design in which all factors are reflected in one artificial language, a direct comparison can be made between the relative importance of each factor.

2.4. *An experimental comparison of substance, locality, and amount of exposure*

In order to investigate the influence of substance, locality, and amount of exposure, we use the Artificial Language Paradigm, which is also referred to as the Poverty of the Stimulus Paradigm (Wilson 2006; Hayes et al. 2009). In such an experiment, participants are asked to generalize patterns to new items on the basis of material they have been exposed to during a listening experiment. Test stimuli, then, are different from training stimuli. We created three artificial languages that differ only in the rules for plural formation. These exploit the segmental inventory of German and were taught to German-speaking adults. The rules differ with respect to substance (present or absent phonetic grounding of the alternation), locality (suffix-triggering element on the same tier [local] or on different tier [non-local]), and amount of exposure (more or fewer occurrences of an alternation). We tested the generalization of these rules to novel items: a local, substantively motivated rule, a local, arbitrary rule, and a non-local, arbitrary rule. Each rule was offered frequently in one condition and infrequently in another condition.

Our artificial languages consist of forms with only a stem (singular form) and of forms with a stem and an alternating suffix (plural form). A rule determines whether the required suffix was the front -[y] or the back -[u]. The nature of the rule differs across experimental groups. We compare the acquisition of three rules that differ with respect to substance and locality. All three rules were presented to two experimental groups: one with a greater amount of exposure and one with less.

The first rule (R1) is a vowel harmony rule, a local alternation that is substantively based. The participants needed to learn that the choice of the alternating suffix depended on the backness of the stem vowel. Thus, whenever the stem vowel was front, the artificial language requires a suffix with a front vowel. Whenever the stem vowel was back, the artificial language requires a suffix with a back vowel. We chose vowel harmony as an example of a substantively based alternation because various phonetic factors support it (Linebaugh 2007). A vowel harmony process facilitates both perception and production (Kaun 2004) and can therefore be considered phonetically grounded, i.e., substantively based, which may in turn be responsible for its occurrence in many of the world's languages (Wilson 2006).

The second rule (R2) is a local, arbitrary rule, in which the choice of a back or front suffix is dependent on the tenseness of the stem vowel. In fact, two feature specifications can be used for the description of this rule. German tensed vowels are also long (Wiese 1996), and therefore, the rule can be described as a dependency between tenseness (of the stem vowel) and backness (of the suffix), or as dependency between length (of the stem vowel) and backness (of the suffix). Hence two local relations can be used by the German adult learner. Rule R2 is structurally equal to R1 in that the dependency is a relation between two vowels, adjacent on one tier. However, contrary to R1, R2 is not substantively based.

The third rule (R3) is an arbitrary rule, in which the choice of a back or front suffix is dependent on the sonority of the first consonant of the stem. This rule is not substantively based and is non-local. The alternation concerns a consonant and a non-adjacent vowel. Although to the best of our knowledge R2 and R3 are not attested in any of the world's languages, similarly arbitrary patterns do exist in the world's languages, though they are found less often than substantively based rules. There is evidence that demonstrates the productivity of comparable arbitrary patterns – arbitrary from a phonetic point of view – such as velar softening in English (Pierrehumbert 2006) and post-nasal devoicing in Tswana (Coetzee et al. 2007), and vowel alternations in German (van de Vijver and Baer-Henney 2011). In spite of their productivity, it is subject to debate whether such patterns are part of synchronic grammars as their productivity seems to be restricted (Pierrehumbert 2006; Coetzee et al. 2007).

We note above that the frequency of occurrence of a morphophonemic alternation in the lexicon might be a factor influencing its acquisition. The implication is that the more frequently an alternation occurs, the easier it is to detect and acquire.

The ALP allows an accurate investigation of the influence of all these factors – substance, locality, and amount of exposure. The design of our artificial language allows us to compare the learnability of three rules, a local, substantively based one, one which is local but not substantively based, and a third rule which is non-local and not substantively based. Since we have experimental groups with frequently and infrequently occurring alternations, we are able to compare the acquisition of each rule after different amounts of input. In addition we compare the rules among each other at different amounts of exposure. Although the alternations we compare are very different in nature, the ALP allows the design of very similar artificial languages among which the only difference is the trigger of the alternation.

Depending on the task used to assess learning, some ALP experiments show that arbitrary sound patterns are learnable (Peperkamp and Dupoux 2007) while other ALP experiments show no learning of arbitrary patterns (Peperkamp, Skoruppa, and Dupoux 2006). Although the learning phase was the same for these studies, the test phase was not. In the Peperkamp and Dupoux (2007) study, the test phase consisted of a production task, and the results showed a significant difference between the arbitrary rule and the substantively based rule. In the Peperkamp, Skoruppa, and Dupoux (2006) study, however, the participants' task was a less demanding perception test. They succeeded in generalizing both kinds of rules to the same degree. This is in line with findings that comprehension precedes production in language acquisition (Smolensky 1996; Pater 2004). Our study is also concerned with the acquisition of phonological rules, so to test for effects of substance, locality, and frequency on acquisition, we also use a more demanding production task. We believe that to show that a pattern is acquired it is not enough to show perceptual learning; the learner should also be able to apply the rule productively. We therefore do not limit ourselves to perceptual learning but test acquisition more generally, through both perceptual learning and productive application. In the next section, we describe the nature of our artificial languages, and then we introduce the experimental methods.

3. Experiment

There were six experimental groups, each of which was exposed to artificial stimuli that differed with respect to type of alternation and amount of exposure. Each group was exposed to one rule in one frequency condition, so there were 6 groups (3 rules × 2 frequency conditions). After being exposed to items of the language, participants were asked to generalize their experience to new artificial items.

3.1. *Artificial language grammars*

Three independent artificial languages, λ1, λ2, and λ3 were designed from one core lexicon. λ1 displays a local alternation which is substantively based, λ2 has a local alternation which is not substantively based, and λ3 has a non-local alternation which is not substantively based. The shared properties of λ1, λ2, and λ3 are summarized in Section 3.1.1.

3.1.1. *The shared properties of λ1, λ2, and λ3* Each singular form consists of a $C_1V_1C_2$ stem, and is exactly the same for λ1 and λ3. In order to investigate the behavior of the local alternation which was not based substantively (λ2), we needed to change two of the segments as compared to λ1 and λ3. Apart from this necessary variation, λ2 singular forms were the same as those of λ1 and λ3. Hence, λ1, λ2, and λ3 singular forms were as similar as possible.

Plurals are formed by adding a suffix to the stem. The actual form of the suffix depends on the specific alternation (see Section 3.1.2). For the moment, we can say that the suffix is either -[y] or -[u] and the choice was a matter of the language-specific alternation. Hence, each plural form had the syllable structure $C_1V_1.C_2V_2$.

Only German phonemes were used for the construction of the stems and suffixes. All words complied with the phonotactics of German. Each phoneme occurred only once in a word with the exception of [m] which was used as onset and coda consonant in λ2. In the following section, a description is given of the phonemes by position.

For $C_{1[+\text{sonorant}]}$ in λ1, λ2, and λ3, we used the sonorants [m], [n], [j], and [l]. For $C_{1[-\text{sonorant}]}$ in λ1, λ2, and λ3 we used the obstruents [f], [z], [d], and [k]. The consonant phonemes of the onset of the stem varied along the feature dimensions of place of articulation, continuancy, and voice. We used [ɪ], [e], and [œ] for $V_{1[-\text{back}]}$ and [ɔ], [o], and [ʊ] for $V1_{[+\text{back}]}$ in λ1 and λ3. The vowel phonemes varied along the feature dimensions of height and tenseness for all V_1. For V_1 of λ2, we needed an equal number of tense and lax vowels, so we used the previously described choice of V_1 vowels excluding [ɔ] but including [a]. This resulted in [ɪ], [ʊ], and [œ] as $V_{1[\text{lax}]}$, and [e], [o], and [a] as $V_{1[\text{tense}]}$. These vowel phonemes varied along the feature dimensions of backness and height. For C_2 in λ1 and λ3 we used the obstruents [p], [s], [ʃ], [t], and the only remaining sonorant [ŋ]. The stem-final consonant phonemes varied along the feature dimensions of place of articulation and continuancy. In order to avoid conflicts with the process of final devoicing in German, only voiceless obstruents were chosen. Due to a phonotactic constraint against [ŋ] after tensed vowels (Wiese 1996; Féry 2000), we replaced [ŋ] with [m] for C_2 in λ2 in order to get as many CVC singular forms with tensed V_1 as CVC singular forms with lax V_1 ending in a nasal. Still, the stem-final consonant phonemes varied along the feature dimensions of place of articulation and continuancy. For V_2 in λ1, λ2, and λ3, two vowels were chosen that only differ in the dimension of backness, namely [y] and [u]. They agree with respect to the feature dimensions of height, roundness, and tenseness. As mentioned earlier, the actual distribution of these vowels occurred on the basis of a language-specific alternation and varied across experimental groups.

The assignment of phonemes to positions in each language is summarized in Tables 1 and 2. Complete lists of the experimental stimuli are provided in Tables A2–A7 of the online supplement.

Given this distribution of phonemes, we built a lexicon of (8 × 6 × 5 =) 240 lexemes each for λ1, λ2, and λ3. Due to the phonotactic constraint against [ŋ] after

Table 1. *Phonotactics of λ1 and λ3.*

C1	V1	C2	V2
[+sonorant]: [m], [n], [l], [j] [−sonorant]: [f], [d], [k], [z]	[−back]: [ɪ], [e], [œ] [+back]: [o], [ɔ], [ʊ]	[t], [s], [ʃ], [p], [ŋ]	[y] [u]
singular form: $C_1V_1C_2$			
plural form: $C_1V_1C_2V_2$			

Table 2. *Phonotactics of λ2.*

C1	V1	C2	V2
[+sonorant]: [m], [n], [l], [j] [−sonorant]: [f], [d], [k], [z]	[tense]: [a], [e], [o] [lax]: [œ], [ɪ], [ʊ]	[t], [s], [ʃ], [p], [m]	[y] [u]
singular form: $C_1V_1C_2$			
plural form: $C_1V_1C_2V_2$			

tense vowels mentioned above, those items were removed from the set of possible lexemes. We thus removed all 8 items with tensed vowels [eŋ] – in $V_{1[-\text{back}]}$ – and all 8 items with [oŋ] in λ1 and λ3. Finally we removed phonotactically legal items with the sequences [œm] and [em] in λ2 so that there were as many plural forms in λ2 as in λ1 and λ3. This resulted in a final lexicon of $N = 224$ lexemes in λ1, λ2, and λ3. The differences between λ1, λ2, and λ3 are summarized in the next section.

3.1.2. *The differences between the languages λ1, λ2, and λ3* The differences between the languages λ1, λ2, and λ3 result from the rules that generate the plural form. To form the plural in the artificial languages, a plural morpheme is added. For λ1, λ2, and λ3 there are two allomorphs, namely -[y] or -[u]. The choice of whether a word needed the one or the other suffix was determined by a language-specific alternation:

– In λ1 the choice of the suffix depends on the backness of V1. The suffix was -[y], a front vowel, if the stem vowel V_1 was [−back]. The suffix was -[u], a back vowel, if the stem vowel V_1 was [+back]. We will refer to this type of alternation as R1. R1 is a local dependency and is grounded in a natural phonetic process, one which is often phonologized into a morphophonemic alternation in vowel harmony languages. Hence, the alternation R1 is substantively based.
– In λ2 the choice of the suffix depends on the tenseness of V1. We created two versions of λ2 to capture all possible variations. Later, we used these versions $λ2_A$ and $λ2_B$ distributed equally across the experimental groups of λ2. In $λ2_A$ the suffix was -[y] if the stem vowel V_1 was [lax]. The suffix was -[u] if the

Table 3. *Plural rules in λ1, λ2, and λ3.*

Language	Rule description
	local rule, substantively based
λ1	R1
	$V_2 \rightarrow V_{2[-back]}$ / $CV_{1[-back]}C\_\#$
	$V_2 \rightarrow V_{2[+back]}$ / $CV_{1[+back]}C\_\#$
	local rule, not substantively based
$λ2_A$	R2
	$V_2 \rightarrow V_{2[-back]}$ / $CV_{1[lax]}C\_\#$
	$V_2 \rightarrow V_{2[+back]}$ / $CV_{1[tense]}C\_\#$
$λ2_B$	R2
	$V_2 \rightarrow V_{2[-back]}$ / $CV_{1[tense]}C\_\#$
	$V_2 \rightarrow V_{2[+back]}$ / $CV_{1[lax]}C\_\#$
	non-local rule, not substantively based
λ3	R3
	$V_2 \rightarrow V_{2[-back]}$ / $C_{1[+sonorant]}VC\_\#$
	$V_2 \rightarrow V_{2[+back]}$ / $C_{1[-sonorant]}VC\_\#$

stem vowel V_1 was [tense]. In $λ2_B$ the suffix was -[y] if the stem vowel V_1 was [tense]. The suffix was -[u] if the stem vowel V_1 was [lax]. For analysis and discussion, we combine the versions $λ2_A$ and $λ2_B$ and refer to this type of alternation as R2. R2 is a local dependency and is not grounded in a natural phonetic process, so by hypothesis it is unlikely to be phonologized in any language.

– In λ3 the choice of the suffix depends on the sonority of C_1 of the stem. The suffix was -[y] if the initial consonant C_1 was [+sonorant]. The suffix was -[u] if the initial consonant C_1 was [−sonorant]. We refer to this type of alternation as R3. R3 is a non-local dependency and is not substantively based (not phonetically grounded).

The rules are summarized in Table 3. Of the alternations in λ1, λ2, and λ3, none are present in German phonology.

The design of singular and plural forms allowed the final creation of the λ1, λ2, and λ3 lexica. All lexica contained $N = 224$ singular forms and $N = 224$ plural forms. Singular forms were the same for both λ1 and λ3. In order to fulfill the experimental criteria, the λ2 singular forms were slightly different from those of λ1 and λ3. Instead of forms with the stem vowel [ɔ], we included forms with the stem vowel [a]. Hence, λ2 shared 83.3% of the λ1 and λ3 singular forms.

Plural forms differed according to the application of the local, substantively based alternation R1 in λ1, the local alternation R2 in λ2, which was not substantively based, or the non-local alternation R3 in λ3, which was not substantively based. However, the architecture of the three languages causes an overlap in the plural forms, as well. The overlap between λ1 and λ3 plurals is 50% (i.e., half of λ1 plurals are also in the set of λ3 plurals), 42.9% between λ1 and $λ2_A$, 28.6% between λ1 and $λ2_B$, 35.7% between $λ2_A$ and λ3, and 35.7% between $λ2_B$ and λ3. As many plural lexemes from λ1, λ2, and λ3 as possible were the same. Others differed only in the alternation-appropriate choice of the plural suffix or the changes to the stem vowel in order to create λ2 stimuli.

3.1.3. *Preparation of the item sets for experimental groups* We prepared six item sets in which two factors, type of alternation and amount of exposure, were manipulated. We distinguished three levels within the factor type of alternation (ToA): R1, R2, and R3. The levels of the factor amount of exposure (AoE) depended on whether the alternation occurred frequently or infrequently. For each ToA R1, R2, and R3, there was a frequent and an infrequent condition. Participants in the frequent condition were familiarized with a frequently occurring alternation while those in the infrequent condition were exposed to the alternation less frequently.

Thus, the combination of every level of each factor resulted in six independent subgroups: R1-freq, R1-infreq, R2-freq, R2-infreq, R3-freq, and R3-infreq. The stimulus material of each R*-freq condition consisted of 50% plural forms (with alternation) and 50% singular forms (without alternation), while the corresponding proportions for R*-infreq conditions were 25% plural forms and 75% singular forms. Group and stimulus design is summarized in Table 4.

For each of the six experimental conditions a specific item set was prepared for the exposure phase. In addition, there was a different item set for the test phase, which was the same for conditions R1-freq, R1-infreq, R3-freq, and R3-infreq. Given the slightly differing λ2 items in terms of V_1, the test phase for R2-freq and R2-infreq conditions differed from the test phase of the other conditions in terms of V_1. Instead of test items with V_1 = [ɔ], there were test items with V_1 = [a] in the R2-freq and R2-infreq conditions. The application of the alternation depended on the characteristics of the C_1 (in λ3) or the characteristics of the V_1 (in λ1 and λ2), hence artificial lexical entries were divided into exposure phase items and test items on the basis of C_2.

Next we describe the internal composition of both the exposure phase and test phase item sets. For the R1 and R2 item sets, all items were listed first and assigned to four groups in such a way that the properties of the first C and V were counter-

Table 4. *Experimental design groups.*

type of alternation (ToA)	R1	R1	R2	R2	R3	R3
stimulus material	λ1	λ1	λ2	λ2	λ3	λ3
substance	yes	yes	no	no	no	no
locality	yes	yes	yes	yes	no	no
amount of exposure (AoE)	frequent	infrequent	frequent	infrequent	frequent	infrequent
plural forms	50%	25%	50%	25%	50%	25%
singular forms	50%	75%	50%	75%	50%	75%

balanced in each group. These four groups are: $C_{1[+sonorant]}$ and $V_{1[-back]}$, $C1_{[+sonorant]}$ and $V1_{[+back]}$, $C1_{[-sonorant]}$ and $V_{1[-back]}$, and $C_{1[-sonorant]}$ and $V_{1[+back]}$. The groups were randomized separately. The same was done in a second step with respect to the tenseness of V_1 and again the sonority of C_1 in order to adjust the relevant conditions for the R2 item sets. For the frequent groups we chose 64 forms from the singular form lists and 16 language-appropriate plural forms from each plural form list. Finally, these sets contained 50% singular forms and 50% plural forms. For the infrequent groups we chose 96 singular forms and 8 language-appropriate plural forms from each plural form list. These item sets contained 75% singular forms and 25% plural forms. There were two versions of R2 item sets: one on the basis of $\lambda 2_A$, where the lax stem vowel triggered the front suffix, and one on the basis of $\lambda 2_B$, where the tense stem vowel triggered the front suffix. In the analysis both versions were combined in the R2-groups.

The results of this procedure were item sets that fulfill the intended stimulus design previously described (see Table 4). Finally the order of presentation was prepared by randomizing each collection of items. For each group a second exposure phase item set was prepared to rule out item-specific or sequence-specific effects. These versions had the same properties as the ones described above. Thus, we prepared 16 exposure phase item sets, two for each group R1-freq, R1-infreq, R3-freq, and R3-infreq and 4 for each group R2-freq and R2-infreq.

For the test phase we only used items of which the singular ended in [s] or [p] ($N = 96$). Since any alternation was independent of both phonemes, the distribution of two kinds of allomorphs was counterbalanced in λ1, λ2, and λ3. The reason for using these items in the test phase only was to show that a pattern might be extended to new items rather than memorized on the basis of attested forms (Pierrehumbert 2006). Only if an abstract pattern is learned can it be generalized to new items. The test phase item set was presented in randomized order to all participants of all experimental groups (where all items containing the stem vowel [ɔ] in the R1 and R3 groups were replaced with items containing the stem vowel [a] in the R2 groups).

3.1.4. *Recording of the stimuli* Stimuli were recorded by a 25-year-old, phonetically trained, female native speaker of Standard German. All stimuli have been recorded in an anechoic chamber embedded in a carrier sentence *Ich habe X gesagt.* ('I said X.') We extracted the target stimuli and scaled their intensity to 70 dB using Praat software (Boersma and Weenink 2009).

3.2. *Participants*

120 participants were tested. All of them were adult native German speakers with normal hearing and normal or corrected-to-normal vision. They were recruited from the experimenters' environment and from among students at the University of Potsdam. All volunteered to participate. Students were given course credits. A

language history questionnaire ensured no previous knowledge of a harmony language. Twenty participants were randomly assigned to each of the six experimental groups. Their mean age was 23.1 years, ranging from 18 to 50. 96 participants were women, 24 were men. The participants had no background in linguistics.

3.3. *Procedure*

A grey-scaled picture of an object from the Snodgrass and Vanderwart collection was randomly assigned to each singular item (Rossion and Pourtois 2004). Again, items with the stem vowel [ɔ] from λ1 and λ3 were treated the same as items with the stem vowel [a] from λ2: the same picture was assigned to counterpart words across the three artificial languages. The object illustrated the meaning of the word form. Each plural form was prepared with two appropriate object pictures. During the exposure phase the participants were familiarized with the artificial language and its alternation R1, R2, or R3. Each participant was randomly assigned to 1 of the 16 lists for the exposure phase. During the test phase, new items of the artificial language were provided and participants were prompted to provide the plural forms in a wug-test-like task (Berko-Gleason 1958). This was the same for all groups. The experiment took place in a quiet room using headphones, microphone, and a computer and lasted no longer than 15 minutes.

3.3.1. *Exposure phase* Each participant was exposed to the group-specific exposure list of artificial items twice. Instructions only included the advice to pay attention to the words of a new language. While the participants listened to auditory stimuli, visual stimuli were shown that referred to the meaning of the auditory stimuli. In order to mirror the natural language acquisition process, no additional instructions were given in this implicit learning task. Each stimulus was presented for 2 seconds.

There was a short introduction with 6 German examples to familiarize the participants with the task. The procedure was the same as in the exposure phase with new language items. The introductory items of German were arranged as follows for each participant: *Auge, Röcke, Stern, Sterne, Rock, Augen* ('eye', 'skirts', 'star', 'stars', 'skirt', 'eyes'). For a schematic illustration of the procedure of the exposure phase, see Figure 1.

3.3.2. *Test phase* After the exposure phase, participants were told they would be tested on their aptitude in the new language. Presented with new words and pictures from the test item set, the task of the participant now was to construct appropriate plural forms. To this end, for each singular form the audio file and corresponding picture were presented simultaneously, with the picture displayed for 2 seconds. Subsequently, a visual stimulus with two pictured objects (denoting the plural form) and a question mark was shown for 3 seconds. The question mark was meant to invite the participant to produce a plural form as a spoken response. Thus

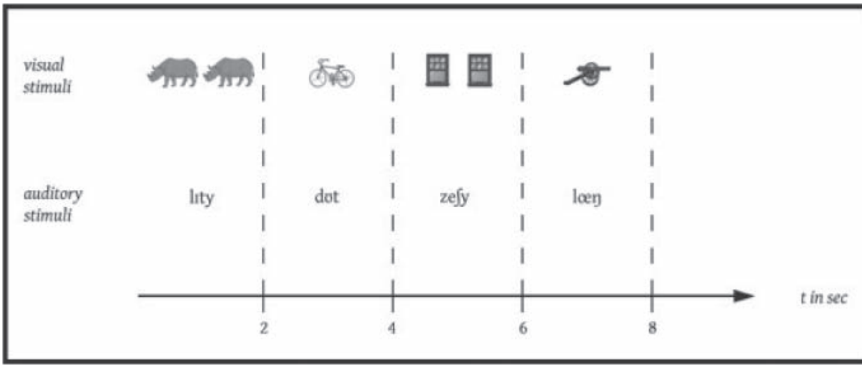

Figure 1. *Exposure phase.*

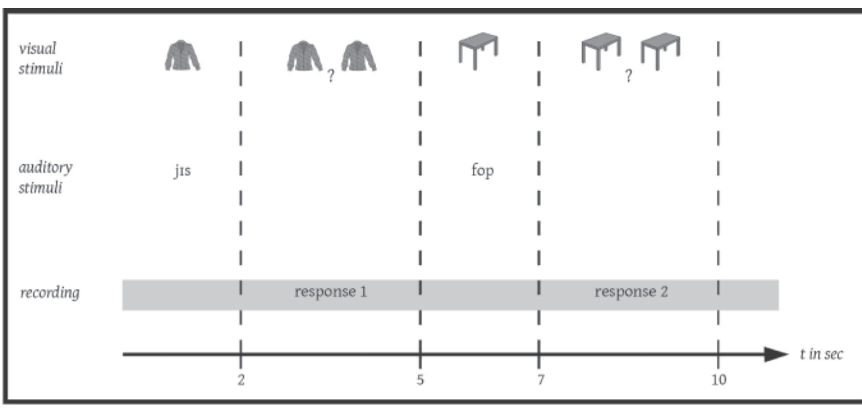

Figure 2. *Test phase.*

the singular form was presented and the participant formed the plural by adding a suffix. The participants' productions of plural forms were recorded.

This procedure was followed for all items of the test set ($N = 96$) with a break after every 32 stimuli (two breaks in total). For a schematic illustration of the procedure of the test phase, see Figure 2.

4. Analysis and results

The plural word productions of each participant were transcribed twice in random order by the experimenters. Since we only needed to ensure that the answers had a -[u] or -[y] suffix, the reliability between both transcriptions was high and a 100%

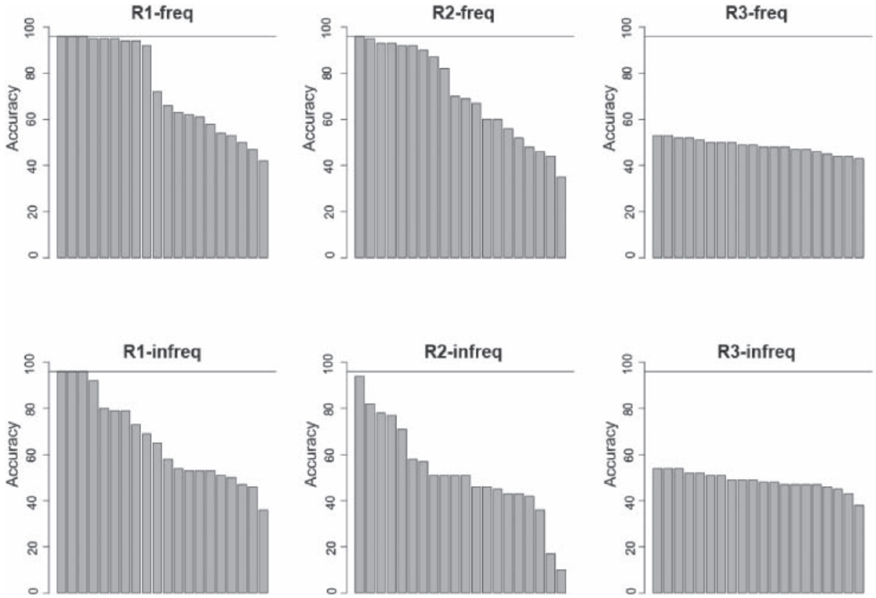

Figure 3. *Sorted individual results for groups R1-freq, R1-infreq, R2-freq, R2-infreq, R3-freq, R3-infreq (note: horizontal line marks the full competence at* N *= 96).*

agreement between independent transcriptions was reached. The accuracy of plural forms containing the [y]-alternation and those containing the [u]-alternation was counted, where accuracy was determined for each participant's productions by the artificial language that the participant was exposed to. A participant who had reached full competence in his/her language gave 96 correct answers – 100% accuracy. Participants who did not achieve competence could guess at the correct answer and have on average 50% accuracy with 48 correct answers. Individual results in the subgroups R1-freq, R1-infreq, R2-freq, R2-infreq, R3-freq, R3-infreq are displayed in Figure 3 arranged in decreasing order. For the actual degree of accuracy and individual scores, see Table A1 of the online supplement.

The R1-freq group reached the highest mean accuracy with 77.14%, followed by R2-freq with 74.32%, and R1-infreq with 69.06%. Group R2-infreq had a mean accuracy of only 54.64%, and both R3 groups performed at chance accuracy: R3-freq at 50.47%, R3-infreq at 50.57%. Figure 4 gives an overview of the groups' means, quartiles, minima, and maxima.

For the statistical analyses we split up the data into groups according to the ToA and compared across groups. This resulted in three main comparisons: R1-learning groups were compared to R2-learning groups, R1-learning groups to R3-learning groups, and R2-learning groups to R3-learning groups. For these we used a logit regression to predict the correctness of an answer from the ToA and AoE (Agresti

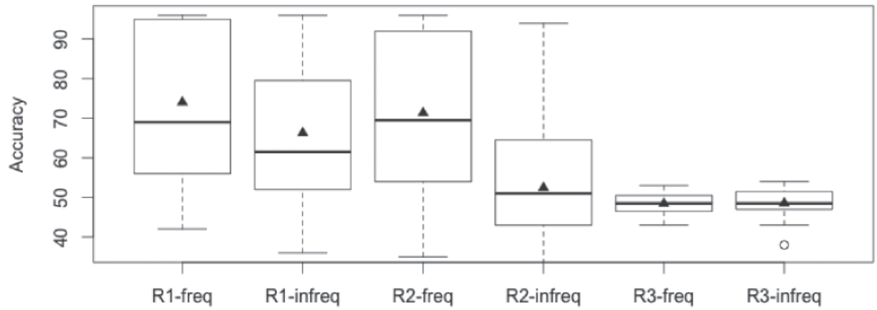

Figure 4. *Accuracy in groups. Boxplots of medians and quartiles of the correct answers; triangles show the means.*

Table 5. *Results of the logit analyses.*

R1–R2 comparison	Estimate	Std. error	*z* value	*Pr* (> |*z*|)
(Intercept)	1.35526	0.04689	28.901	$<2^{-16}$
ToA	−0.41280	0.05020	−8.223	$<2^{-16}$
AoE	−0.66065	0.05044	−13.096	$<2^{-16}$
R1–R3 comparison	**Estimate**	**Std. error**	***z* value**	***Pr* (> |*z*|)**
(Intercept)	1.09078	0.04427	24.637	$<2^{-16}$
ToA	−0.98062	0.04869	−20.138	$<2^{-16}$
AoE	−0.17858	0.04836	−3.693	0.000222
R2–R3 comparison	**Estimate**	**Std. error**	***z* value**	***Pr* (> |*z*|)**
(Intercept)	0.80756	0.04202	19.22	$<2^{-16}$
ToA	−0.58128	0.04693	−12.39	$<2^{-16}$
AoE	−0.41044	0.04691	−8.75	$<2^{-16}$

2002). Both ToA and AoE are significant predictors in all comparisons. When comparing R1 and R2 groups, the odds of a correct answer in the R1 group are 1.51 times higher than in R2 overall and 1.94 times higher in the frequent condition compared to the infrequent condition. Comparing the R1 and R3 groups, the odds of a correct answer in R1 are 2.67 times higher than for R3 overall and 1.2 times higher for the frequent compared to infrequent condition. Comparing R2 and R3 groups, the odds of a correct answer in R2 are 1.79 times higher overall and 1.51 times higher in the frequent condition (these ratios are the exponentiated coefficients – the column labeled Estimate – of the logit analysis in Table 5, in which the results are summarized). It is clear that only groups that were exposed to λ1 and λ2 showed a learning effect. Experimental groups that were exposed to the non-local alternation of λ3, which was not substantively based, failed to learn the

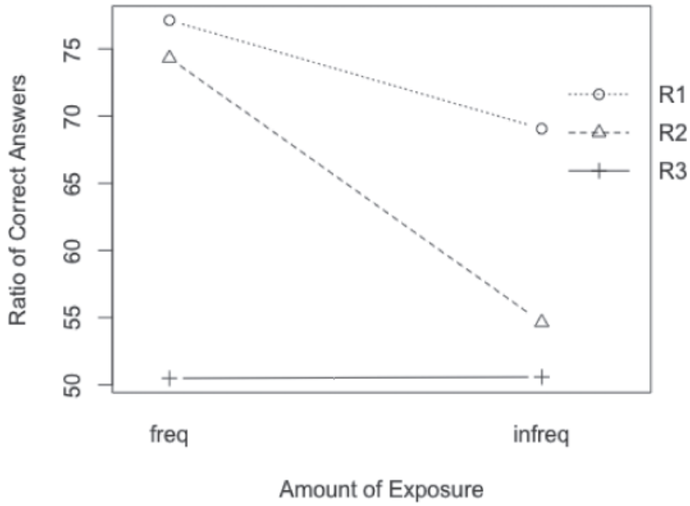

Figure 5. *Interaction of the factors.*

generalization behind the alternation. Figure 5 shows the interaction between factors across experimental groups.

Comparisons between pairs of subgroups were conducted by calculating the likelihood of getting the number of correct answers of one subgroup when the starting distribution of correct answers was that of the other subgroup (exact binominal test; Hollander and Wolfe 1973). We calculated the 95% interval of this distribution by sampling a million random numbers ranging from 1 to 1920 (the total number of answers = 20 × 96) on the basis of this distribution.

We then calculated whether the number of correct answers from another subgroup fell within the 95% quantile area of the first subgroup. First, we compared the frequent and infrequent condition per ToA (R1-freq vs. R1-infreq, R2-freq vs. R2-infreq, and R3-freq vs. R3-infreq). For the R1 and R2 groups alike, the probability of observing the results of the infrequent exposure group (R1-infreq, R2-infreq) given the distribution of correct answers in the corresponding frequent exposure group (R1-freq, R2-freq) is very low – on the lower end of the distribution of the frequent group and below the 2.5% quantile. Thus, frequent exposure of the alternation pattern in R1 and R2 results in faster learning (as measured by higher accuracy), compared to infrequent exposure. In the R3 groups, the probability of observing the results of R3-infreq given the distribution falls within the 95% confidence interval for the R3-freq group, which means that there is no significant difference in learning outcomes between frequent and infrequent exposure for the R3 groups. These results are shown in Figure 6.

Second, we compared the ToAs among each other in the frequent and infrequent conditions. In the frequent condition as well as in the infrequent condition, R1 is

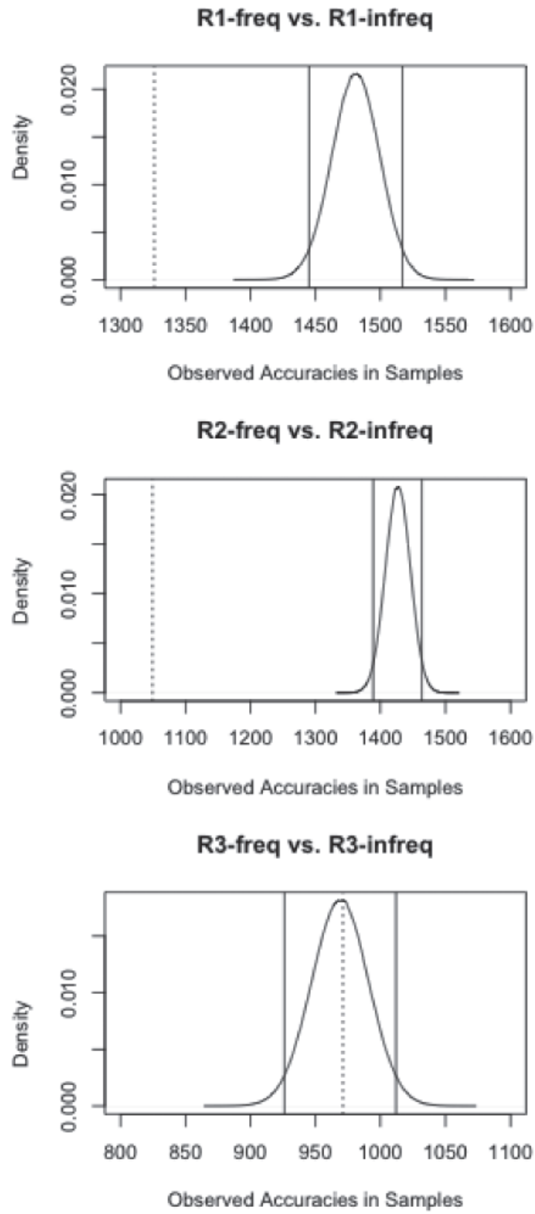

Figure 6. *Calculations of comparisons within one language λ1, λ2, and λ3. Results of multiple group comparisons; the curve shows the binomial distribution of the number of correct answers of the frequent condition of each language, the area between the solid lines includes 95% of the expected number of correct answers. The dotted line is the number of correct answers of the infrequent group of each language.*

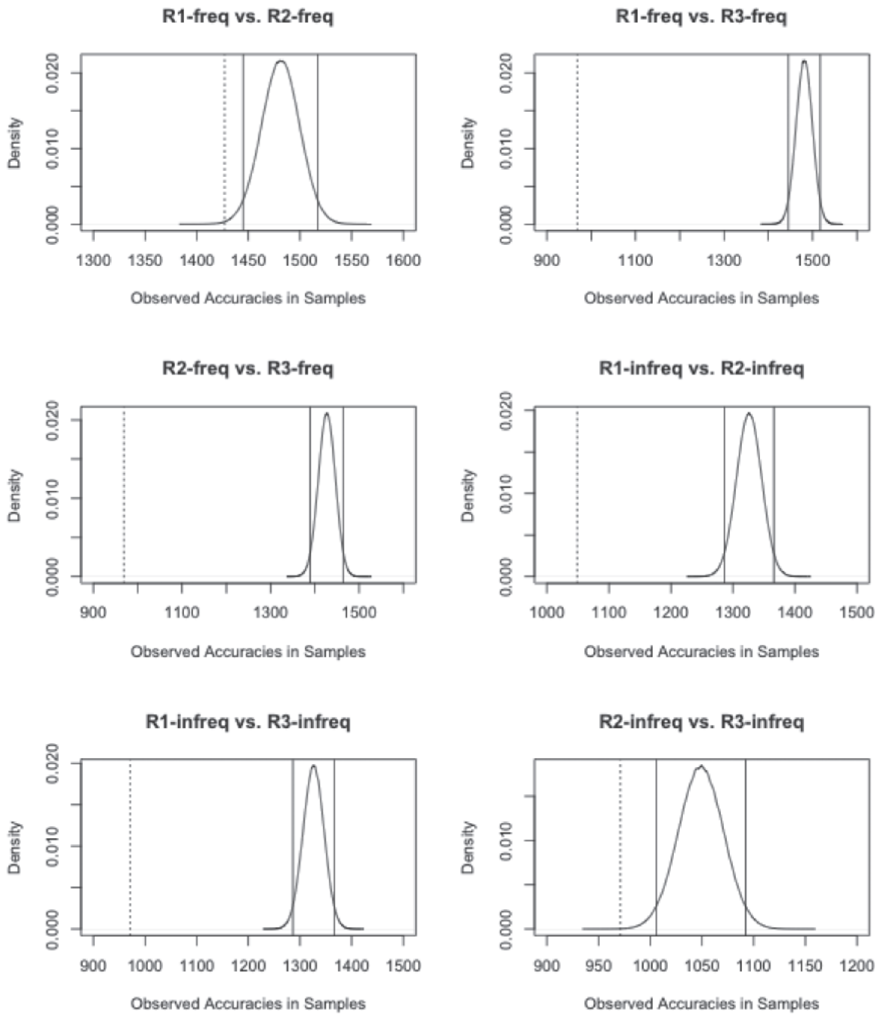

Figure 7. *Calculations of comparisons of the languages λ1, λ2, and λ3 among each other. Results of multiple group comparisons; the curve shows the binomial distribution of the number of correct answers of one language (first one of the pair), the area between the solid lines includes 95% of the expected number of correct answers. The dotted line is the number of correct answers of the other language (second one of the pair).*

learned best, followed by R2. Learning of R3 was less successful, and in fact, participants appear not to have learned the alternation of λ3 at all. In both the frequent and infrequent exposure conditions, R1 is learned more accurately than both R2 and R3, and R2 is learned more accurately than R3. Comparisons are shown in Figure 7.

5. Discussion

The acquisition of morphophonemic alternations depends on the nature of the alternation; different alternations follow different paths of acquisition, since several factors seem to play a role. Not all factors have the same influence: substance, locality, and amount of exposure all influence the acquisition process to different degrees.

We compared the learnability of alternations in artificial languages that differed with respect to their phonetic grounding (whether or not the alternation was substantively based), their locality (whether the dependency was a local or a non-local one), and their amount of exposure (more or less frequency of occurrence). In our experimental design we differentiated between three rules and two levels of exposure. The first rule (R1) was a vowel harmony, a process common in the world's languages, substantively based and local. The second rule (R2) was an arbitrary rule where the backness of one vowel was dependent on the tenseness and length of another vowel, hence a local alternation that is not substantively based. The third rule (R3) was an arbitrary rule where the backness of one vowel was dependent on the sonority of a non-adjacent consonant; this alternation was non-local and not substantively based. We investigated the influence of the type of alternation and amount of exposure across experimental groups. Overall we observed a high variability in all groups; some participants did well and reached full competence in the alternation just learned, while others performed at a chance level when asked to generalize the alternation to new items. The manipulation of amount of exposure was a significant effect, in that an alternation presented more frequently was more likely to be learned. The type of alternation was another crucial factor: R1 learners performed best followed by R2 learners. R3 learners brought up the rear. Greater exposure did not help any of the R3 learners to learn this alternation.

Our data suggests that substance as well as locality act as a strong bias in the acquisition process. Even with little exposure, learners generalized an alternation which was substantively based better than alternations that were not. With more exposure, more learners showed learning effects. This tendency reflects the advantage of phonetically grounded patterns during the initial stage of acquisition (Demuth 1995; Jusczyk, Smolensky, and Allocco 2002; Gnanadesikan 2004; Hayes 2004). Substantively based patterns are learned more accurately and on the basis of lesser evidence; this is consistent with their common occurrence in the world's languages (Hayes and Steriade 2004). We reason that the learner's experience with her perceptual and production system helps her to generalize alternations to more abstract levels of representation; in this way the emergence of constraints is influenced by phonetics (Redford 2008). This bias toward phonetically grounded patterns has recently become a matter of discussion and is argued to have a more (Becker, Ketrez, and Nevins 2011) or less strong (Hayes et al. 2009) influence.

A second factor which affects the acquisition process is locality. Only local alternations were learned, while non-local ones were not. Within local alternations, amount of exposure played a role in that there was more learning as a result of more experience with an alternation. However, learners with a great deal of exposure to a local alternation which was not substantively based still performed significantly worse than learners of the substantively based alternation. Even with less exposure, R1 learners still have an advantage. Learners of R3, which involved a non-local alternation that is not substantively based, failed completely, whether they were presented with it more or less frequently. We believe, however, that it is possible to learn an arbitrary pattern such as the one we investigated with enough exposure as suggested by the mild productivity of an arbitrary pattern such as velar softening in English (Pierrehumbert 2006) or postnasal devoicing in Tswana (Coetzee et al. 2007). We do not want to claim that it is impossible to learn such an alternation, although our data yields no evidence learning the arbitrary patterns. We think substance is probably a gradient notion, with processes being more or less substantively based. In the present study, we differentiated between only two levels: weak or no phonetic grounding (not substantively based) and strong phonetic grounding (substantively based). An investigation of the claim of the gradient nature of substance is beyond the scope of this experiment but should be the subject of further research. We showed that there are several factors that play a role during the acquisition of morphophonemic alternations, and we emphasize that each of these factors makes its own contribution to the acquisition process. Phonetics serves as a bias in learning, and so does locality. Unsurprisingly, learners are more successful the more they are exposed to a pattern.

6. Conclusion

Learners rely on the phonetic basis of an alternation during the acquisition process. They acquire a substantively based alternation more easily than an alternation which is not substantively based. In fact, phonetic substance facilitates the acquisition of morphophonemic alternations even in the condition of limited exposure to the alternation. Although our participants failed to learn the non-local alternation which was not substantively based, we do not exclude the possibility that non-substantively based alternations can be learned. In fact, we showed that one type of non-substantively based pattern, a local one, can be learned. However, it was learned less well than a local alternation that was substantively based. Locality as the sole explanatory factor is not sufficient to account for this finding from our study. Rather, these findings show that substance as a sole factor can facililate the acquisition of alternations. In addition, our comparison of two types of non-substantively based alternations, a local one and a non-local one, shows that locality is also a crucial factor in the acquisition of alternations. The local dependency showed a clear advantage in acquisition compared to a non-local one.

Our results are in agreement with many of the studies reported in Hayes et al. (2004), and specifically with that of Hayes and Steriade, who propose that substance influences synchronic grammar and is the source of markedness constraints. Substance is manifested in the speaker's competence, and the early output of children can be traced back to these emerging grammatical constraints. Such a bias would have a positive influence on the acquisition of certain patterns. The implication would be that the learner relies on cues which are available to her because of her knowledge of her perception or production processes. Our data are in line with the growing body of literature that argues that substance serves as a bias (Wilson 2003, 2006). In a recent study, such an analytic phonetic bias appears to guide German children in their generalization of two equally frequent alternations to pseudowords (van de Vijver and Baer-Henney 2012). Five-year-old children tend to produce more voicing alternations than 7-year-old children, who, in turn, produce more alternations than adults, but 5-year-olds produce fewer vowel alternations than 7-year-olds, who, in turn, produce fewer vowel alternations than adults. In other words, the tendency to produce voicing alternations decreases with age, while the tendency to produce vowel alternations increases with age. Early on, learners appear to be predisposed toward patterns that are grounded in phonetics. The learners' own phonetic experience biases them towards the substantively based alternation. Even with less evidence during the acquisition process, there is an advantage for such patterns. In line with Wilson (2006), we want to point out that we argue for substance as a bias rather than a restriction.

Our results are not in line with Blevins' Evolutionary Phonology (Blevins 2004), which allows the influence of substance only diachronically. In language change, substantively based patterns may have an advantage over those that are not substantively based. However, Evolutionary Phonology does not argue for an influence of substance in language acquisition. Hence, it also denies an influence such as the one we observed during the language acquisition process. Evolutionary Phonology proposes that there is no difference between substantively based patterns and non-substantively based ones in acquisition, since there are patterns of both kinds in the world's languages. Every pattern must be learned at some point, whether it is defined as substantively based or not. However, our results show that there is indeed an advantage of substantively based patterns over non-substantively based ones.

Additionally, our results are not fully in agreement with Bybee (2001). Her framework predicts that if two alternations have the same type and token frequency, they will be acquired in the same way, even if they differ in terms of substance. Our material was carefully controlled for amount of exposure, substance, and locality. We found that variation in terms of substance or locality crucially affects learning. The variation in amount of exposure only played a role if the alternation was substantively based or local. If that was the case, the acquisition process benefited from a more frequently occurring alternation. Moreover, the substantively based local alternation was generalized more often than the non-substantively based local alternation when the alternation was infrequently present in the input. A model which is based on frequency alone cannot account for our data. Our results support a growing body of research that shows that factors other than frequency support the acquisition of alternations. It is therefore necessary to set up a more detailed model of the acquisition of alternations than previously assumed.

There are open questions for further research. For instance, our training data are quite unrealistic – our stimuli simplify natural languages. This was necessary because of the experimental design, and it allowed us to investigate the effects of substance, locality, and frequency while minimizing spurious effects from other influences. Natural language, however, is much more variable and the learner needs to cope with that. The mapping from phonetics to phonology might not always be clear, and phonetics differs much more dialectically than phonology does. Dillon, Idsardi, and Phillips (2008) show that variation can cause serious problems if phonological acquisition is reduced to statistical learning and the influence of phonetics alone. So what happens if the link between phonetics and phonology is not as clear as in our substantively based example? Future research with more realistic data will have to shed light on this issue. Another issue is that alternations are not always as regular as in our example where the rules were completely surface true. Most alternations in the world's languages do not apply in all contexts in which they could apply, for instance, German vowel and voicing alternation (van de Vijver and Baer-Henney 2011, 2012). How will the learning mechanisms affect alternations that have exceptions? If learners are exposed to such an alternation, would they rely more strongly on substance, locality, or lexical frequency? These questions show that we are still far from a complete understanding of how learners acquire alternations.

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