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Interaction of phonological biases and frequency in learning a probabilistic language pattern

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A R T I C L E I N F O

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A B S T R A C T

We examine how learning a phonological rule in an artificial language interacts with morphological and lexical learning. We exposed adult participants to an artificial language in which noun plurals were marked by one of two prefix forms (*ba-* or *ni-*), one of which also triggered a velar palatalization rule (e.g., singular *kimu*, plural *ni-chimu*). In some conditions, the rule additionally created homophony. We also manipulated the relative frequency of the two prefix variants. The results showed that participants shifted away from using the rule-triggering prefix (*ni-*), but only when it was already the less frequent prefix. We attribute this effect to a paradigm uniformity bias leading participants to avoid phonological alternations (particularly in the stem). When the rule created homophony between lexical items, participants were less able to learn the rule, but it did not affect their choice of prefix. We attribute this effect to homophony avoidance interfering with participants' ability to extract the phonological generalization.

1. Introduction

Learning a language requires acquiring many different types of knowledge, including the language's sound system, phonology, lexicon, word order, and so on. Even though we often study these various aspects of language independently, some learning across these areas will happen (at least partially) in parallel, meaning that various learning processes can interact with each other. In this study, we examine how morphological and lexical learning can influence learning a phonological rule and vice versa.

We focus on two factors that could cause an interaction between these domains of learning. The first factor is *avoidance of phonological alternations.* Phonological alternations arise when a morpheme has distinct pronunciations in different contexts due to the application of a phonological rule. For example, the final /t/ phoneme of the verb stem *pat* becomes 'flapped' in American English when the *-ing* suffix is added (*patting*). Previous studies have suggested that phonological alternations are initially disfavored by learners, in artificial language learning experiments with adults and children (Kapatsinski, 2009; Smolek, 2019; Smolek & Kapatsinski, 2018; Stave, Smolek, & Kapatsinski, 2013; Tessier, 2012; White, 2013, 2014) as well as in children's natural language acquisition (Do, 2018; Kerkhoff, 2007). The second factor we consider is *homophony avoidance*. Phonological rules sometimes create homophony; for instance, the flapping rule in American English (mentioned above) affects both *pat* and *pad* when the *-ing* suffix is added, causing the words *patting* and *padding* to be functionally homophonous.[1] Previous work has shown that adults find it more difficult to learn new phonological rules in an artificial language when those rules create homophony compared to when they do not (Kapatsinski, 2009, 2013; Yin & White, 2018). We additionally explore how these factors interact with the frequency with which learners encounter evidence for the phonological rule and its trigger in the input. A number of studies have examined these factors individually, but much less research has explored their interaction within a single experiment, with the notable exception of a line of research by Kapatsinski and colleagues (e.g., Kapatsinski, 2009, 2010, 2012, 2013, 2018; Smolek, 2019; Smolek & Kapatsinski, 2018; Stave et al., 2013), discussed in more detail below.

In the current study, we tested adult participants on an artificial language learning task that required them to learn three types of information: novel lexical items (nouns), a novel morphological construction in which plurals are probabilistically marked by one of two prefix forms, and a novel phonological rule triggered by one of the two

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[1] Despite subtle acoustic differences between flapped words like *patting* and *padding*, adult native speakers are unable to reliably distinguish the words in perception (Herd, Jongman, & Sereno, 2010).

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prefix forms. The probabilistic prefix pattern was not lexically determined; the prefix options had the same relative frequency across all noun stems. Our focus is on three main research questions. First, does evidence that one morphological construction triggers a phonological rule cause participants to underuse that construction (relative to the other) to avoid phonological alternations? Second, does exposure to a rule that creates homophony between distinct lexical items impact either the learnability of the rule or participants' preference of morphological construction? Third, what role does the frequency of the rule (and its trigger) in the input play in these effects? In the following sections, we provide more background on these issues before describing the current experiment in greater detail.

1.1. Phonological alternations and paradigm uniformity

Most phonological rules have a functional grounding related to speech articulation and/or perception (e.g., Archangeli & Pulleyblank, 1994; Blevins, 2004; Hayes, Kirchner, & Steriade, 2004; Stampe, 1973); that is, they usually facilitate speech in some way, either from the perspective of the speaker or listener. For instance, a common phonological rule found across languages is velar palatalization, whereby the articulation of velar consonants is fronted to the palatal region when they occur next to high front vowels (e.g., Russian [dura**k**] 'fool' → [dura**tʃ**-i-t^j] 'to fool'; Kapatsinski, 2010). Because high front vowels are also articulated with the tongue in the palatal region, velar palatalization has the effect of reducing the distance the tongue needs to move across the sequence (e.g., see Keating & Lahiri, 1993). However, phonological alternations also add variability and complexity to a language. Having a phonological alternation means that there is no longer a one-to-one correspondence between form and meaning, as a single morpheme will have multiple forms depending on its context. Language learners must track these forms and eventually acquire a system of rules (or other generalizations) that explains their distribution (e.g., Peperkamp, Le Calvez, Nadal, & Dupoux, 2006).

Numerous studies have suggested, however, that adult and child learners show a dispreference for phonological alternations (Do, 2018; Hayes, 1997, 2004; Kapatsinski, 2009, 2013; McCarthy, 1998; Tessier, 2012; White, 2014, 2017). A common explanation for this tendency is that learners have a bias that favors *paradigm uniformity* (Steriade, 2000), meaning that they initially expect a morpheme to have the same form across its various morphological constructions (e.g., Hayes, 2004; White, 2017; cf. Kapatsinski, 2018, ch. 7 for arguments that this bias is learned). One source of evidence for this idea comes from language change, where *paradigm leveling* (also known as *analogical leveling*) is a common phenomenon (Bybee & Brewer, 1980; Hayes, 1997; McCarthy, 1998; Tiersma, 1982). Paradigm leveling occurs when alternations between paradigmatically related forms are eliminated over time, resulting in more consistency between the shared forms in a morphological paradigm (e.g., pre-classical Latin *honōs* →*honor*, becoming consistent with *honōris*, *honōrī*, *honōrem*, etc.; Hock, 1991, p. 180; Albright, 2005).

Evidence of paradigm uniformity effects has also come from learning experiments. For instance, Tessier (2012) taught four-year-olds an artificial language with two-syllable pseudowords, such as *zitchdin* and *wutchdel*. The pseudowords were presented to the children either as monomorphemic mass nouns (e.g., 'some *zitchdin'*) or morphologically complex count nouns with a noun stem and plural suffix (e.g., 'one *wutch'*, 'three *wutch-del'*). The children were more likely to produce the word-medial consonants faithfully when the words were suffixed forms with a corresponding bare noun stem than when the words were monomorphemic (i.e., fewer errors in forms like *wutch-del* from singular *wutch* than in mass nouns like *zitchdin*), suggesting that analogy to another member of a paradigm increased faithfulness. Likewise, artificial language experiments with adults have found that adult learners also have a default preference for the stems of paradigmatically related words to have identical forms (e.g., Kapatsinski, 2009, 2013; McMullin & Hansson, 2019; Stave et al., 2013; White, 2014). Accounting for this preference in a learning model requires the implementation of some type of paradigm uniformity bias or stem perseveration bias (see Kapatsinski, 2013; McMullin & Hansson, 2019; White, 2017).

There are several specific mechanisms that have been proposed to account for such effects, in addition to a general paradigm uniformity bias. One is a stem faithfulness bias (i.e., specifically avoiding changes to the stem; e.g., Beckman, 1998). Support for a specific stem faithfulness bias comes from research showing that adults avoid changes to stems during learning tasks, but not changes to non-stems (Finley, 2015). Paradigm uniformity and stem faithfulness make similar predictions, but differ on whether they predict overgeneralization of a phonological rule beyond the context where it should apply (paradigm uniformity) or not (stem faithfulness).[2] Another potential mechanism to explain paradigm uniformity effects is that learners acquire a 'copy' generalization whenever they encounter paradigmatically related pairs with identical stems, and this 'copy' generalization competes with other generalizations (e.g. phonological rules) that would encourage stem changes (Kapatsinski, 2018, ch. 7–8). Finally, stem perseveration has been proposed as a production-internal mechanism that could contribute to paradigm uniformity effects, especially in tasks involving oral production (Kapatsinski, 2013; Stave et al., 2013). Stem perseveration is supported by research showing that the tendency to avoid alternations is much stronger in tasks involving oral production than in tasks involving ratings or forced-choice responses (e.g., Kapatsinski, 2012; Stave et al., 2013; White, 2013).

Turning to native language acquisition, Do (2018) found that Korean children (age 4–7) avoided producing an expected (adult-like) pattern of irregular verbal inflection that would require applying a phonological rule (e.g., base stem: [jəɾ] 'open', [jə-n-da] 'open (present declarative)'). Younger children in the study (age 4–5) tended to use the correct inflectional morphology but without applying the required phonological rule (e.g., by incorrectly adding a filler vowel [ɨ] to preserve the base stem form, which can only occur before vowels, as in *[jəɾ-ɨ-n-da]). Older children (6–7) used a different strategy to avoid applying the rule. They tended to use alternative extended constructions—which were grammatical but not used by adult participants—that required additional morphemes but did not require applying a phonological rule (e.g., [jəɾ-ə-bo-n-da] 'try to open'). In a follow-up experiment, when the task was changed such that the older children were obliged to use the simpler construction, they were actually successful at applying the phonological rule as required. The results therefore suggest that even once children have mastered phonological rules, paradigm uniformity might still influence them to use constructions where phonological rules do not need to be applied.

In the current study, we test whether adults will demonstrate a similar effect when learning an artificial language. Specifically, we test whether evidence that one morphological construction (but not the other) triggers a phonological rule will cause them to prefer the construction that does not trigger the rule.

1.2. Neutralization and homophony avoidance

In addition to avoiding phonological alternations generally, there is reason to believe that learners may have a particular aversion to alternations that neutralize phonemic contrasts, especially when they create new cases of homophony (Yin & White, 2018). Phonological rules are considered *phonologically neutralizing* when they eliminate the distinction between two phonemes, such as the flapping rule in American English (mentioned above) that removes the contrast between /t/ and /d/ in certain phonological contexts. Neutralizing phonological rules (like flapping) can also result in derived homophony (Silverman, 2010,

[2] They also have distinct formal representations in constraint-based models of phonology (i.e., output-output faithfulness constraints vs. stem-faithfulness constraints; see Benua, 1997).

2012), whereby two distinct base forms are rendered homophonous due to a rule's application, such as when *pat* and *pad* become homophonous in American English when *-ing* is added (*patting/padding*) due to the flapping rule.

Much of the previous work on neutralization and homophony avoidance has taken a historical approach, focusing on language change. For instance, Korean is known to have several phonologically neutralizing rules that create homophony (e.g., see Silverman, 2010), such as the rule that neutralizes the three-way laryngeal contrasts in plosives when they are followed by another consonant. However, quantitative analyses have shown that the existing neutralizing rules in Korean produce less homophony than other hypothetical sets of comparable (but non-existing) rules would (Kaplan, 2011; Silverman, 2010). Moreover, a statistical analysis of nine languages found that the number of word pairs distinguished by a pair of sounds was a significant predictor of whether those pairs of sounds would become neutralized (Wedel, Kaplan, & Jackson, 2013), consistent with the view that homophony avoidance plays a role in constraining language change (see also Blevins & Wedel, 2009).

These studies only indirectly speak to the effect of homophony avoidance during learning, under the assumption that learning is one (but not the only) mechanism that shapes language change. Yin and White (2018) looked directly at the effect of neutralization and homophony avoidance during learning. Using an artificial language learning experiment, they exposed adult learners to a set of phonological rules and manipulated whether the rules were non-neutralizing or neutralizing, as well as the amount of homophony created when the rules were neutralizing. They found that the phonological rules were learned more poorly when they were neutralizing (compared to non-neutralizing), but only when the neutralizing rules also created homophony. The results suggest that homophony avoidance is a factor that impacts learners' ability to acquire phonological rules.

Research by Kapatsinski (2009, 2012, 2013) has also examined the effect of neutralization and homophony on adult's phonological rule learning. In a series of experiments, Kapatsinski (2009, ch. 3-4, 2012) taught adults an artificial language in which noun stems were followed by one of two plural suffixes, *–a* or *-i*. The language also had a velar palatalization rule, which changed stem-final [k] and [g] into [tʃ] and [dʒ],[3] respectively, when they occurred before *-i*. Kapatsinski compared two types of languages, one which had additional cases of singular stems ending in [tʃ] and [dʒ] (which made the palatalization rule neutralizing and created homophony) and one without such cases. There was also a comparison between two types of tasks, one intended to favor source-oriented generalizations (e.g., singular [k] → plural [tʃi]) by highlighting singular-plural pairs and one intended to favor product-oriented generalizations (e.g., 'plurals end in [tʃi]'; see Bybee, 2001) by obscuring the singular-plural connections. The results showed that in the source-oriented task, the addition of the homophony-creating forms caused application of the palatalization rule to be reduced. Kapatsinski's explanation for the reduction, however, was not that the homophony itself affected performance on the rule, but rather that the additional singular-plural pairs demonstrating [tʃ] → [tʃi] bolstered the strength of the general source-oriented generalization *C* → *Ci* (and therefore the tendency to maintain velar consonants, i.e. [k, g] → [ki, gi]). This generalization (*C* → *Ci*) competed with the palatalization rule, [k, g] → [tʃi, dʒi]. The explanation relies on the fact that the homophony cases were *additional* trials, thereby adding additional support for the general C → Ci generalization. In the product-oriented task, by contrast, the application of the palatalization rule increased when homophony-creating cases were added. Kapatsinski's explanation for this different result was that the additional trials demonstrating [tʃ] → [tʃi] in the product-oriented task bolstered the product-oriented generalization 'plurals end in [tʃi],' which further motivated palatalization rather than competing against it.

Even though Kapatsinski (2009, ch. 3; 2012) and Yin and White (2018) both found reduced performance on accurately applying phonological rules when they created homophony (in a task that highlights singular-plural pairs), their explanations of this reduction are different. In the current study, we conduct an experiment similar to Kapatsinski's (2009, ch. 3), but with some key differences. Most importantly, rather than adding new examples to create homophony, we *exchange* some of the existing stems with ones that will produce homophony. As a result, we can test the effect of homophony while keeping constant the overall number of stems that support the generalization C → Ci across the two conditions, allowing us to test whether there is an effect of homophony avoidance in the absence of additional support for the competing C → Ci 'no change' generalization. We also test the interaction between homophony and frequency, which has not been examined in previous work.

1.3. Probability matching and regularization

While linguistic patterns are sometimes deterministic, many patterns found in languages involve some degree of probabilistic variation. A probabilistic pattern can refer to two distinct kinds of variation in language. The first kind of variation occurs when two (or more) variants can be used in a given instance, but various (linguistic and social) factors may influence the likelihood that each will be used. For example, there are two ways to form a dative construction in English (e.g., *gave you the watch* vs. *gave the watch to you*); both options are possible, but various quantifiable factors affect the likelihood of each being used (Bresnan & Ford, 2010). The other kind of variation occurs when each *type* (in the sense of, e.g., a particular lexical item) has only one possibility, but across the full set of types (e.g., across all lexical items), there is a pattern that can form the basis of a generalization. For example, when Dutch speakers are asked to guess the voicing of the final consonant of novel stems (which is neutralized due to final devoicing), they respond probabilistically generalizing over the stem types in their lexicon (Ernestus & Baayen, 2003). The first kind of variation is associated with token frequency, and the second with type frequency. The distinction between these kinds of variation can have important implications for learning. For instance, Schuler (2017) found that type frequency was more important than token frequency in determining whether children would form a productive rule in artificial language learning, whereas adults treated token and type frequency similarly. When it comes to phonotactic knowledge that adult speakers have about their own native language, the generalizations are based on lexical types more so than token frequency (e.g., Daland et al., 2011; Hay, Pierrehumbert, & Beckman, 2004; Richtsmeier, 2011).

How do participants in learning experiments react when they encounter probabilistic patterns in their input? In many cases, adults successfully track the relative frequency of variants in their input and (at an aggregate level) reproduce a similar distribution in their own productions, a behavior known as *probability matching* or *frequency matching* (e.g., Austin, 2010; Hayes, Siptár, Zuraw, & Londe, 2009; Hudson Kam & Newport, 2005, 2009; Schuler, 2017). For instance, Hudson Kam and Newport (2005) exposed English-speaking adults to an artificial language in which determiners sometimes appeared after nouns and sometimes were omitted. The probability of the determiner appearing after a noun varied according to condition (ranging from 45% to 100% of instances). At an aggregate level, the use of the determiner in the test phase closely matched the probability observed in exposure, and at an individual level, few adults regularized the pattern to be more systematic. Beyond artificial language learning experiments, probability matching behavior has also been found in experiments requiring adult

[3] The symbols [tʃ] and [dʒ], respectively, represent the sounds for 'ch' in the English word *cheese* and 'j' in the English word *jump* in the International Phonetic Alphabet. When we write full stimuli used in our experiment, we use the letters 'ch' and 'j' respectively to make them easier to read; otherwise, we use the IPA symbols.

participants to apply type-based probabilistic patterns from their native language lexicons to novel words, including experiments with speakers of Hungarian (Hayes et al., 2009), Dutch (Ernestus & Baayen, 2003), Spanish (Eddington, 1996), Tagalog (Zuraw, 2010), Korean (Jun & Lee, 2007), Arabic (Frisch & Zawaydeh, 2001), and English (Albright & Hayes, 2003; Bailey & Hahn, 2001; Coleman & Pierrehumbert, 1997).

In some cases, we see that learners regularize probabilistic patterns in experiments, boosting the frequency of the most frequent variant while reducing the frequency of other variants in their output. Regularization has the effect of reducing the variability in a pattern and shifting it in a more deterministic direction. Research suggests that children are much more likely to regularize than adults. For instance, when children in Hudson Kam and Newport's (2005) study were exposed to an artificial language in which determiners followed nouns 60% of the time, the majority of the children developed a systematic pattern, meaning that they used one variant (either including or omitting the determiner) more than 90% of the time; in some cases, they even innovated their own systematic pattern. Adults exposed to the same language tended to probability match rather than shift towards a more deterministic pattern. Striking examples of children making a language more systematic have also been found in special cases of natural language acquisition involving highly inconsistent input, such as studies of deaf children who were exposed to inconsistent sign language input from their parents (e.g., Ross, 2001; Singleton & Newport, 2004) and the rapid systematization that was led by children in the early development of Nicaraguan Sign Language (Senghas & Coppola, 2001).

Though children are more prone to regularization than adult learners, adults sometimes regularize probabilistic language patterns in experiments as well, particularly when a pattern is complex. For instance, Hudson Kam and Newport (2009) found that adults probability matched when learning an artificial language pattern with only two options, either presence or absence of a determiner following nouns (replicating their 2005 study). However, when the pattern included a main determiner (used in 60% of cases) and several less frequent 'noise' determiners (either 2, 4, 6, 8 or 16), adults began to regularize the main determiner. Regularization of the main determiner increased as the number of infrequent alternatives increased, suggesting that regularization was linked to the complexity of the pattern. These results from language learning echo findings from non-linguistic pattern learning, where children are more likely to regularize than adults, and regularization is more likely (for both children and adults) as the pattern becomes more complex with more variants to track (e.g., see Gardner, 1957; Starling, 2013; Weir, 1964, 1972). The nature of the experimental task and the type of pattern being learned (e.g., type frequency or token frequency) also play an important role in whether learners (adults and children) show probability matching behavior (Austin, 2010; Montag, 2021; Schuler, 2017).

Learners may also shift the relative frequency of variants if one of the variants is disfavored. For instance, Culbertson, Smolensky, and Legendre (2012) exposed adults to an artificial language pattern in which noun phrases had a probabilistic word order, with adjectives and numerals sometimes preceding the noun and sometimes following the noun. When presented with a 70%–30% split in word order (e.g., adjectives precede nouns 70% of the time and follow nouns 30% of the time), they found that participants generally regularized the majority pattern in their responses, using the majority pattern more frequently than it occurred in the input. However, there was one exception to this tendency: when the majority pattern was that adjectives preceded nouns and numerals followed nouns, participants shifted away from it rather than regularizing it. Across languages, that particular pattern (adjectives before nouns, numerals after nouns) is vastly under-represented, which could in part be due to a learning bias against that type of noun phrase structure (see Culbertson et al., 2012 for more discussion). This study suggests that learners may shift away from a variant when learning a probabilistic pattern if the variant is disfavored due to linguistic or domain-general biases.

In the current study, we adopt the general approach of Culbertson et al.'s study, testing whether a bias to avoid phonological alternations will cause participants to shift away from using a morphological construction that triggers a phonological rule.

1.4. Overview of current experiment and hypotheses

We exposed adult participants to an artificial language that required them to learn 10 novel noun stems, a phonological rule (velar palatalization), and a morphological pattern in which plurals were variably marked by one of two prefix forms, one that triggered the rule (*ni-*) and one that did not (*ba-*). Our goals in this experiment were to test whether evidence that one prefix triggered a phonological rule would cause participants to favor the other (non-triggering) variant, to test whether changing the rule to be neutralizing and homophony-creating would make it harder for participants to learn the rule, and to test whether these effects depend on the frequency of the rule (and its trigger) in the input.

The experiment consisted of four phases: stem learning, stem test, prefix learning, and prefix test. In the first two phases (stem learning and stem test), participants learned 10 novel CVCV singular nouns (e.g., *kimu* meaning 'a flower') and were then tested. Once participants demonstrated sufficient knowledge of these 10 nouns, they entered the third phase (prefix learning), where they were exposed to the plural forms of the same 10 nouns. The plurals were formed by adding one of the two prefix forms, *ni-* or *ba-* (i.e., ni-CVCV or ba-CVCV). The choice of prefix followed a probability distribution depending on condition, either 66.7% *ba-* / 33.3% *ni-* (Frequent *ba-* condition), 66.7% *ni-* / 33.3% *ba-* (Frequent *ni-* condition), or an equifrequent 50%–50% split (50–50 condition). Finally, in the prefix test phase, participants were tested using a free production picture naming task. This task allowed us to measure their use of the two prefix forms as well as their production of the stem.[4]

We introduced a phonological rule in some conditions, triggered by the *ni-* prefix. We manipulated the type of phonological alternations triggered by *ni-*. In the No Alternation condition, there was no phonological rule applied (e.g., singular ***kimu***, plural *ni-**kimu***); this condition served as a baseline condition, allowing us to see how participants reacted to the probabilistic prefix pattern alone, without the influence of a phonological rule. In the Non-Neutralizing condition, the *ni-* prefix triggered palatalization when it was attached to stems beginning with the velar stops [k, g] (e.g., singular ***kimu***, plural *ni-**chimu***). This condition allowed us to see whether the phonological rule would influence participants' tendency to choose *ni-*. Finally, in the Neutralizing condition, we changed two of the singular stems of the language such that the velar palatalization rule was both phonologically neutralizing and homophony-creating (e.g., singular ***kimu*** and singular ***chimu***, both *ni-**chimu*** when the *ni-* plural prefix was added). The Alternation Type and Prefix Frequency variables were fully crossed to make a 3 × 3 between-subjects design; each participant was assigned to one of the nine resulting groups.

Hypotheses. We tested four main hypotheses, which we summarize below.

Hypothesis 1. *In the absence of phonological alternations, participants will match the input frequency of ba- and ni- in their responses (probability matching)*. The No Alternation condition serves as a baseline condition in this experiment. It is similar to the binary presence/absence determiner

[4] Our method of first training participants on 10 singular stems and then testing them on a variable affix pattern based on token frequency differs from previous experiments by Kapatsinski and colleagues (Kapatsinski, 2009, 2010, 2012, 2013; Smolek, 2019; Stave et al., 2013), who instead based the affix pattern on type frequency and asked participants to generalize to new stems in the test phase.

pattern used in Hudson Kam and Newport's (2005, 2009) studies, where adults showed probability matching behavior, so we expected probability matching in these groups. However, if there were any general regularization tendency or baseline preference for one prefix form over the other, we should see it in the No Alternation condition.

Hypothesis 2. *Participants will avoid constructions that trigger a phonological rule.* This hypothesis stems from the paradigm uniformity account. Specifically, we predicted that participants would use *ni-* less often (and *ba-* more often) relative to their input frequency when *ni-* triggered a phonological rule (i.e., in the Non-Neutralizing and Neutralizing conditions). We also explore whether this effect depends on frequency; for instance, participants may be more likely to shift away from the rule-triggering *ni-* prefix when it is frequent or infrequent.

Hypothesis 3. *The tendency to avoid the rule-triggering prefix (ni-) will be greater when the rule is neutralizing and homophony creating.* We expected that the additive effects of paradigm uniformity and homophony avoidance would lead to a greater avoidance of the rule-triggering prefix *ni-* in the Neutralizing condition than in the Non-Neutralizing condition.

Hypothesis 4. *Phonological rules are more difficult to learn when they are neutralizing and homophony-creating.* We expected that performance on the palatalization rule would be poorer in the Neutralizing condition than in the Non-Neutralizing condition due to homophony avoidance. Poorer performance on the rule would be indicated by lower (correct) application of the rule after *ni-* and more overgeneralization of the rule to incorrect contexts.

2. Method

2.1. Participants

A total of 225 adult native English speakers (162 females, 63 males; mean age = 24; age range = 18–58) completed the experiment and were included in the analysis. They were each assigned to one of the nine conditions.[5] An additional 50 participants were recruited but were excluded from the analysis because they failed to achieve the 75% accuracy criterion in the stem test phase. Most participants were Southern British English speakers, but some participants spoke another variety of English (e.g., American English, Singapore English, Malaysian English). The experiment was conducted at University College London. Participants were recruited using the UCL Psychology Subject Pool, and they received course credit or monetary compensation.

2.2. Materials

For the stem learning and stem test phases, we created 10 CVCV nonwords to be used as singular noun stems (e.g., *kimu*). The noun stems were identical in the No Alternation and Non-Neutralizing conditions. The stem consonants were chosen from the set of phonemes /p, b, t, d, k, g, m, n/. The velar stops, /k/ and /g/, which were the critical sounds targeted by the palatalization rule, each occurred in the stem-initial position (C_1 in $C_1V_1C_2V_2$) twice. The other six consonants each occurred in the stem-initial position once. The voiceless stops were produced with aspiration ([p^h, t^h, k^h]) to help our English-speaking participants distinguish them from the corresponding voiced stops. The stem vowels were drawn from the set /i, a, u/; these vowels are highly distinct and are common cross-linguistically. Each vowel was used a similar number of times in the V_1 and V_2 positions. Words that sounded similar to existing English words were avoided. We also ensured that the velar stops (/k, g/) never occurred in C_2 position after the vowel /i/. Word stress was always placed on the first syllable of the stem. We designed two pairs of stems to be identical except for the initial consonant to allow for our homophony manipulation in the Neutralizing condition (described in detail below). Each stem was assigned to a picture of a singular object or animal to represent its meaning.

For the prefix learning and prefix test phases, we created two plural forms for each stem by adding the *ba-* prefix and *ni-* prefix.[6] In the No Alternation condition, neither prefix caused a change to the stem (e.g., stem *kimu*; plurals *ba-kimu* and *ni-kimu*). In the Non-Neutralizing and Neutralizing conditions, *ni-* (but not *ba-*) triggered progressive palatalization in stem-initial velars, as can be seen in (1) below. For example, the singular stem ***k**imu* had two plural forms: *ba-**k**imu* and *ni-**ch**imu*. We chose to use progressive palatalization, even though regressive palatalization is more common cross-linguistically (Bateman, 2007), to ensure that the rule would be unfamiliar to our native English-speaking participants. English contains some phonological patterns that resemble regressive palatalization. These include velar softening (e.g., *electric* vs. *electricity* and *analog* vs. *analogy*; Halle, 2005), and the alternation in pairs such as *elate* vs. *elation*. Four of the stems (out of 10) contained initial velar stops (two /k/ and two /g/) and therefore demonstrated the velar palatalization rule when *ni-* was added.

(1) Velar palatalization rule[7]
   a. k → tʃ / i _
   b. g → dʒ / i _

In the Neutralizing condition, we modified the stems so that the palatalization rules would create homophony. The two stems beginning with /t/ and /d/ had their initial phonemes replaced by the palatalized sounds /tʃ/ and /dʒ/ (i.e., stem *timu* was instead *chimu*, and *dapi* was instead *japi*). Other than this change to two of the stems, the stimuli in the Neutralizing condition were identical to those in the Non-Neutralizing condition. This change to the stems caused the palatalization rule to be phonologically neutralizing in the Neutralizing condition, sometimes resulting in cases of derived homophony. To be explicit, four stems (*kimu, gapi, kuta, and gaku*) were palatalized in the Neutralizing condition, and two of those stems resulted in homophony with distinct stems (*chimu* and *japi*) when palatalization occurred (*kimu, chimu* → *ni-chimu*; *gapi, japi* → *ni-japi*). The other two velar-initial stems (*kuta* and *gaku*) also demonstrated palatalization, but did not result in homophony. Table 1 presents a subset of the stimuli across the three conditions, highlighting the crucial differences between the conditions. A full list of stimuli is provided in the Appendix.

The stimuli were recorded by a phonetically trained female native speaker of Cypriot Greek in a sound-attenuated booth using a RODE-NT1-A large diaphragm condenser microphone and RME Fireface UC audio interface recorder at a sampling rate of 44,100 Hz and 16 bits. Stimuli were normalized in terms of intensity and set to a comfortable listening volume.

2.3. Procedure

The experiment consisted of four phases: stem learning, stem test, prefix learning, and prefix test. Before starting the experiment, participants were informed that an alien instructor would be teaching them an alien language, and that their goal was to fit into the alien society by learning how to communicate with the aliens. No instructions were given in advance about the specific aims of the experiment.

[5] The Frequent *ni-* Non-Neutralizing condition had 26 participants and the 50–50 Non-Neutralizing condition had 24. Each of the other conditions had 25 participants.

[6] Even though we told participants that they would be learning plural forms, we cannot be certain that they interpreted the *ba-* and *ni-* forms as prefixes rather than standalone quantifiers (like *some* in English). However, it does not change our basic findings or conclusions even if they were interpreted this way.

[7] Note that these two statements (*a* and *b*) can be combined into a single rule using phonological features; we list them separately here for simplicity.

Table 1
Sample of singular noun stems and plural forms by alternation type condition.

Alternation type	Noun stem	Plural forms	
No Alternation	*puti*	*ba-puti*	*ni-puti*
	kimu	*ba-kimu*	*ni-kimu*
	timu	*ba-timu*	*ni-timu*
	gapi	*ba-gapi*	*ni-gapi*
	dapi	*ba-dapi*	*ni-dapi*
Non-Neutralizing	*puti*	*ba-puti*	*ni-puti*
	***k**imu*	*ba-**k**imu*	*ni-**ch**imu*
	timu	*ba-timu*	*ni-timu*
	***g**api*	*ba-**g**api*	*ni-**j**api*
	dapi	*ba-dapi*	*ni-dapi*
Neutralizing	*puti*	*ba-puti*	*ni-puti*
	***k**imu*	*ba-**k**imu*	*ni-**ch**imu*
	***ch**imu*	*ba-**ch**imu*	*ni-**ch**imu*
	***g**api*	*ba-**g**api*	*ni-**j**api*
	***j**api*	*ba-**j**api*	*ni-**j**api*

2.3.1. *Phase 1: stem learning*

During the stem learning phase, participants were exposed to the 10 singular noun stems. Each trial began with a picture of the alien instructor on the right side of the screen; the picture of a singular object then appeared on the left side of the screen.[8] After a 500 ms delay, a speech bubble appeared above the alien instructor (to suggest the alien was speaking), and participants heard the matching singular noun stem for the picture through headphones. Participants were instructed to repeat the word that they heard in each trial aloud. Then, they pressed the spacebar to move to the next trial. Stems were presented only as audio; no orthographic forms were provided at any point. There were a total of 100 trials, divided into 10 blocks with each stem occurring once per block. The order of the stems was randomized within each block.

2.3.2. *Phase 2: stem test*

During the stem test phase, participants saw the alien instructor on the right side of the screen and then a picture of a singular object appeared on the left side of the screen. They were asked to produce the correct word into a microphone upon seeing the picture. An experimenter outside of the recording room (who was monitoring the session over headphones) coded the response as correct or incorrect by pressing the appropriate key. Participants' productions were also recorded and saved as audio files so that the responses could be verified offline. After the experimenter pressed a key, a speech bubble appeared above the alien instructor and participants heard the correct word. Fig. 1 provides a visual overview of the test trial procedure. The stem test phase consisted of 50 total trials (10 stems × 5 blocks; order randomized within each block). Throughout the phase, a numerical score appeared at the bottom of the screen. If the response was correct, the score was increased by 5 points. Participants were told before the phase began that they needed at least 190 points to pass the phase (which corresponds to 75% accuracy). Participants who failed to reach over 75% accuracy criterion repeated the stem test phase one more time; if they failed a second time, the experiment terminated and those participants were excluded from the analysis.

2.3.3. *Phase 3: prefix learning*

Trials in the prefix learning phase were identical to trials in the stem learning phase, except that the picture depicted plural objects or animals and participants heard a plural (prefixed) word, either the *ba-* form or the *ni-* form. There was a total of 60 trials, divided into 6 blocks of 10 stems with the order randomized within each block. Each stem occurred once per block, with either the *ba-* or *ni-* prefix. The relative frequency of the *ba-* and *ni-* forms depended on the participant's Prefix Frequency condition, as shown in Table 2. The relative frequency of the two variants (e.g., 66.7% *ba-* and 33.3% *ni-*, etc.) held for the phase as a whole, as well as for each stem individually. The number of times that palatalization was demonstrated in each condition is shown in Table 3.

Before starting the phase, participants were told that they would be learning plural forms of the singular nouns that they had already learned and that there was more than one way to make plurals in the language. They were again asked to repeat the word that they heard aloud before pressing the spacebar to move to the next trial.

2.3.4. *Phase 4: prefix test*

The prefix test phase consisted of 60 trials, divided into 6 blocks of 10 stems with the order randomized within each block. The procedure of the prefix test phase was similar to the stem test phase (as depicted in Fig. 1); however, the coding and scoring systems were different. The trial began with the alien instructor on the right of the screen, and a plural picture then appeared on the left side of the screen. Participants were asked to produce the plural form for the picture by speaking into the microphone. Once participants produced an answer, the experimenter (monitoring from another room) coded the response by pressing a key on a keyboard; the response was coded according to which prefix was used, whether the stem was correct or incorrect, and whether the stem-initial consonant was palatalized, changed in some other way, or left unchanged. This more elaborate coding system ensured that all aspects of the response could be analyzed at a later point. Participants' productions were also recorded and saved as sound files so that the coding could be verified offline. If a response was not given within 10 s, the trial was automatically coded as a timeout error and the next plural picture appeared on the left side of the screen.

After the participant produced a response and the experimenter pressed a key to code it, a speech bubble appeared above the alien instructor and the participant heard one of the two possible correct plural forms (the *ba-* form or the *ni-* form). The proportion of the two plural forms produced by the alien during the prefix test phase matched the proportion from the prefix learning phase (as shown in Table 2). For instance, if participants were in the Frequent *ni-* condition, the alien instructor produced the *ni-* form 66.7% of the time and the *ba-* form 33.3% of the time as feedback during the prefix test phase, matching the relative frequencies observed in the prefix learning phrase. Therefore, the feedback in the prefix test phase reinforced the relative frequencies of the two prefix options from training.

The participant's score at the bottom of the screen was presented throughout the phase and was updated at the end of each trial. During this phase, participants received 10 points if they produced a response that was identical to the one produced by the alien instructor (e.g., alien said: *ni-chimu*, participant said: *ni-chimu*). They received 5 points if they produced the same stem form as the alien, but produced the non-matching prefix (e.g., alien said: *ni-chimu*, participant said: *ba-chimu*). They received 0 points for any other response (e.g., alien said: *ni-chimu*, participant said: *ba-kimu, ni-kimu,* or anything else).[9]

Participants were instructed before the phase that they should try to fit in with the alien community, with the intention of encouraging them

[8] The image of the alien is from a study by Van de Vijver and Baer-Henney (2014). Our thanks go to Dinah Baer-Henney for sharing the alien.

[9] This odd scoring system was not intentional, but occurred due to a coding error that was only discovered after data collection. The intended scoring system was to give 10 points for a correct answer that matched the alien, 5 points for a correct non-matching answer, and 0 points for any error. In the actual scoring system, participants received partial credit for certain incorrect answers, including some overgeneralization errors (e.g., alien said: *ni-chimu*, participant said: *ba-chimu*) and some underapplication errors (e.g., alien said: *ba-kimu*, participant said: *ni-kimu*). They also received 0 points for correct alternatives with non-matching stems (e.g., alien said: *ni-chimu*, participant said: *ba-kimu*). We discuss potential effects of this unintentional scoring system in Section 4.5.

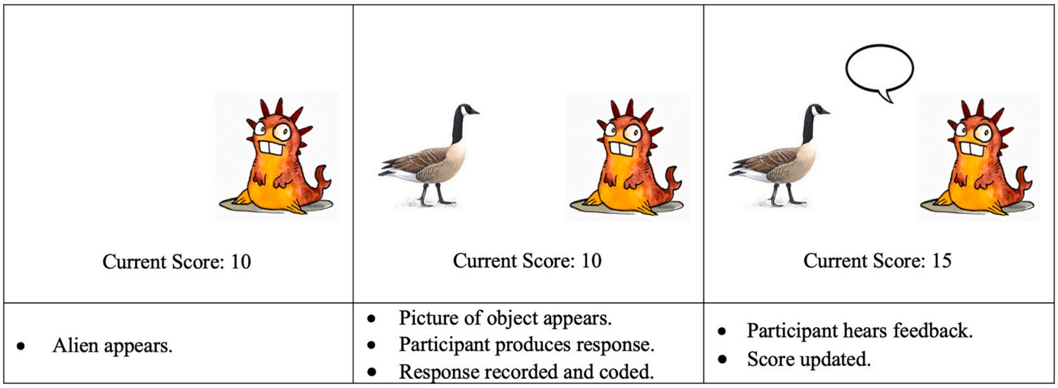

Fig. 1. Overview of the procedure of each trial for the stem and prefix test phases.

Table 2
Frequency of plural forms in the prefix learning phase.

	50–50 condition	Frequent *ba-* condition	Frequent *ni*-condition
ba- form	30 trials (3 per stem) 50%	40 trials (4 per stem) 66.7%	20 trials (2 per stem) 33.3%
ni- form	30 trials (3 per stem) 50%	20 trials (2 per stem) 33.3%	40 trials (4 per stem) 66.7%

Table 3
Number of trials demonstrating the palatalization rule in the prefix learning phase, by condition.

	50–50 condition	Frequent *ba*-condition	Frequent *ni*-condition
No Alternation	0 / 60 trials 0%	0 / 60 trials 0%	0 / 60 trials 0%
Non-Neutralizing	12 / 60 trials 20%	8 / 60 trials 13%	16 / 60 trials 27%
Neutralizing	12 / 60 trials* 20%	8 / 60 trials* 13%	16 / 60 trials* 27%

* Note: Half of the trials with palatalization also created homophony in the Neutralizing condition.

to respond probabilistically rather than using only one of the variants. After the prefix test phase, participants were debriefed and asked about their response strategies during the experiment.

3. Results

We first examine how often participants used the two prefix forms. We then look at how often participants applied the palatalization rule.

3.1. Prefix form selection

Fig. 2 shows how often participants chose the frequent prefix option in the prefix test phase according to Alternation Type (No Alternation, Non-Neutralizing, or Neutralizing) and Prefix Frequency (Frequent *ba*-, Frequent *ni*-, or 50–50). We excluded trials in which participants produced a different stem than intended, trials in which they produced neither *ba*- nor *ni*-, and trials in which they failed to respond within 10 s. In the 50–50 condition, *ba*- was arbitrarily coded as the frequent prefix (though the two options were in fact equifrequent in that condition). The proportion of times that the frequent prefix was observed during training is shown for each condition as a dashed line in Fig. 2 to facilitate comparison.

The results were analyzed with a mixed effects logistic regression model, implemented in R (R Core Team, 2018) using the *lme4* package (Bates, Mächler, Bolker, & Walker, 2015), predicting the use of the frequent prefix variant. The model included fixed effects for Prefix Frequency (50–50, Frequent *ba*-, or Frequent *ni*-), Alternation Type (No Alternation, Non-Neutralizing, or Neutralizing), and their interaction. We included random intercepts for Subjects and Stems, which was the maximal random effects structure that would converge (see Barr, Levy, Scheepers, & Tily, 2013). As a first step, we performed a likelihood ratio test comparing the full model to a subset model with the interaction effects removed, using the *anova()* function in R (Barr et al., 2013; Jaeger, 2008). The likelihood ratio test confirmed that the set of interaction effects significantly improved the model's fit, $\chi^2(4) = 11.26$, $p = .02$. We therefore retained the full set of fixed effects in the final model. A summary of the model's fixed effects is provided in Table 4.

First, we consider whether participants learned the relative frequency of the two prefix variants in their input. The intercept of the model (corresponding to the 50–50 No Alternation condition) and the simple (non-interaction) effects of Alternation Type (Non-Neutralizing and Neutralizing) were all non-significant, indicating that participants used *ba*- and *ni*- roughly 50% of the time in each of the 50–50 conditions, consistent with the relative frequency of 50% observed in training. The simple (non-interaction) effects of Frequent *ba*- and Frequent *ni*- were both significant (and positive) in the model, confirming that participants used the frequent prefix more often in these groups compared to the 50–50 group in the No Alternation condition.

Taking a closer look at the interaction effects, we see that only the Non-Neutralizing & Frequent *ba*- effect reaches significance. Therefore, when *ba*- was the frequent prefix, it was used more often in the Non-Neutralizing condition than in the No Alternation condition; stated

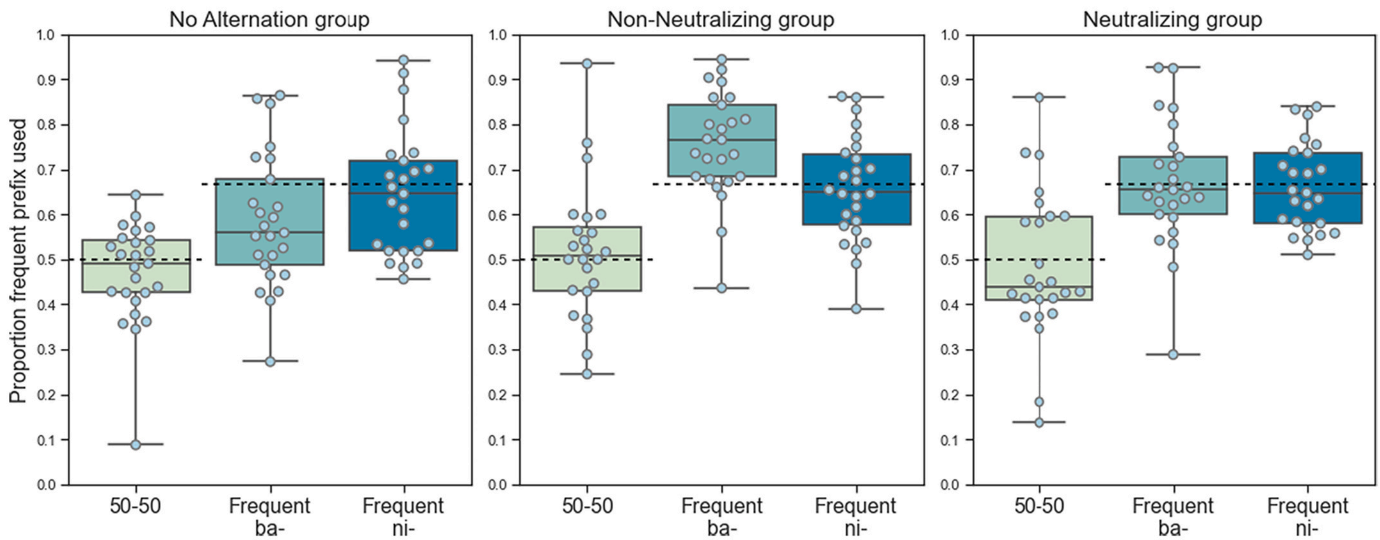

Fig. 2. Proportion of trials in which participants chose the frequent prefix option in the prefix test phase.
Note: Dashed lines show the relative frequency of the frequent prefix form during training. Error bars show 95% confidence intervals.

Table 4
Summary of the fixed effects for the model predicting selection of the frequent prefix.

Fixed effect	Estimate	Standard error	*z*-value	*p*-value
(Intercept)	−0.14	0.12	−1.17	.24
Non-Neutralizing	0.21	0.17	1.18	.24
Neutralizing	0.07	0.17	0.42	.68
Frequent *ba-*	**0.51**	**0.17**	**2.99**	**< .01**
Frequent *ni-*	**0.79**	**0.17**	**4.57**	**< .001**
Non-Neutralizing & Frequent *ba-*	**0.63**	**0.25**	**2.55**	**.01**
Non-Neutralizing & Frequent *ni-*	−0.16	0.24	−0.65	.52
Neutralizing & Frequent *ba-*	0.30	0.24	1.23	.22
Neutralizing & Frequent *ni-*	−0.02	0.24	−0.09	.93

Note: The reference group (intercept) is the 50–50 No Alternation condition.
R code for the final model: glmer(UsedFrequentPrefix ~ PrefixFrequency*AlternationType + (1|Subject) + (1|Stem), data = data, family = binomial).

Table 5
Mean usage of *ni-* for velar-initial and non-velar-initial stems, by condition.

		Prefix frequency		
Alternation type	Stem-initial consonant	50–50	Frequent *ba-*	Frequent *ni-*
No Alternation	Velar	50%	43%	62%
	Non-velar	55%	40%	66%
Non-Neutralizing	Velar	50%	25%	67%
	Non-velar	48%	24%	66%
Neutralizing	Velar	49%	30%	61%
	Non-velar	53%	35%	70%

another way, we can say that there was a significant shift away from *ni-* when it triggered alternations, but only when *ni-* was already infrequent. The other interaction effects were non-significant, indicating that usage of the frequent prefix was comparable across the other Frequent *ba-* and Frequent *ni-* conditions. Numerically, the values of the other conditions were centered around the relative frequency of 66.7% observed in input, indicating probability matching behavior at an aggregate level. Notably, participants in the Neutralizing condition closely matched the input frequency, suggesting there was no tendency to shift away from using *ni-* in any of the Neutralizing conditions.

We next consider whether there was a difference in how often participants used *ni-* with velar-initial stems (where palatalization should have applied) versus other stems. Table 5 shows the mean usage of *ni-* for velar-initial and non-velar-initial stems by conditions. Numerically, we see that the rate of *ni-* usage is very similar for velar-initial stems and non-velar-initial stems. To test whether *ni-* usage varied by the stem type, we implemented a mixed effects logistic regression model predicting *ni-* usage with a fixed effect for Stem Type (velar vs. non-velar), random intercepts for Participant and Stems, and random slopes for Stem Type by Participant. We excluded the No Alternation group from this model given that it did not involve the palatalization rule. The model found that including the fixed effect Stem Type did not significantly improve the model fit ($\chi^2(1) = 0.27$, $p = .60$), indicating that *ni-* was used at a similar frequency with velar-initial and non-velar-initial stems.

The above analysis focused on aggregate results, but we can also

Table 6
Number of participants who shifted towards *ba-* and *ni-*.

Condition		Shifted towards *ba-*	Shifted towards *ni-*	*p*-value (sign test)
No Alternation	50–50	12 / 25 (48%)	13 / 25 (52%)	1
	Frequent *ba-*	7 / 25 (28%)	18 / 25 (72%)	.04
	Frequent *ni-*	14 / 25 (56%)	11 / 25 (44%)	.69
Non-Neutralizing	50–50	12 / 24 (50%)	9 / 24 (38%)	–[a]
	Frequent *ba-*	**21 / 25 (84%)**	**4 / 25 (16%)**	**$<$ .0056**
	Frequent *ni-*	14 / 26 (54%)	12 / 26 (46%)	.85
Neutralizing	50–50	9 / 25 (36%)	16 / 25 (64%)	.23
	Frequent *ba-*	10 / 25 (40%)	15 / 25 (60%)	.42
	Frequent *ni-*	14 / 25 (56%)	11 / 25 (44%)	.69

[a] Three participants in the 50–50 Non-Neutralizing condition matched the 50–50 training ratio exactly, so we did not conduct a sign test for this condition. Hypothetically, this was possible in other conditions as well, but in practice it never occurred. Because we excluded major errors and timeout trials from the analysis, few participants had the full 60 test trials in the analysis, making it much less likely that there would be an exact match to the training ratio.

examine how individual participants used the two prefix options. If there was a tendency to shift away from *ni-* when it triggered alternations, we should see that individual participants tended to use *ba-* more often, and *ni-* less often, relative to the training frequency whenever *ni-* triggered alternations. Table 6 shows the number of participants who used a greater proportion of *ba-* and *ni-* responses, respectively, compared to training, according to Alternation Type and Prefix Frequency conditions.

Following Culbertson et al. (2012), we conducted a one-sample sign test for each condition. To correct for multiple comparisons, we used a Bonferroni-adjusted alpha level of .0056 (i.e., .05 / 9). Assuming participants were unbiased and engaged in probability matching, we would expect about half of them to overuse one prefix and half to overuse the other. In the Frequent *ba-* Non-Neutralizing condition, 21 out of 25 participants (84%) used *ba-* more often in their output than it was observed in the input ($p < .0056$), indicating a significant tendency for participants to shift away from *ni-*. This is the same condition that showed higher use of the frequent prefix (*ba-*) in the aggregate results (see Fig. 2). There was no significant preference to overuse either prefix in the other conditions, consistent with probability matching behavior. Therefore, the individual results support the findings from the aggregate results: participants generally engaged in probability matching behavior, but they shifted away from the *ni-* prefix when it triggered (non-neutralizing) alternations and was also infrequent.

3.2. Application of palatalization rule

In this section, we turn to the question of how well participants learned to apply the palatalization rule (stem-initial [k] or [g] is palatalized when preceded by the *ni-* prefix) in the Non-Neutralizing and Neutralizing conditions. (Recall that the palatalization rule did not apply in the No Alternation condition). Fig. 3 shows how often participants in the Non-Neutralizing and Neutralizing conditions applied the palatalization rule to velar-initial stems when using *ni-* (where the rule should have applied) and *ba-* (where applying the rule was an overgeneralization error).

The results were analyzed using mixed effects logistic regression models predicting application of the palatalization rule, following the general method described in Section 3.1. We created a separate model for trials in which participants used *ni-* in their responses (predicting correct application) and trials in which participants used *ba-* (predicting overgeneralization errors). The initial model for both cases contained fixed effects for Alternation Type (Non-Neutralizing or Neutralizing), Prefix Frequency (50–50, Frequent *ba-*, or Frequent *ni-*), and their interaction. The model for *ni-* included random intercepts for Subjects and Stems, and the model for *ba-* included random intercepts for Subjects; these were the maximal random effects structures that would converge. In both cases, we used a backwards stepwise comparison procedure to select the final model.[10]

Table 7 shows a summary of the fixed effects for the final model predicting the correct application after *ni-*. A likelihood ratio test indicated that the Alternation Type by Prefix Frequency interaction effects did not significantly improve the model fit, $\chi^2(2) = 4.02$, $p = .13$, and these were therefore removed from the model. Prefix Frequency was also removed from the model as it did not significantly improve the model fit, $\chi^2(2) = 1.54$, $p = .46$. The effect of Alternation Type was significant, according to both the likelihood ratio test, $\chi^2(1) = 10.48$, $p = .001$, and the Wald z test reported in the model summary (see Table 7). The significant effect of Alternation Type indicates reduced application of the palatalization rule after *ni-* in the Neutralizing condition compared to the Non-Neutralizing condition.

Table 8 shows a summary of the fixed effects for the final model predicting the incorrect application after *ba-* (overgeneralization errors). A likelihood ratio test indicated that the Alternation Type by Prefix Frequency interaction effects did not significantly improve the model fit, $\chi^2(2) = 0.71$, $p = .70$, so they were removed from the model. Both the individual effects of Alternation Type ($\chi^2(1) = 8.84$, $p < .01$) and Prefix Frequency ($\chi^2(2) = 31.19$, $p < .001$) significantly improved the model fit, so these effects were retained. The significant effect of Alternation Type indicates that there were more errors in the Neutralizing condition than in the Non-Neutralizing condition. The significant effect of the Frequent *ni-* condition indicates that, overall, there were more overgeneralization errors in the Frequent *ni-* condition compared to the 50–50 condition. The Frequent *ba-* effect was non-significant, meaning that the error rate was comparable in the Frequent *ba-* and 50–50 conditions.

Lastly, we examined how often participants incorrectly palatalized stems that did not start with velar consonants. Overgeneralization to non-velar consonants occurred in less than 1% of cases in all conditions (across Alternation Type and Prefix Frequency conditions) when using either *ba-* or *ni-*; in other words, participants rarely overapplied palatalization to non-velar-initial stems in any condition.

[10] Beginning with the full model, we removed fixed effects one at a time, starting with the interaction effects, and then compared models with and without the effect of interest using a likelihood ratio test. Fixed effects that did not significantly improve the model fit were removed from the model. All models retained the same random effects structure as the full model (Barr et al., 2013).

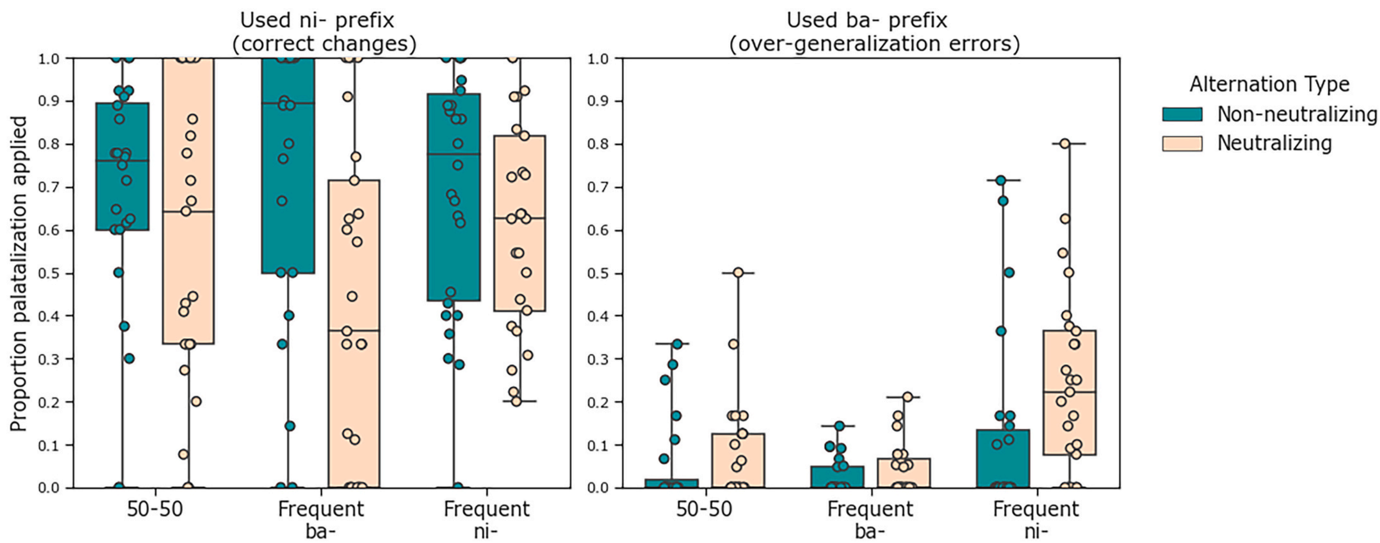

Fig. 3. Proportion of the time palatalization was applied to velar-initial stems when using *ni-* (left) and *ba-* (right).

Table 7
Summary of the fixed effects in the final model predicting correct palatalization after *ni-*.

Fixed effect	Estimate	Standard error	Wald *z*	*p*-value
(Intercept)	**1.30**	**0.22**	**5.80**	**< .001**
Neutralizing	**−0.98**	**0.30**	**−3.30**	**< .001**

Note: The reference group (intercept) is the 50–50 Non-Neutralizing condition. R code for the final model: glmer(AppliedPalatalization ~ AlternationType + (1|Subject) + (1|Stem), data = ni-data, family = binominal).

Table 8
Summary of the fixed effects of the final model predicting overgeneralization errors after *ba-*.

Fixed effect	Estimate	Standard error	Wald *z*	*p*-value
(Intercept)	**−3.74**	**0.36**	**−10.29**	**< .001**
Neutralizing	**0.90**	**0.30**	**2.96**	**< .01**
Frequent *ba-*	−0.72	0.39	−1.86	.06
Frequent*ni-*	**1.36**	**0.35**	**3.85**	**< .001**

Note: The reference group (intercept) is the 50–50 Non-Neutralizing condition. R code for the final model: glmer(AppliedPalatalization ~ AlternationType + PrefixFrequency + (1|Subject) + data = ba-data, family = binominal).

To summarize, participants were poorer at learning to apply the palatalization rule to velar-initial stems in the Neutralizing condition than in the Non-Neutralizing condition. They made more mistakes both by applying the rule less often after *ni-* (where it should have applied) and applying it more often after *ba-* (where it should not have applied).

3.3. Debriefing comments

After the experiment, participants were asked during debriefing to describe their thought process and response strategies. The comments were recorded by the experimenter and were subsequently coded according to how much detail participants were able to express about the phonological rule that they had learned, using an ordinal scale with values from 1 (least detailed) to 5 (most detailed). The results for the Non-Neutralizing and Neutralizing conditions are given in Table 9, along with the criteria used to code the responses. Responses were coded as the highest category for which they met the criteria. Responses in the No Alternation condition were not coded since no phonological rule was introduced in that condition.

We analyzed the distribution of the comments along the scale to get a sense of how well participants had internalized the phonological rule in the Non-Neutralizing and Neutralizing conditions. A Mann-Whitney *U* test found a significant difference between the Non-Neutralizing and Neutralizing conditions ($U = 3672$, $p < .001$). Participants in the Non-Neutralizing condition (median = 4) offered more detail about the rule than participants in the Neutralizing condition (median = 2). Whereas 39 of 75 participants (52%) in the Non-Neutralizing condition were able to offer some specific details about the target and/or trigger of the rule (i.e., level 4 or higher on the scale), only 13 of 74 participants (18%) in the Neutralizing condition were able to offer this level of detail. We did not find any overall difference in the detail of the comments between the three Prefix Frequency conditions (median = 3 in all three conditions, when aggregated across Alternation Type).

Although participants' self-reports during debriefing should be interpreted with a certain degree of skepticism, the debriefing comments are still suggestive, providing further support for the conclusion that participants in the Neutralizing condition learned the palatalization rule less well than those in the Non-Neutralizing condition.

4. Discussion

In this study, we required participants to learn a probabilistic prefix selection pattern in an artificial language while (in some conditions) also learning a phonological rule triggered by one of the two prefix options. Our aim was to test (a) whether the fact that one prefix option (but not the other) triggered a phonological rule would lead participants to prefer the non-triggering prefix option, (b) whether making it such that the rule created homophony would alter either its learnability or its effect on prefix selection, and (c) how each of these effects would be impacted by the frequency of the rule-triggering prefix. To summarize the results, we found that participants generally showed probability matching behavior on the prefix selection pattern; that is, the relative frequency of the two prefix variants in participants' responses closely matched their relative frequency in training (consistent with Hypothesis 1 outlined in Section 1.4). There was one exception to this generalization: participants shifted away from the variant that triggered the

Table 9
Breakdown of participants' comments during debriefing along with coding criteria.

Scale value	Coding criteria	Non-neutralizing condition				Neutralizing condition			
		50–50	Freq *ba-*	Freq *ni-*	**Total**	50–50	Freq *ba-*	Freq *ni-*	**Total**
5.	Explicitly mentioned at least one of the phonological changes ($k \rightarrow ch$ or $g \rightarrow j$).	3	4	2	**9**	2	0	4	**6**
4.	Mentioned that *ni-* triggers a change, but *ba-* does not, without accurately describing any phonological changes.	9	10	11	**30**	2	4	1	**7**
3.	Mentioned that noun stems are changed, but nothing about the specific sounds or triggers involved.	4	1	4	**9**	3	6	9	**18**
2.	Mentioned two different options for plural forms but did not specifically mention that a change occurred.	5	7	6	**18**	8	10	7	**25**
1.	Did not mention anything related to the phonological rule.	3	3	3	**9**	10	5	3	**18**

Note: One participant in the Frequent *ni-* Neutralizing condition declined to complete the debriefing and has been omitted.

phonological rule (*ni-*) when it was already infrequent during exposure, further boosting the frequency of the variant (*ba-*) that did not trigger the rule (partially consistent with Hypothesis 2). However, when the phonological rule created homophony, we saw a different effect. In that case, participants had greater difficulty learning the phonological rule (consistent with Hypothesis 4), and we no longer saw a shift away from *ni-* in prefix selection (contrary to Hypothesis 3). We discuss the implications of these findings in turn.

4.1. Probability matching

Our finding that participants generally matched the relative frequency of the prefix variants observed in training is consistent with previous work showing probability matching behavior in adults, including for artificial language patterns learned in the lab (e.g., Austin, 2010; Hudson Kam & Newport, 2005, 2009; Schuler, 2017), probabilistic native language patterns based on the lexicon (e.g., Ernestus & Baayen, 2003; Hayes et al., 2009), and non-linguistic patterns (e.g., Gardner, 1957; Weir, 1972). We did not see any general tendency to regularize the frequent variant in this study, which is consistent with previous work showing that adults are less likely than children to regularize their responses in language learning tasks (e.g., Austin, 2010; Hudson Kam & Newport, 2005, 2009; Schuler, 2017). This overall probability matching behavior is not particularly surprising given that (as mentioned above) adults often show probability matching behavior in these tasks; moreover, we designed the experiment with the goal of encouraging participants to use both prefix options. Task demands and experimental design strongly influence whether learners will show probability matching behavior in a given task (for a review, see Montag, 2021).

It is worth noting that adults do not always show probability matching behavior in artificial language learning tasks. For instance, Culbertson et al. (2012) found that adult learners showed a general tendency to regularize a probabilistic word order pattern in an artificial language as long as the pattern did not violate word order universals. This finding is particularly interesting because the current study used a similar experimental design to Culbertson et al.'s (2012), yet we did not find a general regularization tendency. The frequent variant in our study occurred at a similar relative frequency (66.7%) as it did in Culbertson et al.'s study (70%); however, it may be that the relative frequency threshold for triggering regularization behavior (as opposed to probability matching) with adult learners in this type of task is very close to that value (70%), with 66.7% being just under the threshold (Culbertson, p.c.). It could also be that the nature of the probabilistic pattern, such as whether it involves word/allomorph selection (e.g., as in the current study and Hudson Kam & Newport, 2005) or word order (as in Culbertson et al., 2012), has an impact on the tendency to regularize. The discrepancy between these studies highlights the need for more learning studies focusing on a wider variety of probabilistic language patterns.

4.2. Under-use of the rule-triggering prefix, paradigm uniformity, and stem faithfulness

We predicted that when the *ni-* prefix triggered a phonological rule, it would cause participants to under-use *ni-* in their responses in order to avoid a phonological alternation. We found that participants did shift away from *ni-*, but only when *ni-* was already the infrequent prefix in the input (and when the rule was non-neutralizing, an issue we return to below). When *ni-* was at least as frequent as the alternative, there was no tendency to shift away from *ni-* when it triggered a phonological rule. Individual results suggested that the pattern observed in the aggregate results is robust, with 21 out of 25 participants in the Frequent *ba-* Non-Neutralizing condition using *ni-* less often than it occurred in training. A reduction in the use of *ni-* was found in that condition even though participants had high accuracy (74% on average) at applying the rule when they did use *ni-*. This result cannot be attributed to the scoring system because participants did not receive any points for using the correct unpalatalized *ba-* form when the alien used a palatalized *ni-* form, so the scoring would have in fact discouraged them from shifting to *ba-* if it had any effect. (We revisit the potential effects of the scoring system in Section 4.5).

The finding that learners in our study sometimes avoided using *ni-* when it triggered a phonological rule is consistent with the view that learners favor paradigm uniformity, meaning that they prefer morphemes to have the same phonological form across the contexts in which they appear (Hayes, 2004; Steriade, 2000). Paradigm uniformity effects have been found in a number of artificial language experiments with adults (Kapatsinski, 2009, 2010, 2013; McMullin & Hansson, 2019; Smolek, 2019; Smolek & Kapatsinski, 2018; Stave et al., 2013; White, 2013, 2014) and children (Tessier, 2012). Much of the previous research on paradigm uniformity has focused on the application of a phonological rule itself, that is, whether a rule is under-applied (alternation avoidance) or over-applied (overgeneralization) in order to make members of a paradigm more similar to one another (see Smolek, 2019 for discussion of these two paradigm uniformity effects). In the current study, we saw that this pressure also influenced which morphological construction was used when participants had the option of one that triggered, and one that did not trigger, an alternation; similar effects have been found in adult artificial language experiments by Stave et al. (2013) and Smolek (2019, ch. 5).[11] This finding echoes the results of Do (2018), who studied Korean children's production of irregular verbal inflections in their native language. Do found that the older children in her study (6- to 7-year-olds) preferred to use an alternative morphological construction,

[11] See (Kapatsinski, 2018, ch. 8) for discussion about whether these effects are due to avoidance of the affix that triggers the rule or overgeneralization of the non-triggering affix. In the current study, the two affixes occurred with the same relative frequency for all items (and all types of items) in exposure, so it is unlikely that the shift from *ni-* was due to overgeneralization of *ba-* from one context to another.

which did not require applying a phonological rule, rather than using the target construction that did require a rule, even though the children were highly accurate at applying the rule when forced to use the target construction. (See the discussion in Section 1.1 for an example). The current study found a similar effect—a tendency to opt for an alternative construction as a way to avoid phonological alternations—with adult learners acquiring a novel phonological rule in an artificial language.[12]

We tested stem alternations in this experiment, raising the possibility that the effect was due to stem faithfulness rather than paradigm uniformity per se. Whereas paradigm uniformity would mean that participants in the experiment were biased to maintain similarity between singulars and plurals, a stem faithfulness bias would mean that participants had a preference to avoid stem changes specifically.[13] Both explanations can account for a preference to avoid alternations to the stem. The main difference between these concepts in terms of their predictions is that paradigm uniformity predicts learners should sometimes use the palatalized stem form in contexts where it should not be palatalized (i.e., after *ba-*), whereas stem faithfulness would not predict this type of overgeneralization. We did find a non-trivial amount of overgeneralization after the *ba-* prefix, especially when *ni-* was frequent, which provides some support for the paradigm uniformity account over the stem faithfulness account. It is worth noting, however, that overgeneralization could be caused by a different mechanism even if there is a stem faithfulness preference (see Section 4.3).[14] There are also some aspects of the experimental design that encourage *stem perseveration*, which has been argued to be a production-based mechanism that underlies many stem faithfulness effects (Kapatsinski, 2013, 2018; Smolek, 2019; Stave et al., 2013). For instance, participants produced their responses orally, and we also required participants to first memorize all of the stems before learning the prefixes and phonological rule; both of these factors would encourage stem perseveration.

The interaction with frequency that we observed is reminiscent of findings by Hudson Kam and Newport (2009), who examined the effect of increased complexity on learners' tendency to regularize a probabilistic language pattern. They taught adult participants an artificial language with one main noun determiner (occurring in 60% of cases) and some number of infrequent alternatives (depending on condition); in addition, the alternatives were either consistent (i.e., each infrequent determiner was always used with a specific noun) or inconsistent (i.e., the alternatives were 'noise' determiners that varied randomly). They found an interaction between frequency and consistency: participants began to regularize when the alternatives became infrequent and there was also a lack of consistency. Both were needed to induce regularization. Taken together, the results from Hudson Kam and Newport (2009) and the current study suggest that having a combination of two factors—low frequency of the alternative(s) in addition to some other factor that further disfavors the alternative(s)—makes regularization in adult learners more likely. These results highlight the need for more studies that incorporate frequency when testing for the effects of other biases on language learning, given the complex ways that these factors can interact with each other.

We did not find any difference in *ni-* usage depending on whether the stem began with a velar (which would have been affected by palatalization) or with other sounds. The reduced use of *ni-* that we saw in the Frequent *ba-* Non-Neutralizing condition was a global one, in that it occurred with both velar-initial stems and other types of stems. Kapatsinski (2010) compared various models on their ability to account for velar palatalization and suffix selection data from Russian loanword adaptation and from an artificial language experiment. He outlines two basic architectures for the interaction between affix selection and phonological rule application: (1) a one-stage model in which affix selection and phonological rule application happen simultaneously, and (2) a two-stage model in which affix selection occurs first, followed by phonological rule application. His data required a one-stage model to account for the fact that properties of the stem influenced affix selection. In the current study, the data suggest that participants were processing stimuli in a way more akin to a two-stage model, where they first selected a prefix form and then applied the phonological rule (or not) after it was concatenated with the stem, meaning that the likelihood of choosing each prefix was independent of the stem's features (and thus whether it would cause palatalization). Learning that *ni-* triggered palatalization reduced the likelihood that participants used *ni-* in the Frequent *ba-* Non-Neutralizing condition, but it did so for all stem types, not just velar-initial stems. The difference in these findings could be due to a left-to-right word planning strategy (e.g., Roelofs, 1996), given that the current study used prefixes whereas Kapatsinski's (2010) data involved suffixes.

Curiously, we did not see any shift away from *ni-* when it triggered a rule that was neutralizing and homophony creating (Neutralizing condition), even when *ni-* was infrequent, contrary to our Hypothesis 3. This may be due to the fact that participants were poorer at learning the rule in that condition; their accuracy at applying the rule when they used *ni-* was only 45% on average in the Neutralizing condition (compared to over 70% accuracy across all of the Non-Neutralizing groups). We discuss the effect of homophony in more detail in the following section.

4.3. Homophony avoidance

Participants showed poorer learning of the phonological rule when it created homophony. Specifically, participants in the Neutralizing condition were less likely to apply the rule when it should have applied (i.e., velar-initial stems after *ni-*), and they were more likely to make overgeneralization errors by applying the rule incorrectly after *ba-*, compared to those in the Non-Neutralizing condition. The impaired learning of the neutralizing rule was found across all three of the Prefix Frequency conditions. These behavioral results were supported by the participants' statements during debriefing, where those in the Neutralizing condition were less able to give details about the rule compared to those in the Non-Neutralizing condition. Because the phonological rule was identical in the two conditions (as well as all other aspects of the design), the greater difficulty in learning the rule in the Neutralizing condition must be due to phonological neutralization and/or homophony, not something inherent to the phonological rule itself.

These findings provide further support for the idea that phonological rules are disfavored in learning when they create homophony (Yin & White, 2018). Yin and White (2018) found that the learnability of phonological rules was significantly reduced when those rules were phonologically neutralizing compared to when they were non-neutralizing, but only when the neutralizing rules created homophony. In their study, participants learned fully deterministic patterns involving four phonological rules, two of which were neutralizing (counterbalanced), and were then given a forced-choice test to determine if they had internalized where to apply the rules. There was no difference between neutralizing and non-neutralizing rules in the absence of homophony, but adding homophony caused the neutralizing rules to be learned more poorly (and no better than chance level in the condition with the most homophony). In the current study, we did not compare neutralizing rules that create homophony to ones that do not,

[12] Despite the similarity, it is important to note that there are fundamental differences in how adults and children learn language (e.g., see Austin, 2010; Schuler, 2017), so we should be careful about concluding that the same mechanism is responsible for both. It would be useful to test for a similar effect with children learning an artificial language.

[13] A general alternation avoidance bias is also possible, but a recent study by Finley (2015) suggested that adults tend to avoid alternations to stems, not alternations in general, in artificial language learning. We only tested stem changes and thus cannot distinguish general alternation avoidance vs. stem faithfulness.

[14] The scoring system also may have (unintentionally) encouraged overgeneralization of the palatalization rule to the *ba-* forms.

but our results confirm that learning a phonological rule that is both neutralizing and homophony creating is more difficult than learning a rule that is non-neutralizing. The fact that we have found the same effect in a very different task than Yin and White (2018)—a production task (rather than a forced-choice test) combined with a probabilistic prefix selection task—adds to the robustness of this finding. It is also notable that we found a strong effect of homophony even though we used a small number of stems, with only four of them being involved in the homophony creation.

In previous work also involving artificial language experiments with adults, Kapatsinski (2009, 2012, 2013) argued that the addition of cases exemplifying neutralization (and homophony creation) can either increase or decrease the tendency to apply a phonological rule, depending on the nature of the task. In a task designed to encourage source-oriented generalizations (Kapatsinski, 2009, ch. 3), the results indicated that adding 20 extra trials showing [tʃ]- and [dʒ]-final noun stems taking an *-i* plural suffix reduced the likelihood that participants applied palatalization to velar-final stems, similar to the results of the current study. Kapatsinski suggested that this occurred not due to the neutralization/homophony per se, but because the 20 extra trials of [tʃ] → [tʃi] provided further support for a general source-oriented generalization for forming plurals, 'C → Ci', which competed with the more specific velar palatalization schema, [k, g] → [tʃi, dʒi]. In a task designed to encourage product-oriented generalizations (Kapatsinski, 2009, ch. 4), the addition of extra trials showing [tʃ] → [tʃi] had the opposite effect, increasing the application of velar palatalization. In this case, Kapatsinski argued that the increase was due to greater support for the general product-oriented generalization 'plurals end in [tʃi]', which promoted both [tʃ] → [tʃi] and [k] → [tʃi] cases.

The current study differed from Kapatsinski's experiments in that, rather than adding additional trials to demonstrate neutralization, we converted the [t]- and [d]-initial stems into [tʃ]- and [dʒ]-initial stems. Therefore, the reduction that we see in the application of palatalization cannot be due to increased support for a general source-oriented generalization 'C ⟶ ni-C' because evidence for this generalization would be identical in our Neutralizing and Non-Neutralizing conditions. Although changing the [t]- and [d]-initial stems into [tʃ]- and [dʒ]-initial stems in the Neutralizing condition would have provided some additional support for the general product-oriented generalization 'plurals begin with *ni-tʃ/dʒ*' (which favors velar palatalization), we saw a reduction in velar palatalization in the Neutralizing condition, not an increase. Our results indicate that homophony inhibits the ability to learn a phonological rule even if there is not increased support for competing (more general) source-oriented generalizations, suggesting that there is something about homophony specifically that makes it more difficult for learners to extract phonological rules (consistent with the findings of Yin & White, 2018). Requiring participants to memorize the stems before learning the prefixes and phonological rule may have enhanced the effect of homophony in this study by highlighting the fact that the rule was creating two-to-one mappings (i.e., distinct lexical items mapped to a single plural form) when homophony was created.

4.4. Overgeneralization of palatalization

We found some overgeneralization of the palatalization rule to cases where the *ba-* prefix was used, even though participants never encountered the palatalization rule being applied after *ba-* during training. The overgeneralization was higher when *ni-* was frequent and especially in the Neutralizing condition, which is noteworthy given that correct palatalization (after *ni-*) was applied less often in the Neutralizing condition.

One possible explanation for the overgeneralization is that participants were learning some product-oriented generalizations; however, there is not much evidence that product-oriented generalizations played a large role in this experiment. First, the overgeneralization cannot be due to the generalization 'plurals begin with *ba-*[tʃ/dʒ]' because although training for the Neutralizing condition did include some instances of the sequences [batʃ] and [badʒ] at the beginning of plurals, there were more examples of these sequences in the Frequent *ba-* condition (8/60 trials; 13%) than in the Frequent *ni-* condition (4/60 trials; 7%). However, overgeneralization of palatalization to *ba-* forms was much higher in the Frequent *ni-* condition than in the Frequent *ba-* condition, suggesting that exposure to [batʃ] and [badʒ] during training was not the primary cause of the overgeneralization. Second, participants could have learned a different product-oriented generalization such as 'plural *stems* begin with [tʃ/dʒ].' This type of generalization could be described as a 'prosodic template' for plurals, saying that plurals should have the general shape CV-{*tʃ/dʒ*}VCV (Kapatsinski, 2018, ch. 7). There were more cases of [tʃ] and [dʒ] in plurals overall in the Frequent *ni-* condition (28/60 trials; 47%) than in the Frequent *ba-* condition (20/60 trials; 33%), so this could potentially explain the greater overgeneralization in the Frequent *ni-* condition. However, given that the generalization 'plural stems begin with [tʃ/dʒ]' also supports palatalization after *ni-*, the fact that correct application after *ni-* was *lower* in the Neutralizing condition suggests that participants were not primarily relying on this generalization.

Another aspect of the results that raises doubts about participants learning product-oriented generalizations is that we saw virtually no overgeneralization of palatalization to non-velar sounds in this experiment (1% or less in all conditions). Previous experiments looking at palatalization before an *-i* suffix (Kapatsinski, 2009, 2012, 2013) found a high amount of overgeneralization to non-velars, particularly [t] and [d]. Our Neutralizing condition did not have [t]- and [d]-initial stems (they were converted to [tʃ] and [dʒ]), but in the Non-Neutralizing condition, overgeneralization to these sounds was less than 1%. A strongly weighted product-oriented generalization such as 'plural stems begin with [tʃ/dʒ]' should cause some overgeneralization of palatalization to non-velars because it does not care about the source (i.e., the singular stem consonant). These observations suggest that this experiment heavily favored source-oriented generalizations over product-oriented generalizations. According to Kapatsinski (2009, 2012), tasks that highlight the connection between the source and the product (i.e., the singular and plural forms in this case) are more likely to favor source-oriented generalizations. The current study required participants to memorize a small number of stems (10 stems) and their meanings (pictures) before being exposed to the plural forms. This memorization of the stems likely made the singular-plural pairs very salient for participants, even though the singulars and plurals were not presented near each other in time, therefore favoring source-oriented generalizations over product-oriented generalizations.

A general paradigm uniformity bias (e.g., Hayes, 2004; Steriade, 2000) could lead to some overgeneralization to velar-initial stems after *ba-*, in addition to causing the shift away from *ni-* that we saw in the Frequent *ba-* Non-Neutralizing condition. It also would (correctly) *not* predict overgeneralization to non-velar sounds because paradigm uniformity would only affect stems that have a member of their paradigm which undergoes the rule; for instance, because there is no form of the stem *puti* that undergoes palatalization, there would be no pressure to overgeneralize the rule to it. A general paradigm uniformity bias therefore appears to offer the best match to the data overall.

Finally, we still found more overgeneralization to *ba-* in the Neutralizing condition than in the Non-Neutralizing condition (across the three Prefix Frequency conditions). This suggests that part of the overgeneralization was due to the presence of homophony, which seemingly made it difficult for participants to confidently extract the trigger of the rule. This conclusion is reinforced by the participant self-reports at the debriefing, where 61/74 participants (82%) in the Neutralizing condition did not even mention that the trigger of the rule was *ni-*, compared to only 36/75 (48%) in the Non-Neutralizing condition. Although self-reports may not be accurate reflections, the difference is certainly suggestive.

4.5. Potential effects of the scoring system

A potential limitation of this study is that the scoring system was not implemented as intended due to a coding error; however, it is unlikely that this error confounded our results of interest. Recall that in the prefix test phase, participants received 10 points for a correct response that matched the alien's production, 5 points for a response with the same stem form as the alien's production but a different prefix, and 0 points for any other response. This error in the scoring system meant that, for velar-initial stems only, participants received partial credit for certain incorrect responses (e.g., alien said: *ni-chimu*, participant said: *ba-chimu*) and 0 points for correct alternatives to the alien's utterance (e.g., alien said: *ni-chimu*, participant said: *ba-kimu*). The error in the scoring system only affected cases where the participant's response had a different stem form (palatalized or non-palatalized) than the alien's utterance. Therefore, the No Alternation groups and the trials with non-velar stems (in all conditions) were unaffected, given that these did not involve alternations of the stem. Note that participants always received full points for correct responses that matched the alien's utterance, as intended.

This (unintended) scoring system could have potentially affected the results in a couple of ways. The most likely impact is that it could have made the palatalization rule more difficult to learn by giving partial credit for overgeneralization errors after *ba-* (e.g., incorrect *ba-chimu* when the alien said *ni-chimu*) and underapplication errors after *ni-* (e.g., incorrect *ni-kimu* when the alien said *ba-kimu*). If participants were paying close attention to their score, it is possible that the overall rates of underapplication and overgeneralization of the rule were slightly higher than they would have been otherwise due to the partial reinforcement of these responses in the test phase. Crucially, however, the scoring system *cannot* explain the differences between the Neutralizing condition and the Non-Neutralizing condition in the rates of correct application or overgeneralization of the rule. The same scoring system was used in both conditions and thus cannot be the primary cause of these differences.

In terms of prefix selection, the scoring system might have added some noise to the responses, but it is unlikely to have pushed the results in a specific direction. For velar-initial stems, participants who learned to apply the palatalization rule correctly would have received full points for choosing the matching prefix (e.g., alien said: *ni-chimu*, participant said: *ni-chimu*) and 0 points for choosing the non-matching prefix (e.g., alien said: *ni-chimu*, participant said: *ba-kimu*). Participants who palatalized inconsistently (e.g., pseudo-randomly) would still get more points overall by using the frequent prefix more often than the infrequent one (as in the intended scoring system), given that they always received the full 10 points for a response that matched in both prefix and stem form. The scoring might have favored the frequent prefix more than the intended system (though we did not find a general tendency towards regularization in the results), but it did not systematically favor one prefix form over the other.

It is worth noting that the scoring could have only impacted the results if participants were paying close attention to the changes in their score. In their study of a probabilistic word order pattern, Culbertson et al. (2012) noted that participants behaved similarly when the feedback from the alien instructor and the associated scoring system were removed, suggesting that participants may not be strongly affected by seeing their score as feedback in this type of task. In addition, the error affected only velar-initial stem trials in the final test phase, which occurred after the training block where participants were exposed to the rule and the prefix pattern. Participants never heard the alien actually produce incorrect responses in any of the training or test phases. Finally, no participants mentioned any oddities in the scoring in their debriefing comments. Overall, we conclude that although the error in the scoring system could have influenced the results, particularly in terms of making the palatalization rule more difficult to learn in general, the effect of the scoring is likely small and cannot explain the differences that we found between conditions.

4.6. Conclusions and future directions

We draw two main conclusions from this study. First, a phonological rule that creates homophony is harder to learn than one that does not create homophony (at least for adults in an artificial language). This result was found across the three frequency conditions tested, and it could not be attributed to greater support for a 'no change' generalization in the input (cf. Kapatsinski, 2009, Kapatsinski, 2012). Finding a strong effect of homophony on rule learning in a very different task than the one used by Yin and White (2018) adds robustness to the finding. We are unaware of any experimental studies specifically comparing the learnability of homophony-creating and non-homophony-creating phonological rules in young children. Given that the well-known mutual exclusivity bias (e.g., Merriman, Bowman, & MacWhinney, 1989), which could be related to homophony avoidance (Yin & White, 2018), has been displayed by children as young as 17 months old (Halberda, 2003), it is an interesting question for future work to confirm whether this homophony avoidance effect also occurs when children learn phonological rules.

Our second conclusion is that adult learners have a preference to avoid phonological alternations, and this preference could influence which morphological constructions are used when multiple constructions are possible. However, the frequency of the options appears to be an important factor in this effect; we only found a shift away from the rule-triggering construction when it was already infrequent. The pattern of overgeneralization in the experiment suggests that a general paradigm uniformity bias (e.g., Hayes, 2004; Steriade, 2000) is a better explanation for the alternation avoidance in this study compared to alternatives (i.e., stem faithfulness or stem perseveration). This finding supports Do's (2018) conclusions from an experiment with Korean children, who used alternative constructions to avoid phonological alternations. Given the large differences in how adults and children learn frequency-based patterns (e.g., Austin, 2010; Schuler, 2017) more studies investigating this type of effect with children would be valuable.

Finally, the effects observed in this study also have implications for language change. Persistent biases, even if small, can have a large impact on a language over time, as generations of speakers subtly shift a language pattern in a certain direction (e.g., see Culbertson et al., 2012; Kalish, Griffiths, & Lewandowsky, 2007; Kirby, Smith, & Brighton, 2004; Moreton, 2008; Reali & Griffiths, 2009; White, 2017). If speakers have a slight preference to favor constructions that do not require a phonological alternation, then this could impact which vocabulary and constructions become dominant in a language over time as new words and phrases are introduced (and die out). Moreover, our finding that learners find it more difficult to learn phonological rules that cause homophony supports the idea that learning is one mechanism that could inhibit phonological rules that cause large amounts of homophony from developing in a language, as suggested by Yin and White (2018).

CRediT authorship contribution statement

Hanbyul Song: Data curation, Formal analysis, Visualization, Writing – review & editing. **James White:** Supervision, Conceptualization, Methodology, Formal analysis, Resources, Visualization, Writing – review & editing.

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Appendix: List of stimuli.

Stem	*ba-* form	*ni-* form		
		No alternation condition	Non-neutralizing condition	Neutralizing condition
puti	*ba-puti*	*ni-puti*	*ni-puti*	*ni-puti*
bagu	*ba-bagu*	*ni-bagu*	*ni-bagu*	*ni-bagu*
***t**imu* / ***ch**imu*	*ba-**t**imu* / *ba-**ch**imu*	*ni-**t**imu*	*ni-**t**imu*	*ni-**ch**imu*
***d**api* / ***j**api*	*ba-**d**api* / *ba-**j**api*	*ni-**d**api*	*ni-**d**api*	*ni-**j**api*
mipa	*ba-mipa*	*ni-mipa*	*ni-mipa*	*ni-mipa*
niba	*ba-niba*	*ni-niba*	*ni-niba*	*ni-niba*
***k**imu*	*ba-**k**imu*	*ni-**k**imu*	*ni-**ch**imu*	*ni-**ch**imu*
***g**api*	*ba-**g**api*	*ni-**g**api*	*ni-**j**api*	*ni-**j**api*
***k**uta*	*ba-**k**uta*	*ni-**k**uta*	*ni-**ch**uta*	*ni-**ch**uta*
***g**aku*	*ba-**g**aku*	*ni-**g**aku*	*ni-**j**aku*	*ni-**j**aku*

Note: Stem forms *timu* and *dapi* occurred only in the No Alternation and Non-Neutralizing conditions. Stem forms *chimu* and *japi* occurred only in the Neutralizing condition (replacing *timu* and *dapi*).

Appendix A: Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2022.105170.

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