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Tracking phonological regularities: exploring the influence of learning mode and regularity locus in adult phonological learning

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Abstract: Research on phonological learning has shown that adult learners are capable of effectively tracking regularities in phonological patterns. In our study, we investigated the dynamics of the learning process for regularity tracking. Adult learners participated in a phonological learning experiment where they acquired vowel harmony rules for forming plurals. The experiment had four conditions, varying in learning mode (goal-oriented vs. exploratory) and the locus of phonological regularity (phonotactics vs. alternation). When learners had no explicit learning goal and when the language involved random alternation patterns, their learning process showed a strong preference for regularity. This suggests that the application of statistical learning metrics is influenced by two factors: greater uncertainty in the exploratory conditions compared to the goal-oriented conditions, and a stronger inclination to avoid irregularities in alternation compared to phonotactics.

Keywords: statistical learning; regularities; phonology; phonotactics; alternation

1 Introduction

Human learners can track the regularities of the perceptual input (Cook et al. 2011; Schulz 2015), and linguistic regularities are not an exception (Aslin and Newport 2008; Gómez and Gerken 2000; Jurafsky 1996; Saffran et al. 1997). Natural languages exhibit both regular and irregular phonological patterns (e.g., Kornai 1987; Vago 1976), and many experimental studies have explored how phonological (ir)regularities are acquired in a laboratory setting (Baer-Henney et al. 2015; Finley 2015, 2021; Hughto et al. 2019; Zuraw 2000). We note that all previous studies examined "learning outcome" as a proxy for understanding statistical learning metrics used in learning phonological regularities (e.g., Skoruppa and Peperkamp 2011; Szagun et al. 2007). Learning outcome as such reflects the working of statistical learning, thus it is an important clue to understanding how regularities are acquired. However, if learners tackle a phonological learning problem by resorting to statistical reasoning – that is, using a metric related to the counting of statistical regularities – not only the learning outcome but also the "learning process" should reflect the working of the statistical learning metric. Statistical learning, by definition, refers to the process of extracting a probabilistic structure from input, and learning progresses as learners induce the shapes of concrete elements to learn about a system's regularity (for a review, see Romberg and Saffran 2010).

The current study examines adult learners' process of tracking phonological regularities and the factors that influence this process, specifically learning mode and locus of phonological regularity. In the context of language learning modes, "inductive and explicit learning" is commonly characterized by the inclusion of explicit encouragement for learners to discover rules within a specific domain, along with their awareness of these rules (Dulany et al. 1984; Reber and Allen 1978). While the precise definitions and working of "implicit" and "explicit"

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learning have been subject to ongoing debate (DeKeyser 2003; Ellis 1994; Moreton and Pertsova 2016), this study differentiates the learning modes specifically based on whether the learning goal is explicitly stated in the instruction (see more details in Sections 2.2 and 2.4).

The second factor we aim to investigate is whether the phonological (ir)regularity is manifested in phonotactics or alternation, two of the major components of phonological knowledge (Hayes 2004). The reason we take the locus of (ir)regularity into account in the exploration of the learning process is that the two types of phonological knowledge are argued to be acquired using different learning modes and strategies: phonotactic learning is facilitated by implicit and unsupervised training (cue-based), whereas alternation knowledge is acquired through more explicit and supervised ways (rule-based) (Moreton et al. 2017). Given the potentially different mechanisms underlying phonotactics and alternation learning, we expect learners to react differently to phonotactic and alternation (ir)regularities in the learning process.

Our study focuses on the process of learning vowel harmony regularities, presented in both phonotactic and morphophonological alternation forms. We employ an artificial language learning paradigm.

2 Methods

2.1 Participants

Students from the first author's institute (N = 198) were recruited. They were all native speakers of Hong Kong Cantonese with no hearing impairments or color vision deficiencies. They were given either extra course credits or a cash reward for participation. We manually filtered out participants who reported knowledge in languages exhibiting vowel harmony patterns (i.e., Japanese, Korean, Finnish, Hungarian, or Turkish). We removed a further 16 participants who consistently chose only one of the two options throughout all five repetitions, and the remaining 182 participants' data entered the analysis (condition 1: N = 47; condition 2: N = 46; condition 3: N = 42; condition 4: N = 47).

2.2 Design and predictions

Our experiment[1] followed a two-by-two factorial design, yielding four experiment conditions differing in the learning mode (goal-oriented vs. exploratory) and the locus of phonological irregularity (phonotactics vs. alternation; see Table 1), to which participants were randomly assigned. In the goal-oriented conditions, participants were explicitly instructed to acquire the alternation rule for forming plurals. In the exploratory conditions, participants received no explicit instruction regarding the specific learning objective and were simply asked to learn a language. These two learning modes also differed in stimulus presentation: in the goal-oriented mode, the stem and its suffixed form were displayed together in one trial, whereas the exploratory mode presented the two forms of the same word in separate and randomized trials (further details are in Section 2.4). Phonological regularities were realized in phonotactics and/or alternation. Regularity in phonotactics was manifested through vowel harmony patterns among stem vowels, while alternation regularity was shown as the harmonic relation between the suffix vowel and the stem-final vowel (see Section 2.3). Irregularities, on the other hand, were implemented through a random mixture of vowel harmony and vowel disharmony patterns in phonotactics or alternation, exhibiting no dominant or regular pattern. A fully regular system contained vowel harmony patterns in both phonotactics and alternation domains, while partially regular systems exhibited vowel harmony patterns in either phonotactics or alternation. In each of the four conditions, a partially regular system was consistently paired with a fully regular system. Table 1 shows the specific locus of (ir)regularity in the partially regular system in each condition.

1 The experiment materials, data, and analysis can be found in the OSF link: https://osf.io/anf4u/.

Table 1: Design of the four experiment conditions. This table outlines the two factors: (i) learning mode and (ii) locus of phonological (ir) regularity in the partially regular system in each condition. In all conditions, the fully regular systems were completely regular in terms of both phonotactics and alternation. The alternative, the partially regular systems, differed in terms of phonotactic or alternation (ir)regularity as shown.

Learning mode	Locus of (ir)regularity in the partially regular system	
Goal-oriented learning	**Condition 1**: Regular phonotactics & irregular alternation	**Condition 2**: Irregular phonotactics & regular alternation
Exploratory learning	**Condition 3**: Regular phonotactics & irregular alternation	**Condition 4**: Irregular phonotactics & regular alternation

The experiment involved an encounter with an alien society on Planet Green and Planet Yellow. Planet Green consistently represented the fully regular option, while Planet Yellow represented the partially regular option, which varied depending on the specific condition assigned to participants, as outlined in Table 1. Participants were not informed about which planet corresponded to the fully regular system. They were told that they can learn the alien's language from both planets, but their urgent mission was to learn the alien language as soon as possible. The urgency nature of the task motivated the participants to strongly utilize statistical learning metrics by tracking the regularities exhibited in one of the two planets. Based on the existing literature, we had the following predictions:

- Goal-oriented mode (conditions 1 and 2): Learners will focus on regularity in the target patterns, specifically alternation. This is driven by the explicit learning goal and the cues that indicate paradigmatic regularity (see Section 2.4). As they progress in their learning, they will increasingly prefer the fully regular system as they detect and internalize regularity.
- Exploratory mode (conditions 3 and 4): Since learners in this mode are not bound by a specific learning goal and have the freedom to explore various aspects of the language, we expect that they will not show a consistent preference for either system, regardless of its locus of (ir)regularity.

2.3 Stimuli

Each training item in the artificial language contained a noun stem (CV.CV disyllable) and a plural suffix (CV monosyllable). Each system contained 24 unique stems. The fully regular system was a modified form following Finley (2020). The consonants included /pʰ, tʰ, kʰ, p, t, k, m, n/ and vowels were /i, u, e, o/. The fully regular system encompassed vowel harmony patterns in both phonotactics and alternation. Regarding phonotactic regularity, all items in the fully regular system demonstrated agreement in rounding between the two stem vowels, such as [kʰuko] but not *[kʰiko]. Each of the eight harmonic VV sequences (i.e., [u-u, o-o, u-o, o-u, i-i, e-e, i-e, e-i]) was embedded in three distinct stems. In terms of alternation regularity, the plural suffix alternated between [-vo] and [-ve] to match the stem-final vowels in [round], with half of the vowels agreeing in [+round] (e.g., [mutʰo-vo]) and the other half in [–round] (e.g., [tʰipʰe-ve]). The system with regular phonotactics but irregular alternation, utilized in conditions 1 and 3, was constructed by swapping the two consonants of the fully regular system's stems while preserving the vowel sequences (e.g., [**n**o**p**ʰu] → [**p**ʰo**n**u]). The swapped consonants in the stems ensured that the stimuli in the partially regular system were distinct from those in the fully regular system. By keeping the stem vowels unchanged, the regularity in phonotactics was maintained. The irregular alternation of this system involved half of the stems exhibiting harmonic allomorphs (e.g., [nupo-vo]), while the other half displayed disharmonic allomorphs (e.g., [nutʰu-ve]), devoid of any regular vowel harmony patterns. The system with regular alternation but irregular phonotactics, employed in conditions 2 and 4, was also created by exchanging the two consonants of the fully regular system's stems, for the same purpose of keeping stimuli distinct across the two systems. To introduce irregular phonotactics, half of the stems underwent a substitution of the first vowel with a vowel of the same height but with the opposite rounding feature, resulting in phonotactic irregularity (e.g.,

[m**e**pe] → [m**o**pe]). Regular alternation was maintained, with all the suffix vowels aligning with the stem-final vowels in terms of rounding.

The phonotactics test comprised eight testing pairs. Four stems with harmonic vowels were drawn from the fully regular system's stems as old items. Another four novel stems contained harmonic vowel sequences, and two consonants from the set /s, f, p^h, t^h, p, k/ (e.g., [sopo], [t^hefi]). In each novel stem, one of the consonants was a fricative (i.e., /s, f/), ensuring the novelty in the consonant skeleton. Irregular choices were created from the paired regular choices by substituting the first (N = 4) or the second vowel (N = 4) with one that had the same vowel height but opposite rounding value (e.g., [sop**o**] → [sop**e**]). The alternation test consisted of 12 pairs of plural items. We also selected four old stems from the fully regular system. For the other eight new stems, consonants were selected in the same way as in the phonotactics test. For all items, the rounding feature of the stem-final vowels was balanced. Each pair contained one item with a harmonic suffix and one with a disharmonic suffix (e.g., [fuki-ve] and [fuki-vo]). Each training item and pair of testing items was randomly paired with a unique visual referent of an alien image (Sporepedia 2022). A single alien represented a singular form and a configuration of three aliens displayed in triangle represented the plural.

A female bilingual English and Mandarin speaker with a formal training in phonetics provided the recording of stimuli. Stress was produced on the initial syllable in all stems. The recording was made using an Onyx Blackjack 2 × 2 in WAV format with a 48 kHz sampling rate and a 24-bit depth. All audio files were normalized to an average amplitude of 70 dB using Praat (Boersma and Weenink 2021).

2.4 Procedure

The experiment was programmed using PsychoPy3 and conducted online through Pavlovia (Peirce et al. 2019). Participants completed the experiment on their personal computers, with an average completion time of 30 minutes. They were advised to sit in a quiet environment and use headphones to minimize distractions. Prior to each trial, a fixation point appeared at the center of the screen for 0.5 seconds. The presentation order of stimuli was randomized both across rounds and participants. Visual stimuli accompanied the audio stimuli, and no written representation of the items was provided.

In the training phase, the stimuli were repeated in five rounds, allowing participants sufficient opportunities to explore the language patterns. In each trial, participants were asked to choose between Planet Green and Planet Yellow by pressing the corresponding keys on the keyboard. Planet Green always mapped on to the fully regular system and Planet Yellow consistently represented the partially regular system. Participants were not informed about the specific systems corresponding to the two planets. After making their selection, an audio file was played, accompanied by a picture of one alien (singular) and/or three aliens (plural). The experiment automatically advanced to the next trial after the audio and visual stimuli were presented. Participants in the goal-oriented conditions completed 24 trials per round, with the singular and plural forms presented together in the same trial, exhibiting paradigmatic relation of the two forms (Figure 1). This presentation design served to facilitate the learning of morphophonological alternation (Baroni et al. 2002; Kapatsinski 2012; Smolek 2020; Smolek and Kapatsinski 2023). In the exploratory mode, the singular and plural forms were shown in 48 separate and randomized trials per round. This means that participants saw either only a single alien or a group of three aliens in the center of the screen, accompanied by the corresponding audio file. However, the two forms of the same word never appeared in the same trial, providing cues that were less direct for the paradigmatic relation of singular and plural forms. This design allowed participants to freely allocate their learning efforts to explore other aspects of the language than alternation, such as phonotactics or lexical items. Consequently, there seemed to be less necessity for them to actively seek regularities or utilize statistical learning metrics to achieve a specific learning goal. Prior to the training phase, participants were informed that there would be five rounds of learning.

After the final training round, the experiment proceeded to a two-alternative forced-choice phonotactics test. Participants were shown a singular visual stimulus and were asked to choose the correct name from the two audio options they heard, which differed only in vowel harmony pattern (see Section 2.3). They were allowed to replay the audio by pressing the R key. No feedback was provided. The last phase was a two-alternative forced-

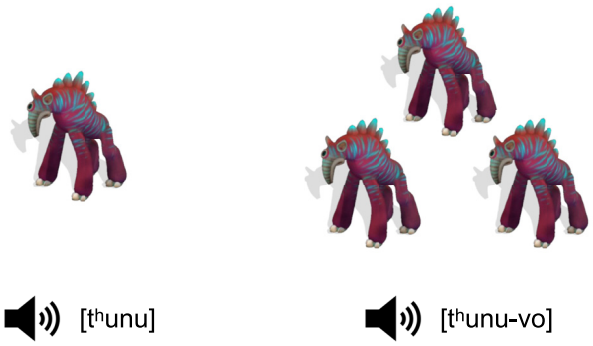

Figure 1: Still from a training trial of the goal-oriented mode. After participants chose from the two planets, a single alien picture appeared on the left side of the screen, accompanied by the audio of the singular form, followed by three aliens displayed on the right side of the screen with the audio of the plural form.

choice alternation test. Participants were presented with an audio of a singular alien, two possible options for referring to three aliens, and the corresponding visual referent of them. The options differed only in the suffixes. They were required to choose the correct plural form for three aliens. Other procedures and layout were the same as the phonotactics test. In both test phases, the position ordering of the two alternatives on the screen was counterbalanced and randomized across trials.

3 Results

3.1 Learning process

We first analyzed the learning processes of participants by focusing on how they chose planets throughout learning. Because of the experiment design, the learning mode (goal-oriented vs. exploratory) and the irregularity locus (phonotactics vs. alternation) might potentially play a role in the learning behaviors of the participants. Additionally, a participant's preference for a specific system (Planet Green for the fully regular system or Planet Yellow for the partially regular system) might change as the experiment went on. This suggests that the consecutive trial number could also have an influence. Because the number of trials per round differed across the goal-oriented and exploratory conditions (24 vs. 48), we scaled and centered the consecutive trials per participant. These three predictors – scaled trial number, learning mode, and irregularity locus – all entered the mixed-effects logistic regression model. We adopted the sum coding scheme[2] for the categorical variables, and the reference levels (coded as –1) were "exploratory" for learning mode and "phonotactics" for irregularity locus (i.e., condition 4). The dependent variable was the choice for the fully regular system (Planet Green; coded as 1) or the partially regular system (Planet Yellow; coded as 0). The maximal model that reached convergence and was justified by the experiment design included a three-way interaction among the three predictors, and by-participant varying intercepts and slopes of scaled trial number with intercept-slope correlation (Barr et al. 2013). As participants were free to choose between two sources of stimuli and thus might have different training exposure, the experiment design did not allow by-item random effects (see also Matuschek et al. 2017; Winter 2019: 241–244). Moreover, we did not implement by-participant random slopes for the other two predictors, learning mode and irregularity locus, as not all learners received the same instruction or regularity. The model we report here significantly outperformed the other models by Akaike information criterion (AIC) score. Figure 2 displays the predictions of the model.

The results (Table 2 in the appendix) show a significant positive intercept, which is indicative of an overall preference for the fully regular system. There is also a significant boosting effect for choosing the fully regular system, namely when the irregularity locus was alternation. This corresponds to conditions 1 and 3, where the partially regular systems involved regular phonotactics but irregular alternation. In other words, participants'

2 All of the categorical variables had only two levels, including those in the model of the test phase. All non-reference levels were coded as 1, following the sum coding approach.

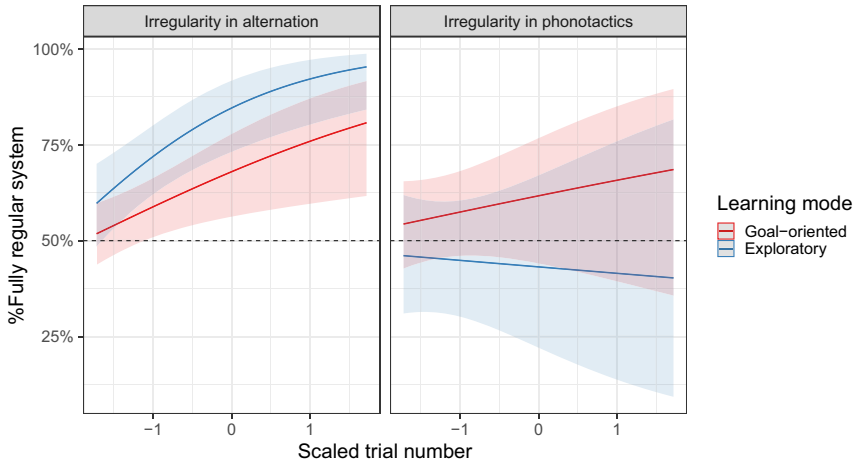

Figure 2: Predicted probabilities of the training choices and the interactions between learning mode, locus of irregularity, and progress within the experiment (scaled trial number). The left facet is the predictions for the conditions with irregularity in alternation (red: condition 1; blue: condition 3) and the right facet corresponds to irregularity in phonotactics (red: condition 2; blue: condition 4).

preference for the fully regular system was motivated by their avoidance of alternation irregularity. To confirm this effect, we ran a post hoc pairwise comparison with Tukey's HSD correction, probing into the interaction of learning mode and irregularity locus. The only significant comparison was between conditions 3 and 4 (β = 1.977, *SE* = 0.731, z = 2.705, p = 0.035), suggesting that in the exploratory mode, learners were especially more inclined to eschew irregular alternation (condition 3) but not irregular phonotactics (condition 4). No such significant contrast was found between conditions 1 and 2, suggesting that the avoidance of alternation irregularity only emerged in the exploratory mode but not in the goal-oriented mode. The main effect of irregularity locus is thus underpinned by the significant difference between conditions 3 and 4. In Figure 2, we observe that in condition 3 (blue line, left facet), the predicted rate of choosing the fully regular system was significantly above chance level and significantly higher than that of condition 4 (blue line, right facet). This indicates that while there was no overall main effect of learning mode, the exploratory mode was a necessary condition for learners to avoid alternation irregularity. The scaled trial number also had a significant positive effect, indicating that learners tended to increase their choice of full regularity as learning progressed. Since the categorical predictors were sum-coded, this main effect can reflect an overall upward tendency across the board (Brehm and Alday 2022). This tendency was consistent with our prediction, suggesting that learners increasingly adopted the statistical learning metric and tracked regularities.

3.2 Learning outcomes: the phonotactics test and alternation test

We examined the correlation between the learners' training and testing performances. There was a significant positive correlation between the rate of choosing the fully regular system during training and the rate of choosing vowel harmony options in the phonotactics test (r = 0.289, p < 0.001). By contrast, no such correlation was found between training and the alternation test (r = −0.021, p = 0.780). In other words, learners' acquisition of vowel harmony patterns in the two tests was influenced differently by exposure to regularities during the training phase. To account for this difference, we included test phase as a predictor in the mixed-effects logistic regression model. The dependent variable was the choice for the vowel harmony pattern (coded as 1) or the disharmony pattern (coded as 0). As predictors, we included learning mode (exploratory vs. goal-oriented), irregularity locus (phonotactics vs. alternation), test phase (phonotactics test vs. alternation test), percentage of choosing the fully regular system in the training phase (%, referred to as "training percentage" hereinafter), and item type (old vs. new item). The categorical predictors in this model were also sum-coded, and the reference levels (coded as −1) were the exploratory mode, irregularity in phonotactics, alternation test, and the old items. Ranking by AIC values indicated that the most ideal model had interactions between test phase and irregularity locus, and between test phase and training percentage. Additionally, we fitted by-participant varying intercepts and random slopes of test phase without intercept-slope correlation, as well as by-item varying intercepts. For the same reason as in the

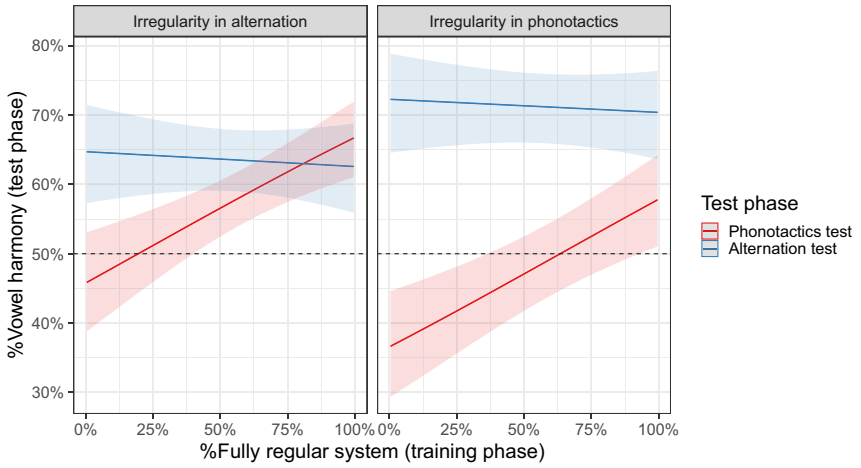

Figure 3: Predicted probabilities for the learning outcomes and the interaction effects of the two tests (left facet: conditions 1 and 3; right facet: conditions 2 and 4). Learning mode and item type were not included in the plot as they were not involved in interaction in the model.

training model, random slopes of learning mode and irregularity locus were not added. This was the maximal model justified by the experiment design that reached convergence. The results of the model are presented in Table 3 in the appendix and plotted in Figure 3.

The intercept of the model is significant and positive, indicating a higher likelihood of choosing vowel harmony as the response. This also suggests overall success in learning vowel harmony rules. The predictor of test phase has a significant negative effect, suggesting that the learners' acquisition of vowel harmony was less successful in the phonotactics test compared to the alternation test. This observation aligns with Figure 3, in which the predicted learning results for alternation (blue lines) were consistently better than those for phonotactics (red lines) in both facets. Additionally, there is a significant negative effect attributed to new items, indicating that the introduction of novel items decreased the application of harmony rules.

There are two significant interaction effects found in the analysis. The first is a significant positive interaction between irregularity locus and test phase. The result indicates that when participants were exposed to a partially regular system with regular phonotactics and irregular alternation patterns (conditions 1 and 3), they were more likely to choose vowel harmony patterns in the phonotactics test. This finding is not surprising, as these conditions by their design provided more input on phonotactic regularity. The second significant positive interaction is between training percentage and test phase. This suggests that learners' acquisition of vowel harmony in the phonotactics test was more dependent on their exposure to the fully regular system during training compared to the alternation test. This observation is consistent with the distinctly positive slopes of the predicted lines for the phonotactics test (in red) in Figure 3, while the lines for the alternation test (in blue) appear relatively flat. This effect is also congruent with the earlier correlation discrepancy we discussed, providing further support for the idea that learners relied more on exposure to regularity in learning phonotactics, while alternation learning required less regularity input.

4 Discussion

Research has demonstrated that from an early stage of learning, learners take an active role by selectively focusing on learning stimuli showing specific characteristics (Schulz and Bonawitz 2007; Sim 2016; Sim and Xu 2014). Specifically in language learning, it has been shown that children selectively prefer words with the phonemes they have already acquired while avoiding those beyond their phoneme inventory during early language acquisition stage (Schwartz and Leonard 1982). This study expands on the research about active learning in adults. It demonstrates that adult learners actively look for patterns and avoid irregularities when it comes to learning phonological patterns. They are guided by a statistical learning metric that helps them identify and understand these regularities. We have shown that two factors are relevant to this statistical learning strategy in their learning process: learning mode and locus of phonological (ir)regularity.

We expected that an explicit learning goal would result in more frequent regular choices (Aslin et al. 1999; Aslin and Newport 2012; Romberg and Saffran 2010; Saffran et al. 1999; Siegelman 2020). However, the goal-oriented conditions in the current study did not consistently lead to a higher selection rate towards the regularity of the target pattern. Moreover, we expected minimal or no differences in the choices between the fully and partially regular systems in the exploratory conditions where no explicit learning goal was provided. However, our findings revealed the opposite effect. When the learning task was not explicitly specified, learners showed a particular preference for the fully regular system. This suggests that in the absence of a specific learning goal, learners faced uncertainty and had to determine their own learning objective. As a result, they consistently chose alternation as the target pattern to learn and applied statistical learning strategies by avoiding irregularity in alternation.

The results indicate that a preference for statistical regularities only emerges in conditions involving a higher level of uncertainty in learning, such as learning a language compared to learning a specific aspect within a language, like plural formation. There is evidence in auditory stimulus learning suggesting that uncertainty regarding a learning stimulus, such as unexpected or irregular instances of a target pattern, hinders adults' perception and learning abilities (Niemi and Näätänen 1981; Nobre et al. 2007; Nobre and van Ede 2018). Instead, learning with certainty, characterized by high predictability of a target stimulus, has been shown to improve the processing performance of adult learners (Coull and Nobre 1998; Coull et al. 2000; Griffin et al. 2001, 2002; Miniussi et al. 1999; Nobre 2001). Specifically in the domain of phonological learning, it has been found that acquiring new and irregular phonological patterns poses a greater challenge compared to learning regular and predictable patterns (Agus and Pressnitzer 2013; Agus et al. 2010; Andrillon et al. 2015, 2017; Luo et al. 2013).

It should be noted that the higher degree of uncertainty in the exploratory conditions may not solely arise from the absence of an explicit learning objective. The two learning modes also differed in how they presented morphologically related forms, specifically singular and plural forms. In the goal-oriented mode, the singular and plural forms of the same word were presented side by side in the same trial, while in the exploratory mode, the morphologically related forms were displayed separately. The perceptual contiguity between morphologically related forms, as seen in the goal-oriented mode, has been shown to enhance the salience of differences and similarities between associated forms, thereby facilitating the acquisition of alternation patterns (Baroni et al. 2002; Kapatsinski 2012; Smolek 2020; Smolek and Kapatsinski 2023). Therefore, the absence of an explicit learning goal and the lack of close proximity in the presentation of paradigmatic mappings may have collectively contributed to the high level of uncertainty in the exploratory mode. This would have put pressure on the participants to strategically determine their own learning objective. The combination of these factors likely required participants to engage in more active statistical learning processes during the learning task.

Additionally, we also found that participants particularly tended to avoid irregularities in alternation. One reason could be that, even in the exploratory conditions where singular and plural pairs were not presented on a single page, the contrast between the two and their corresponding visual referents in the same round (a single alien vs. a configuration of three) still made the alternation across morpheme boundaries a more salient pattern compared to static phonotactic generalizations within a stem. Previous research suggests that such alternation patterns are more likely to attract learners' attention, leading participants to put in more effort to increase regularities (Kerkhoff 2004; Whang and Adriaans 2017; White et al. 2008; Zamuner et al. 2016). In addition, previous work consistently demonstrates that learners have a tendency to amplify patterns' regularities during the learning process, especially when these patterns are presented in perceptually salient phonological contexts (Ellis 2017; Gervain and Endress 2017). The current results may suggest that the contrast between singular and plural forms, even when nonadjacent, attracted learners' attention and motivated them to more actively apply statistical learning metrics and track phonological regularities.

Another sign that learners actively applied statistical learning strategies was the overall increase in preference for the fully regular system as learning progressed. Since there were five rounds of training with the same stimuli, learners had multiple opportunities to become familiar with the language patterns. After exploring the systems initially, they could identify the more reliable source of phonological regularities that supported their learning objective and use statistical learning metrics by favoring the fully regular system. The observed trend of increasing preference indicates learners' inclination to track phonological regularities.

Previous studies suggest that uncertainty hinders learning performance in auditory contexts. In our study, the absence of an explicitly stated learning objective and the lack of clear evidence in the exploratory mode increased uncertainty compared to the goal-oriented mode. In these uncertain learning conditions, participants felt pressure to minimize risks by selecting a perceptually salient pattern – that is, alternation – as the learning objective. They relied heavily on statistical learning metrics to maximize learning cues (paradigmatic mappings), resulting in a conservative approach to the artificial language learning task. Although the ways in which they utilized the statistical learning metric differed from our expectations, this study provides evidence that adult learners strategically use these metrics to enhance the regularities of a system when learning phonological patterns. The specific methods used vary depending on the learning mode and locus of phonological regularity.

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Appendix

Additional information on data analysis: We used R 4.3.0 “Already Tomorrow” (R Core Team 2022) as well as the following packages: tidyverse (Wickham et al. 2019), fs (Hester et al. 2021), here (Müller 2020), broom (Robinson et al. 2023), broom.mixed (Bolker and Robinson 2022), lme4 (Bates et al. 2015), lmerTest (Kuznetsova et al. 2017), partykit (Hothorn and Zeileis 2015; Hothorn et al. 2006; Zeileis et al. 2008), performance (Lüdecke et al. 2021), ggpubr (Kassambara 2023), ggsci (Xiao 2023), ggridges (Wilke 2022), sjPlot (Lüdecke 2023), and emmeans (Lenth 2023, for post hoc pairwise comparison).

Table 2: Mixed-effects logistic regression model for the training phase. Estimates are given in logit. $C = 0.91$.

Term	Coefficient	*SE*	*z* ratio	*p* Value	
(Intercept)	0.664	0.255	2.600	0.009	**
ScaledTrialNumber	0.315	0.151	2.084	0.037	*
$\text{LearningMode}_{\text{goal-oriented}}$	−0.050	0.255	−0.194	0.846	
$\text{IrregularityLocus}_{\text{alternation}}$	0.563	0.255	2.204	0.027	*
ScaledTrialNumber: $\text{LearningMode}_{\text{goal-oriented}}$	−0.030	0.151	−0.198	0.843	
ScaledTrialNumber: $\text{IrregularityLocus}_{\text{alternation}}$	0.262	0.152	1.729	0.084	.
$\text{LearningMode}_{\text{goal-oriented}}$: $\text{IrregularityLocus}_{\text{alternation}}$	−0.425	0.255	−1.665	0.096	.
ScaledTrialNumber: $\text{LearningMode}_{\text{goal-oriented}}$: $\text{Irregularity}_{\text{alternation}}$	−0.152	0.151	−1.006	0.315	

**$p < 0.01$. *$p < 0.05$. A period indicates that $p < 0.1$.

Table 3: Mixed-effects logistic regression model for the phonotactics and alternation tests. Estimates are given in logit. $C = 0.80$.

Term	Coefficient	*SE*	*z* ratio	*p* Value	
(Intercept)	0.708	0.148	4.765	<0.001	***
$\text{LearningMode}_{\text{goal-oriented}}$	−0.031	0.064	−0.486	0.627	
$\text{IrregularityLocus}_{\text{alternation}}$	0.007	0.069	0.107	0.915	
$\text{TestPhase}_{\text{phonotactics\_test}}$	−0.571	0.130	−4.402	<0.001	***
TrainingPercentage	0.387	0.218	1.776	0.076	.
$\text{ItemType}_{\text{new}}$	−0.465	0.059	−7.839	<0.001	***
$\text{IrregularityLocus}_{\text{alternation}}$: $\text{TestPhase}_{\text{phonotactics\_test}}$	0.183	0.059	3.085	0.002	**
TrainingPercentage: $\text{TestPhase}_{\text{phonotactics\_test}}$	0.480	0.187	2.559	0.01	*

***$p < 0.001$. **$p < 0.01$. *$p < 0.05$. A period indicates that $p < 0.1$.

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