Statistical learning of orthotactic constraints: new insights from typing

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Abstract

Phonotactic and orthotactic constraints determine the possible spoken and written sequences of a language. Adult speakers quickly learn simple new phonotactic rules, but they only learn the more complex second-order rules (e.g., "/k/ is an onset only if the vowel is /æ/, but a coda if the vowel is /ɪ/") after the first day of training, whereas children learn the same rules on the first day. In this study, we first show that adults learn simple new rules of sequencing in typing as quickly as in speaking. We then show that, despite a much higher error rate and opportunities for error-based learning, the timeline for learning the second-order rules in typing is similar to speaking. Finally, we demonstrate that what is learned in a second-order rule, as in the example above, is the coda —and not the onset— constraint, pointing to a chaining-type mechanism for learning new rules of sequencing.

Keywords: orthotactic constraints; language production; typing; statistical learning

Introduction

Phonotactic constraints of a language determine the possible sequences of *phonemes* in that language. For example, in English, /h/ can appear in the onset but not the coda position, while in Farsi, /h/ can be either an onset or a coda. Similarly, orthotactic constraints of a language determine the possible sequences of *letters* in the written form of that language. Orthotactic and phonotactic constraints of a language are not identical. For example, /h/ is not a coda in spoken English, but it can be a coda in written English (e.g., "Noah"). While much research has focused on phonotactic constraints, relatively little attention has been paid to orthotactic constraints. In this paper, we argue that studying orthotactic constraints, e.g., in typing, not only provides a basis for comparing learning across different language modalities, but can answer some of the open questions from the phonotactic learning literature.

Phonotactic learning: findings and open questions

Phonotactic constraints have a special place in the cognitive studies of language, as they reflect the learning of implicit rules. Adult speakers rarely violate the phonotactics of their native tongue, a pattern that is evident even in their speech errors (e.g., Dell et al., 2000). Moreover, speakers show robust evidence of learning simple new phonotactic constraints in less than an hour. In a series of studies, Dell and colleagues had participants read aloud sequences of four consonant-vowel-consonant (CVC) syllables with artificially embedded constraints, such as "/f/ always in the onset and /s/ always in the coda position" and recorded their speech errors. An error was coded as "legal" if the constrained phonemes preserved their syllabic positions. Otherwise, it was coded as "illegal". The results showed that 98% of the errors involving the letters with artificial constraints were legal. This percentage was very close to language-wide constraints (e.g., /h/ always in the coda position), and significantly higher than the unrestricted control phonemes in the experiments (68%; Dell et al., 2000; see also Taylor & Houghton, 2005; Warker & Dell, 2006; Warker et al., 2009).

Not all constraints are learned so quickly though. Warker and Dell (2006) turned the simple artificial constraints of Dell et al. (2000) into second-order constraints by making the syllabic position of a consonant contingent on a specific vowel, e.g., "/k/ is an onset if the vowel is /æ/, but a coda if the vowel is /ɪ/". Adult participants did not learn this new constraint on day 1. When they came back to the lab on day 2, however, their speech errors showed evidence of learning of the second-order constraints (see also Warker et al., 2008; cf. Smalle & Szmalec, 2021, who showed quick learning of second-order constraints in French, where vowels are generally more predictive of consonants positions compared to English). In a follow-up study, Gaskell et al. (2014) replicated this finding and further showed that it was specifically sleep, and not simply the passage of time, that was necessary for the emergence of the effect. Interestingly, a similar study in 9-10-year-old children showed that, unlike the adult participants, children learned the second-order constraints on day 1 (Smalle et al., 2017).

To summarize, studies of phonotactic constraints in spoken production have shown that novel first-order constraints can be acquired quickly even in adult speakers who have experienced the phonotactic rules of their native language from infancy, pointing to the continuous nature of learning in language production (Dell et al., 2021). But the same literature suggests limits to the quick learning of more complex rules, such as second-order phonotactic constraints in adults. Why are adults not learning the second-order constraints as quickly as children? One possibility is that children, due to their less mature production systems, make many more speech errors than adults (e.g., Budd et al., 2011; Hanley et al., 2016). If acquiring new phonotactic constraints is driven by error-based learning (Dell et al., 2021), the greater number of errors can drive the faster learning observed in children. A second possibility is the existence of qualitatively different learning patterns in the child vs. the adult systems. For example, while sleep helps consolidate declarative memories in both adults and children, implicit motor learning benefits more from sleep in adults than in children (Wilhelm et al., 2008). Moreover, when cognitive resources are artificially depleted to make the system more child-like, adults learn the second-order constraints on day 1 (Smalle et al., 2021; 2022). These two possibilities give rise to different empirical predictions: the *error-quantity hypothesis* suggests that increasing error rates in adult participants should lead to learning of the second-order constraints on day 1, just like children. The *cognitive-state hypothesis*, on the other hand, suggests that the number of errors should not dramatically alter the pattern; adults would still not learn the second-order constraints on day 1 even with more errors.

A second question that remains unanswered in the phonotactic constraint literature is the mechanism underlying the learning of the second-order constraints. Note that while both onsets and codas are contingent on vowels, their different positions with regard to the vowel can be used to test different learning mechanisms. One possibility is that constraints are learned in a strictly sequential manner (also called *chaining*, Wickelgren, 1965; Lewandowsky & Murdock, 1989). Another possibility is that constraints are learned *hierarchically*, i.e., learning relative to a frame (Dell et al., 1997). Studies of second-order constraints often alternate the vowel predictably across sequences of four syllables, e.g., “*has **f**an kag tad*”, “*ni**f** tig hik dis*”, “***f**as hag nad tak*”. This method cues the conditioning vowel, even before a sequence begins. If learning is strictly sequential, then only the contingency *after* the vowel, i.e., the coda constraint, should be learned. If, on the other hand, learning is hierarchical, it should be possible to learn both contingencies for what comes *before* or *after* the vowel, i.e., both onset and coda constraints. The current study tests these possibilities.

Current study

The current study investigated the learning of orthotactic constraints in typing. The goal was two-fold. First, this is, to our knowledge, the first study of implicit statistical learning of orthotactic constraints in typing. As such, it allows a comparison with phonotactic learning, which, in turn, informs us about the similarities and differences in statistical learning of sequencing rules across different modalities of language production. Second, typing provides us with the opportunity to answer the two open questions from the phonotactic learning literature discussed above. Because of the later age of acquisition and less experience with typing than speaking, error rates are usually three to four times higher in typing than speaking in adult participants (e.g., Pinet & Nozari, 2018; Pinet & Nozari, 2021; Warker et al., 2009). This higher error rate allows us to address the first question. If the slower rate of learning of the second-order constraints in adults vs. children is driven by the lower number of errors in the former, then a 3-4-fold increase in the error rates in typing should lead to some learning on day 1, supporting the *error-quantity hypothesis*. If, on the other hand, the difference reflects different learning mechanisms in adults and children, then we would expect the same pattern in speaking and typing —which raises the quantity of errors without making them qualitatively different from speech errors (Pinet & Nozari, 2018), i.e., no learning of second-order constraints on day 1, in support of the *cognitive-state hypothesis*.

The second question can also be answered very cleanly in a typing study, as the discrete nature of keystrokes removes coarticulation effects that could potentially complicate learning (a typing segment can be planned and executed completely independently of the segments before and after it, whereas such is unlikely in spoken production). Learning that is limited to the coda constraints would provide support for the *chaining hypothesis*. Conversely, observing learning in both onset and coda positions, would support the *hierarchical learning hypothesis*.

We first establish the basic first-order orthotactic learning in Exp 1. To anticipate, the results confirm very similar patterns to phonotactic learning in spoken production. Next, we answer the two questions raised above by testing the learning of second-order orthotactic constraints in Exp 2.

Experiment 1

Methods

Participants Twenty-four native speakers of English (M_{age} = 21.42, SD = 1.64, 12 females) were recruited through Prolific, a platform for online studies. A brief screening test was administered to include proficient typists (Pinet & Nozari, 2021). A headphone check (Milne et al., 2021) was used to include participants who heard the syllables clearly.

Materials The experiment was modeled after Dell et al. (2000, Exp 1). Ninety-six sequences of four CVC syllables were generated using the vowel "e"(/ε/) and 8 consonants, each consonant appearing only once within a sequence (e.g., "*ven fex tek des*"). The consonants belonged to three experimental categories: *language-wide constraints* ("v" and "x"), *experiment-wide constraints* ("t" and "s"), and *unrestricted* ("k", "n", "f" and "d"). Language-wide constraint letters were selected such that their orthographic position was strongly biased towards either the beginning of the syllable ("v") or the end of the syllable ("x") and not vice versa. Note that while /v/ can appear as a coda in spoken syllables, it almost never appears in the coda position in written/typed words in English, as it is usually followed by a silent vowel (e.g., "dove"). Similarly, an onset "x" is rare in orthography (e.g., "Xbox"). A survey of the 3000 highest-frequency words in the English lexicon confirmed that "v" and "x" appeared only 0.5% and 0% in coda and onset positions, respectively, making them good representatives of language-wide orthotactic constraints. In contrast, the rest of the letters selected in this experiment do not show such strong positional biases in the English orthography, making them good candidates for creating new orthotactic constraints. Both letters in the experiment-wide constraint group were typed with the left hand and had a uni-manual transition to the vowel ("e"). Unrestricted letters were chosen with the following constraints: (a) similar to the letters in the experiment-wide constraints group, they did not show a strong positional bias. (b) They minimized the difficulty of phonology-to-orthography conversion, and (c) two of them were typed with the left and two with the right hand, with uni-manual and bi-manual transitions to the vowel, respectively.

In keeping with the language-wide constraints, in the current experiment "v" always appeared in the onset position of a CVC while "x" always appeared in the coda position. The two experiment-wide letters were subject to the artificial constraint that one always appeared as onset and the other always as coda. The assignment of "t" and "s" to onset and coda position was counterbalanced across participants. Finally, unrestricted letters appeared equally often in onset and coda positions. The sequences were recorded using Descript (www.descript.com) with the voice of a native female speaker of American English. Syllables were spoken every 500 ms, making each sequence 2s long.

Procedure The experiment was developed in the jsPsych library (de Leeuw, 2015) and administered online through the JATOS platform (Lange, Kuhn & Filevich, 2015). The task was typing-to-dictation. On each trial, participants first heard the auditory sequence of the four CVCs, one at a time, and typed them individually under no time pressure (the *acquisition phase*). In case of a mistake, the correct CVC was displayed, and participants typed it again until they typed it correctly. Next, the whole sequence was played to them, followed immediately by a beep, and participants typed the four syllables with a deadline of 4s. This was repeated three times (the *test phase*). When ready, participants initiated the next trial by pressing the space bar. The use of backspace was disabled throughout. Participants completed two practice trials, followed by three blocks of 32 trials presented in randomized order, with breaks in between. Keystrokes in the test phase were registered for analysis.

Results & Discussion

The overall error rate per CVC syllable was 26%. In total, 27,396 syllables were produced. Lexical shifts (e.g., *tek* ***dex ven*** *fes* → *tek* ***ven dex*** *fes*) and syllables with structures other than CVC, CV, and VC were excluded (4.6% of the syllables). Of the 78,107 letters in the remaining syllables, letters that were not part of the sequence were excluded from the analyses (< 1%). The rest included 1143, 1071, and 2884 errors on letters in the three language-wide, experiment-wide, and unrestricted categories, respectively. Errors were coded as legal if they migrated to the same syllabic position as the target (e.g., ***t****ek des* → *tek* ***t****es*). Otherwise, they were coded as illegal (e.g., ***t****ek des* → *tek de****t***). Data were analyzed using the non-parametric Wilcoxon test, which makes no assumptions regarding the underlying distributions. P values are reported after the Bonferroni correction for multiple comparisons to avoid type I error.

Figure 1 shows the results. As expected, the proportion of legal errors on letters with language-wide constraints was significantly higher than the unrestricted (96.1% ± 1.67% (SE) vs. 76.1% ± 2.03%; $z = 4.99$, $p < .001$). Importantly, the proportion of legal errors on letters in the experiment-wide condition (96.5% ± 1.65%) was also significantly higher than unrestricted ($z = 4.99$, $p < .001$), and comparable to language-wide ($z = -0.03$, $p \approx 1.00$).

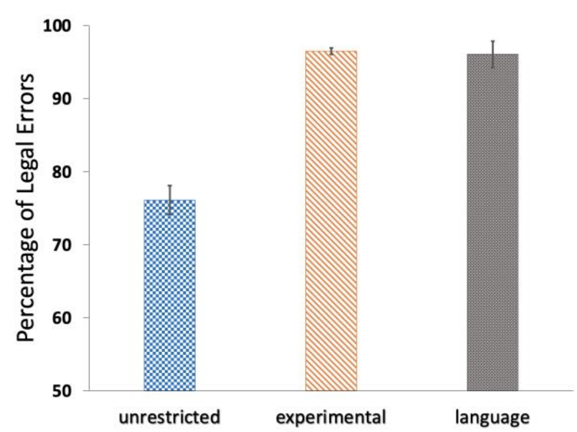

Figure 1: Mean proportion of legal errors ± SE of subject means in unrestricted, experimental and language conditions.

The results closely mirror those in spoken production (e.g., Dell et al., 2000). First, the above-chance legality of errors in the unrestricted condition reflects the fact that errors respect syllabic positions (Nooteboom, 1967, 1969). Second, the near-ceiling proportion of legal errors in the experiment-wide constraint shows that participants were able to quickly learn new orthotactic constraints, just like they did new phonotactic constraints in prior spoken studies. Finally, the comparable rates of experiment-wide and language-wide legal errors shows that, as in spoken language, statistical learning of new sequencing constraints can be complete and at the level of much more well-practiced constraints.

With these similarities confirmed, Exp 2 investigated the learning of second-order constraints in typing.

Experiment 2

Methods

Participants Twenty native English speakers (M_{age} = 22.35, SD = 1.95, 12 females), who had not participated in Exp 1, were recruited through Prolific, after passing the typing screening and headphone check, as in Exp 1.

Materials The experiment was modeled after Warker and Dell (2006, Exp 1). Ninety-six sequences of four CVC syllables were constructed similar to Exp 1, with the same language-wide constraints as first-order constraints. The critical manipulation was constraining the position of the experiment-wide consonants depending on the vowel. Two experiment-wide consonants ("k" and "f") were paired with two vowels "a" (/æ/) and "i" (/ɪ/), such that their syllabic positions were dependent on a given vowel. For example, "k" was an onset and "f" a coda only if the vowel was "a" (e.g., *na**f** vat **k**as dax),* but in the opposite syllabic positions if the vowel was "i" *(e.g., sid vi**k** tix **f**in).* The assignment of letters to positions based on a given vowel was counterbalanced across participants. Four unrestricted consonants ("t", "s", "n" and "d") were paired equally often with the two vowels in onset and coda positions, providing a baseline for comparison. Sequences were constructed with no repeated consonants, and each consonant appeared equally often in the four words in the sequence. The two vowels alternated between sequences. Thus an "a" sequence was always followed by an "i" sequence and vice versa. Sequences were recorded in the same manner described in Exp 1.

Procedure Participants completed the experiment online using the same platforms described in Exp 1. Each participant completed two sessions, 24-48 hours apart. The session structures were identical to one another and to that of Exp 1. The presentation of sequences was pseudo-randomized in each session, preserving the alternation of "a" and "i" sequences, and all keystrokes were registered for analysis.

Results & Discussion

The overall error rate per syllable was 31% on the first day and 22% on the second day. The same exclusion criteria for errors as Exp 1 was enforced, leading to the exclusion of lexical shifts and unacceptable syllable structures (5% and 3% of the total 22,364 and 22,334 syllables produced on days 1 and 2, respectively). Also, letters that were not part of the sequence were excluded (less than 1% of the 63,006 and 64,022 letters produced on days 1 and 2, respectively). Table 1 shows the total number of errors and their breakdown by onset and coda positions on days 1 and 2. As in Exp 1, legality was defined as maintaining the syllabic position when migrating within the sequence. For language-wide errors, this was a first-order constraint, as defined in Exp 1. For the experiment-wide and unrestricted errors, this was a second-order constraint. For the unrestricted consonants, this was simply the baseline tendency to preserve a syllabic position during letter migration (Pinet & Nozari, 2018). Data were analyzed using the same methods described in Exp 1.

The first set of analyses tested the learning of the second-order constraints on day 1 vs. day 2, in keeping with the spoken language literature. Figure 2a shows the results. Bonferroni-corrected p values showed that, on day 1, there was no significant difference between the rate of legal errors in experiment-wide and unrestricted conditions (76% ± 2.41% vs. 80% ± 1.92%; $z = -0.86$, $p \approx 1$), and both were significantly lower than the language-wide condition (94.7% ± 1.51%; $z = -4.62$, $p < .001$, $z = -3.38$, $p = .002$; for experiment-wide and unrestricted, respectively). On Day 2, a different pattern emerged: the rate of legal errors in the experiment-wide condition was now significantly higher than the unrestricted condition (86% ± 2.08% vs. 79% ± 2.23%; $z = 2.92$, $p = .008$), even though it was still lower than the language-wide condition (96.3% ± 1.02%; $z = -3.76$, $p < .001$).

Table 1: Number of errors in the three conditions for the onset and coda positions on days 1 and 2. E = experiment-wide constraint; L = language-wide constraint; U = unrestricted; Cod = coda; Ons = onset.

	Day 1			**Day 2**		
	Ons	Cod	Sum	Ons	Cod	Sum
L	560	491	1051	475	438	913
E	546	611	1157	505	588	1093
U	1197	1679	2876	992	1307	2299

The second set of analyses tested the learning of second-order constraints separately for onset and coda (see Table 1 for the number of errors in each category across conditions and days). Figure 2b shows the pattern. Compatible with the results of the first set of analyses, there was no evidence of robust learning for either position on Day 1. Bonferroni-corrected p values showed no significant differences between the unrestricted and experiment-wide legal errors in either the onset ($z = -1.93$, $p = .11$) or coda ($z = -0.313$, $p \approx 1.00$) positions. On day 2, there was still no evidence of learning for experimental onset vs. unrestricted onset ($z = 0.22$, $p \approx 1.00$). However, the proportion of legal errors in experimental coda was now significantly higher than unrestricted coda ($z = 2.86$, $p = .008$). In fact, the proportion of legal errors on experimental coda was comparable to that of first-order language-wide coda (z = -1.68, p = .186).

The learning of second-order constraints on day 2, but not on day 1, is very similar to the reports in spoken production (e.g., Warker & Dell, 2006). In addition, the current results demonstrated that such learning is restricted to the coda position. Recall that the predictable vowel alternation and three repetitions in the test phase provided many opportunities for learning the constraints regardless of the syllabic position. Nevertheless, the data provided no support for such learning in the onset position. Instead, learning for a coda contingent on a vowel was strong and comparable to first-order constraints on day 2. This pattern pinpoints statistical learning of orthotactic constraints to a chaining-like mechanism of sequencing (Lewandowsky & Murdock, 1989; Wickelgren, 1965), in which transitional probabilities are learned locally from the conditioning segment (i.e., the vowel) to the conditioned segment (i.e., the coda).

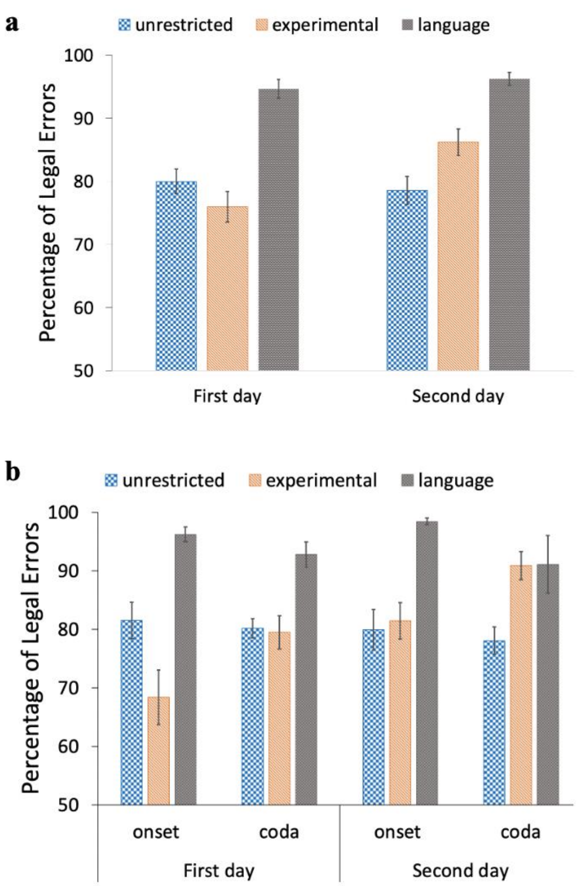

Figure 2: Results of Exp 2. Percentage of legal errors on day 1 and day 2 ± SE (a), and the breakdown by onset/coda positions (b).

General Discussion

In two studies we tested the learning of orthotactic constraints in typing. The results of the first experiment showed that people quickly learned the first-order constraints. The size of this effect (20%) was comparable to studies of phonotactic learning in spoken production (e.g., 24%; Dell et al., 2000). This finding extends the body of research pointing to similar mechanisms underlying language production in spoken and typed modalities, such as similar patterns of errors (e.g., Pinet & Nozari, 2018; 2022), by demonstrating similar mechanisms of statistical learning in the two.

The second experiment tested the learning of second-order constraints. Again, the pattern was strikingly similar to spoken production; there was no robust learning on day 1, followed by solid evidence of learning on day 2. Beyond further supporting the similar mechanisms underlying speaking and typing, this finding answered our first open question; the delay in learning the second-order constraints in adults is not caused by insufficient opportunities to learn from errors. The error rate in Exp 2 was 31% on day 1, more than four times higher than the ~7% error rate reported in spoken production studies by Dell and colleagues. Yet this increase did not translate to better learning on day 1. Instead, the pattern of data is compatible with the *cognitive-state hypothesis*, suggesting that the differences between adults and children in the timeline of statistical learning may reflect qualitative differences in the state of the cognitive system. For example, greater cognitive control in adults may be detrimental for the implicit learning of new constraints (Smalle et al., 2022). Interestingly, the findings on the rapidity of implicit statistical learning in infants and children are not uniform. On the *perception* side, there is evidence for extremely fast learning and generalization of complex phonotactic rules in infants (Chambers et al., 2003; Gerken & Knight, 2015). On the *production* side, children around 6-8 years of age do not learn motor sequences nearly as rapidly as adults, even after sleep consolidation (Wilhelm et al., 2008, 2012). In short, children seem to be particularly apt at rapidly extracting linguistic patterns but not so much in acquiring motor patterns. A study of phonotactic learning in production has both components. Thus, the demonstration of phonotactic learning on day 1 in 9-10- year-old children, but not in adults (Smalle et al., 2017), if replicated, appears to pinpoint the effect to learning at the linguistic —and not the motor— level.

Exp 2 also answered a second open question in statistical learning, namely the mechanism underlying the learning of the second-order constraints. While the coda constraint was fully mastered on day 2 (up to the level of a first-order language-wide constraint), there was no evidence of learning of the onset constraint (statistically on par with unrestricted control segments). This finding supports the *chaining hypothesis*, namely that the system learns to use a local cue (here, the vowel) to predict the next immediate segment (i.e., the coda). This mechanism predicts no learning for onsets, because the onset is never directly preceded by the cue.

Recall that the absence of the onset effect cannot be attributed to the absence of *any* informative cues for learning. The vowel is 100% predictable even before the sequence is presented. Moreover, participants first type all the syllables, one at a time and without time pressure, providing ample opportunities for associating the restricted onset with the constraining vowel. If learning was hierarchical —rather than strictly sequential and chained— there should have been at least some evidence of learning the constraint in the onset position, but this was not the case. Our data, thus, support a mechanism of statistical learning as chaining for orthotactic constraints.

We do not mean to imply chaining as the sole —or necessarily the dominant— mechanism of sequencing in typing. Evidence against simple chaining (or more complex chaining mechanisms such as compound chaining; Goldberg & Rapp, 2008) come from studies of typing errors. For example, gemination errors (i.e., the erroneous doubling of a letter in a target with double letters: “letter” → “leeter”) show several properties that imply that double letters are not simply two independent instances of the same letter appearing one after the other in a chain. Rather they are best modeled by a single copy of a letter attached to two slots in a positional/syllabic frame with a geminate tag (Hepner et al., 2018). This and other findings in the literature has suggested a hierarchical system in which content (e.g., letters/phonemes) is bound to a frame (Dell et al., 1997) through some non-linear sequencing mechanism, such as competitive queuing (e.g., Glasspool & Houghton, 2005; Houghton, 2018). The point of the current study was rather to show that statistical learning relies heavily on simple chaining mechanisms, in which the transitional probabilities of the segments are learned serially. Finally, we must point out that although the many similarities between spoken and typed production make chaining a reasonable candidate for learning phonotactic constraints, this claim must be empirically verified, as there are also nontrivial differences between the two systems, such as the nature of segments, the qualities of the motor apparatus involved in producing speech vs. typed production, and possibly even the scope of planning.

To summarize, this study demonstrated the feasibility and utility of typing in uncovering the cognitive mechanisms underlying sequence learning in the human language production system. Future work can determine the extent of generalization of the findings and conclusions of this work to phonotactic learning in spoken production. Such comparisons, in turn, inform us about the extent to which the principles of sequence learning depend on the nature of the representations and the motor apparatus involved in production.

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