Implicit learning of phonotactic constraints: Transfer from perception to production

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Abstract

This study asked whether new linguistic patterns acquired through recent perception experience can transfer to speech production. Participants heard and spoke sequences of syllables featuring novel phonotactic constraints (e.g. /f/ is always a syllable onset, /s/ is always a syllable coda). Participants' speech errors reflected weaker learning of the constraints present in the spoken sequences (e.g. /f/ must be onset) when they heard sequences with the inverse constraints (e.g. /f/ must be coda), suggesting that the constraints experienced in perception interfered with learning in production. The results did not depend on the presence of a shared orthographic code in perception and production trials, suggesting that direct transfer between heard speech and produced speech is possible, perhaps through prediction via inner speech. Further work is needed to determine the exact mechanism supporting inter-modality transfer of phonological generalizations.

Keywords: phonotactic learning; transfer of learning; implicit learning; prediction; orthography.

Introduction

Humans have a remarkable ability to implicitly learn sequential patterns in a variety of knowledge domains (e.g. Alsin & Newport, 2008). This ability is especially important in language, where it has been hypothesized that linguistic structures are acquired, at least in part, through domain-general learning principles (e.g. Dell, Juliano, & Govindjee, 1993; Elman, 1990). Although much work on implicit pattern detection in language has focused on word identification, investigating learning of more rule-like systems, such as *phonotactics*, is key to understanding language acquisition. Phonotactics are the constraints on possible sound sequences in a language; for example, the sound combination /sr/ can appear as an *onset* (beginning of a syllable) in Russian ("sravnivat", to compare), but not in English. These constraints affect both our language perception (we expect to hear sequences of sounds that follow the phonotactics of our language) and production (our speech conforms to our language's phonotactics).

Native speakers of a language acquire some phonotactic knowledge in the first year of life. Moreover, infants can rapidly learn new artificial phonotactic constraints in laboratory settings simply by listening to syllables that follow the constraints (Chambers, Onishi, & Fisher, 2003). This ability is not unique to children; adults, too, learn new phonotactic constraints. They can even acquire constraints in opposition to native-language phonotactics (e.g. English speakers learning than /ng/ can be an onset, Whalen & Dell, 2006), as when learning a foreign language.

Several studies with adult participants have demonstrated phonotactic learning within the auditory speech-processing system. Participants are exposed to syllables that exhibit new phonotactic constraints, such as /p/ always occurring as an onset, and never in syllable-final (*coda*) position. After listening to these syllables, participants are more likely to accept novel syllables as familiar if they obey, rather than disobey, the constraint (Bernard & Fisher, 2010), and are slower to shadow those that violate the constraint (Onishi, Chambers, & Fisher, 2002). Adults can acquire new phonotactic constraints in language production, as well as in perception. After just 9 trials of producing sequences of syllables that follow a novel constraint, participants' speech errors obey the novel constraint (Taylor & Houghton, 2005). For example, the slips of participants producing syllables, in which /f/ is always an onset and /s/ is always a coda, will mirror that distribution: /f/'s will erroneously move to onset positions, and /s/'s to coda positions (see also, Dell, Reed, Adams, & Meyer, 2000; Warker & Dell, 2006). These production studies thus stand as an experimental analogue to the well known tendency for everyday speech errors to follow the phonotactics of the language one is speaking (e.g. Fromkin, 1971). For example, because English disallows onset /ng/, slips never create such syllables, even though they commonly create nonwords with /ng/ codas.

Phonotactic constraints are first encountered and acquired through listening to language. Eventually, they are also reflected in spoken language. How do they get there? The above studies demonstrate that phonotactic learning can occur *within* the perception and production systems. Consistent with this, neuropsychological data strongly suggest that separate phonological representations are employed in speech perception and production (e.g. Martin, 2003). Are speakers obliged to learn the same constraints separately through listening and speaking, or is it possible for learning to transfer from perception to production? More broadly, how efficient is phonotactic learning? What is its scope and generalizability?

In our experimental paradigm, participants alternate between listening to and rapidly speaking sequences of syllables that follow English phonotactics (e.g. "hes meg fen keng"). Some consonants' positions are "restricted" (English /h/ can only be an onset, and /ng/ can only be a coda), while others are "unrestricted" (e.g. /k/, /g/, /m/ and /n/ can appear freely as onsets and codas). Crucially, two consonants (/f/ and /s/), which are unrestricted in English, are restricted in the experiment. For some participants, /f/ will always be an onset and /s/ will always be a coda, and others will experience the reverse. When quickly producing such sequences, participants tend to make speech errors (e.g. "hes meg feng keng" instead of "hes meg fen keng"). Errors involving /h/ and /ng/ will almost always be *legal* (obey the language-wide constraints, e.g. /ng/ can only slip to coda position). This is the well known phonotactic regularity effect on speech errors. The key findings will concern the experimentally restricted consonants. If errors involving /f/ and /s/ tend to be legal according to the experiment-specific constraints, we can conclude that the constraints have been acquired by the language production system.

We investigate transfer from perception to production by manipulating the relationship between constraints experienced in perception and production. In an *Opposite-constraint condition*, the constraint in sequences that are only heard (e.g. /s/-onset, /f/-coda) is the inverse of the constraint present in sequences to be spoken (/f/-onset, /s/-coda). If there is robust transfer between perception and production, we should see no evidence of the /f/-onset, /s/-coda constraint in participants' speech errors, because the constraints will cancel out one another. There is no longer any restriction of /f/ to onset in production if, half the time, it is heard as a coda, and if this perceptual experience is integrated with production experience. If there is no transfer, we should see strong evidence of the production constraint in speech errors. Participants in a *Same-constraint condition* (e.g. /f/-onset, /s/-coda in both perception and production sequences) should produce errors that obey the constraint, regardless of whether or not there is transfer.

Using this paradigm, Warker, Xu, Dell, and Fisher (2009) found little evidence for transfer. Nothing was found in their first two experiments and a third found weak transfer (learning of the constraint present in spoken syllables differed to a small extent between the Same- and Opposite-constraint conditions). Assuming this latter result is replicable, the various ways in which the third experiment differed from the others leaves open several possible mechanisms of transfer. Transfer could easily have been mediated by orthography. On perception trials, participants listened to sequences spoken by another participant while checking them for errors against a written version, and the production task used written presentation of the sequences as well. Thus, the perceptual and production experiences actually shared a visual representational format.

There is another, more intriguing explanation for the partial transfer observed by Warker et al. (2009). A recent computational model of sentence production learns to "speak" simply from "listening," rather than from direct production experience (Chang, Dell, & Bock, 2006). The model predicts upcoming words in the sentences that it comprehends, and its learning consists of adjusting its ability to predict (e.g. Elman, 1990). Prediction (the generation of expected words and structures) is a process akin to language production, but without articulatory realization. Consequently, learning from comprehension transfers seamlessly to production. The idea that active prediction occurs during comprehension and that prediction is carried out by the production system has become an important component of modern psycholinguistic theory (e.g. Federmeier, 2007; Pickering & Garrod, 2007).

While participants in Warker et al. (2009) were listening, perhaps they were predicting upcoming syllables based on the written text used to check sequences for errors. If the act of prediction activates the production system, this would allow the constraint present in heard sequences to interfere with constraints learned during the speaking trials. Heightened attention to the syllables, required by the error monitoring task, may have facilitated transfer as well.

To investigate the robustness and origin of partial transfer of phonotactic constraints, we explicitly investigated the two hypothesized mechanisms for transfer: prediction and orthography. On each perception trial, participants heard a sequence (e.g. "hes meng fen kes") twice. Their task was to report whether the second presentation of the sequence deviated from the first (e.g. "hes neng fen kes" has an error on the second syllable). Our task forced the participants to form an expectation or prediction of which syllables were about to be heard. For half of the subjects, the first auditory presentation was accompanied by a written version presented on a computer screen (*Orthography condition*). We predict that if transfer is mediated by orthography, only participants in the Opposite-constraint, Orthography condition should show transfer. If transfer is mediated by prediction, all participants in the Opposite-constraint condition should show transfer, regardless of whether they received orthographic input.

Methods

Participants

Thirty-two University of Illinois students participated for psychology course credit. Participants were native English speakers with normal or corrected-to-normal vision and hearing, and no known linguistic or psychiatric disorders.

Stimuli

A total 384 sequences of four syllables were generated by randomly scrambling 8 consonants (/h/, /ng/, /f/, /s/, /m/, /n/, /k/, /g/) and inserting the vowel /ɛ/ into the resulting syllabic structures (e.g. heng fes men keg). All sequences obeyed English phonotactics (/h/ was always an onset and /ng/ always a coda). Half of the sequences only featured /f/-

onsets and /s/-codas (the “fes constraint”), while the other half only featured /s/-onsets and /f/-codas (the “sef constraint”). The 384 sequences were arranged into 4 lists, two lists featuring the fes constraint, and two featuring the sef constraint. Participants in the Opposite-constraint condition were assigned to lists with different constraints in perception and production (either perception-sef and production-fes or the reverse), while participants in the Same-constraint condition were assigned to perception and production lists with the same constraint (both fes or sef).

Deviant versions of 49 sequences in each perception list were created that contained “errors” for the participants to detect during error monitoring. These errors were similar to those made by participants in Warker et al. (2009), except that no errors occurred on restricted consonants /f/ and /s/. The deviant sequences were distributed randomly throughout the experiment. All perception trial stimuli were produced by a female native English speaker from Illinois.

Procedure

Participants viewed stimuli on a Dell computer screen and received auditory input through a set of external speakers. Participants’ voices were recorded by a lapel microphone which fed into a Marantz digital recorder.

Participants alternated between perception and production trials, completing 96 of each type. On a perception trial (cued by a picture of an ear), the numbers 1 2 3 4 appeared in a row on the screen. Subjects heard a sequence of syllables, in which the first syllable was “1”, the second “2”, etc.. Subjects in the Orthography condition saw a written version of each syllable appear on the screen as it was spoken. Next, a gray bar with exclamation marks was shown for 750 ms to cue readiness for the monitoring task. On the next screen, all subjects saw the numbers and listened to a second version of the sequence, which contained errors on 0, 1 or 2 consonants. Subjects were instructed to type in the numbers corresponding to any syllables that contained errors, and to type 0 if there were no errors.

On a production trial (cued by a picture of lips), a sequence of syllables appeared in smaller font at the bottom of the screen. Participants were instructed to press a space bar to start a metronome (2.53 beats per second), wait for 4 beats, and say the sequence twice, timing each syllable to a beat. Producing all syllables was emphasized over accuracy.

Participants practiced perception and production trials before the experiment. The entire procedure, including 2 breaks, took approximately half an hour.

Coding performance in error monitoring task

If a participant correctly detected the presence of any error(s), this was counted as a “correct” response. False alarms (reporting an error when there were none), misses (reporting no errors when there was at least one), and omission responses were coded as “incorrect”.

Coding speech errors made on production trials

Speech errors were coded offline. Errors in which one consonant was replaced by another from the sequence were classified as legal or illegal by the original location of the error consonant in the target sequence. For example, given the target “hes meg fen keng” and the errorful sequence “hes mek feng g-…keng”, the /ng/ in “feng” would be classified as a legal error (/ng/ kept its position as a coda), while the /k/ in “mek” would be classified as an illegal error (/k/ moved from onset position to coda position). Cutoff errors such as “g-…keng” were included in the analysis; omissions, intrusions of consonants not present in the sequence, and unintelligible responses were excluded.

Statistical analysis

A hierarchical logistic regression model was fit to the speech-error data, and focused on the extent to which each error was legal (maintained its status as onset or coda) or illegal (moved to a different position). As the hypotheses of interest dealt only with differences between experimentally restricted consonant (/f/, /s/) and unrestricted consonant (/k/, /g/, /m/, /n/) errors, language-wide restricted consonant (/h/, /ng/) errors were excluded from the regression analysis.

The log odds of an error being legal was predicted from constraint (a contrast-coded variable, Same-constraint condition vs. Opposite-constraint condition), orthography (contrast-coded variable, Orthography condition vs. No orthography condition), restrictedness (a dummy-coded variable where 1=restricted consonant error and 0=unrestricted consonant error), and their interactions. A random error term was also included to model between-subject variability.

Two additional hierarchical logistic regression analyses were run, one on the data from participants in the Same-constraint condition only, and one on data from the Opposite-constraint condition only. In each case, the log odds of an error being legal was predicted from restrictedness and a subject random error term.

Results

A total of 2203 consonant errors were made by the 32 participants, for an overall error rate of 4.4% per consonant. Of these, 1577 met inclusion criteria for statistical analysis.

Participants in the Same-constraint condition showed good evidence of learning: on average, only 1.0% of all experimentally-restricted consonant errors were illegal (see Figure 1), a rate nearly identical to that found for language-wide restricted consonant (/h/ and /ng/) errors (1.1%). Even though these participants had never before encountered the experimental constraints, their slips followed them as strongly as they followed the constraints learned from a lifetime of speaking English. By contrast, on average 31.9% of all unrestricted consonant errors were illegal (see Figure 2), significantly more than for slips of the experimentally restricted consonants (coefficient = 3.404, standard error = 0.725, $p < .001$). More unrestricted consonant errors are legal than would be expected by chance (illegality is below 50%) because even unrestricted consonants tend to stick to their syllable positions in a sequence (MacKay, 1970).

Errors from participants in the Opposite-constraint condition showed a different profile (Figure 1). Most importantly, there was evidence of transfer between perception and production: restricted consonants were illegal 13.5% of the time on average in the Opposite-constraint condition, more than ten times the illegality rate in the Same-constraint condition. By contrast, the illegality rate of unrestricted consonants in the Opposite-constraint condition (36.3% on average) was comparable to that in the Same-constraint condition, an expected result given that unrestricted consonants did not differ in their distribution across conditions (Figure 2). The interaction between constraint and restrictedness was significant (coefficient = 1.049, standard error = 0.384, $p = .006$).

We can be sure that participants learned the constraints present in heard sequences, because these interfered with (Opposite-constraint condition) and/or enhanced (Same-constraint condition) the constraints learned in production, as revealed by their speech errors. This interpretation is bolstered by good error monitoring accuracy of participants in the Opposite- (71.5%) and Same- (73.5%) constraint conditions. This suggests that participants did indeed engage in the task designed to make them predict during perception trials: they remembered the first presentation and used it to monitor the second presentation of the sequence.

The transfer between perception and production, however, was only partial, like that found by Warker et al. (2009). Participants in the Opposite-constraint condition still showed evidence of the production constraint in their speech errors: experimentally restricted consonant errors had a higher legality rate than unrestricted consonant errors (coefficient = 1.266, standard error = 0.235, $p < .001$).

The orthographic manipulation, unlike Same- vs. Opposite-constraint, did not influence speech errors (see Figures 1 and 2). Most importantly, the presence of orthography did not modulate the transfer effect: the interaction of orthography with constraint was not significant for restricted consonants (coefficient = 0.073, standard error = 0.384, $p = .850$). This was true even though seeing orthography during the perception task slightly increased error detection accuracy (76.1% in the Orthography condition, compared to 69.0% in the No orthography condition). There was also no significant main effect of orthography on error legality for unrestricted consonants (coefficient = -0.407, standard error = 0.087, $p = .589$) or restricted consonants (coefficient = -0.107, standard error = 0.384, $p = .781$). Although these null effects must be interpreted with caution, they suggest that orthography is not the mechanism leading to the transfer of phonotactic constraints between perception and production.

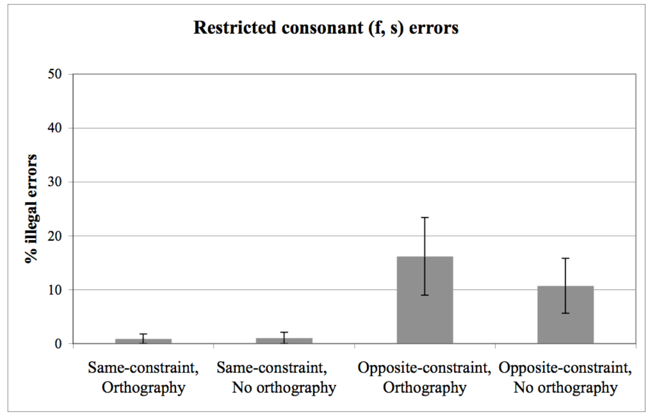

Figure 1: percentages of restricted consonant errors that are illegal across conditions, with standard error of the mean

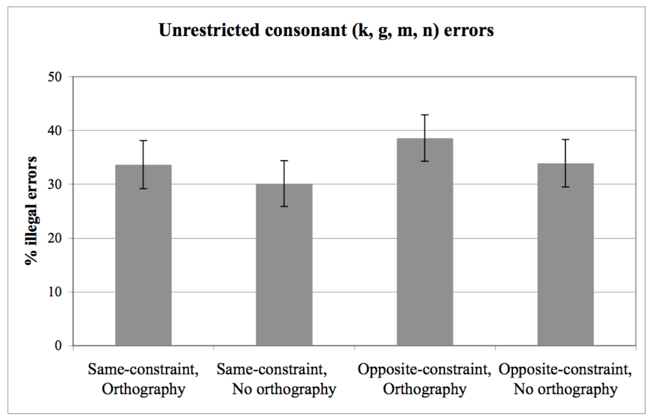

Figure 2: percentages of unrestricted consonant errors that are illegal across conditions, with standard error of the mean

General Discussion

Previous work has shown that transfer of newly acquired phonotactic constraints between the perception and production systems is difficult to achieve, but may be possible under some circumstances (Warker et al., 2009). Moreover, little is known about possible mechanisms for transfer. We explored two such mechanisms: the presence of orthographic mediating representations, and the prediction (via the production system) of upcoming sound sequences during perception. On alternating trials, participants either listened to, or produced, sequences of syllables ("mek nes feng heg") containing either identical or opposing artificial phonotactic constraints. Weakened sensitivity to the production constraint in the speech errors of participants who received opposite constraints indicates transfer between perception and production. Participants receiving identical constraints in perception and production should show good learning of the production constraint in their slips. An additional manipulation of the presence or absence of orthographic input during perception allowed us to evaluate its effect on transfer.

Speech errors collected from participants clearly showed partial transfer of constraints between perception and production. The transfer effect is, thus, robust and, given the third experiment of Warker et al. (2009), replicable. Under the right conditions, learning of phonotactic constraints in one modality leads to their expression in another modality.

Our results go beyond previous findings by showing that the difference between the Same- and Opposite-constraint conditions is truly due to transfer between the speech modalities. The presence of orthography during both perception and production trials in Warker et al. (2009) meant that learning and interference could have taken place at a common, orthographic level. We found a partial transfer effect independent of orthographic input during perception, suggesting that learning from heard speech transfers to produced speech.

The null effect of orthography condition also weakens other hypotheses in which orthography mediates transfer. Thus, enhanced processing of the syllables that could arise from multimodal presentation does not seem to be necessary for transfer. Similarly, activation of production phonology from orthography is not a likely mechanism.

If orthography is not the key to transfer, then what is? In order for constraints in perception to transfer to production, production phonology must have been activated during the perception task. Our results leave open several possible mechanisms of this activation. We designed our perception task to induce prediction of upcoming sequences: participants were expecting the second sequence to be identical or nearly identical to the first, and so they may have mentally anticipated the syllables before the second presentation (it is unlikely that they mouthed them, as all participants were explicitly instructed not to do so). The task used in Warker et al. (2009)'s successful transfer study may also have encouraged prediction. The exact nature of the prediction participants engaged in is unclear, although it is possible that they were using *inner speech* (the "little voice in your head"). Inner speech is much like overt speech, except that lower (e.g. articulatory) levels of representation are not activated (Oppenheim & Dell, 2008). In our experiment, the individual sounds of an upcoming sequence could be activated in production phonology by inner speech. In this way, constraints present in the heard sequences would also effectively be "produced", and could interfere with the constraint present in the spoken sequences, since they are mapped onto the same level(s) of representation. The transfer may be partial because production phonology is only weakly activated by inner speech (as compared to overt speech production; Oppenheim & Dell, 2008), and thus the constraint present in perception sequences may not be represented as robustly.

Inner speech is not so different from the sort of prediction thought to take place in everyday language processing (Federmeier, 2007). Although prediction at the phonological level may not be ubiquitious in normal language comprehension, it does occur if contextual constraints are sufficiently strong (e.g. DeLong, Urbach, & Kutas, 2005). If future work determines that prediction during input processing leads to transfer, this would support the viability of language comprehension theories that incorporate prediction (Federmeier, 2007), and language acquisition theories in which comprehension practice trains production (Chang et al., 2006).

There are, however, other mechanisms that could explain the transfer effect besides prediction via inner speech. Participants had to remember the first presentation of a sequence for the monitoring task, and so they may have subvocally rehearsed the first presentation to check it against the second presentation. Rehearsal could even have been simultaneous with perception, rather than anticipatory. In this case, production phonology would be activated via deliberate rehearsal, rather than more implicit prediction.

Indirect activation of production phonology could also have contributed to the transfer effect. The perception trials in our study and in the successful transfer study of Warker et al. (2009) required participants to monitor for errors, a task involving active processing of the sequences. Perhaps all that is needed for transfer is any kind of task that requires attention. We note, however, that no transfer was found in the experiment from Warker et al. (2009) in which the perception task consisted of monitoring the perceived syllables for a specific target syllable (always "heng"). So, not just any attention-demanding task creates transfer. It is possible, though, that monitoring for error specifically increased attention to individual phonemes of the perceived sequence, and that the resulting high activation of perceptual phonology led to partial activation of production phonology. Although our results cannot rule out these mechanisms, follow-up studies addressing this issue are under way.

Our results can also speak to the degree of overlap between phonological representations in perception and production. If we know the degree of overlap, we can know whether to expect transfer. For example, if you learn how to hear the difference between /r/ and /l/, will you then know how to produce the difference? If the representations are completely shared between modalities, one would expect so. Taking together our findings and those of Warker et al. (2009), the fact that only two out of four experiments found transfer, and that that transfer was incomplete, suggests that representations mediating phonotactic learning are modality-specific. If representations were shared across modalities, participants would be able to learn modality-independent phonotactic constraints from either perception or production experience. However, it seems that only under certain conditions can knowledge learned in one modality transfer to another. For example, transfer of phonotactic constraints may happen as a result of direct activation of production phonology during perception (prediction), which could take place in a system with completely separate perception and production phonologies.

The partial transfer observed in the domain of phonotactics stands in contrast to the full transfer observed in the domain of syntax. Hearing a prime syntactic structure makes the listener as likely to produce that structure compared to when the prime structure is spoken (Bock, Dell, Chang, & Onishi, 2007). This result is taken to suggest that syntactic-level representations are fully shared between production and comprehension. Perhaps transfer at lower levels of linguistic structure is not likely to be more than partial because, as one approaches the periphery (audition vs. articulation), input- and output-oriented representations must necessarily diverge.

Addressing the issue of transfer is not only important for investigating the structural overlap between comprehension and production, but it also has implications for second language acquisition. Although our experiment focuses on learning of English phonotactic constraints, other work has found implicit learning of non-English phonotactics by native-English adults in laboratory settings (e.g. Whalen & Dell, 2006). Is transfer from perception to production possible for these sorts of constraints, as well? Learning a second language in adulthood is notoriously difficult, and so knowing which aspects must be acquired through direct production experience, and which can be subtly trained through comprehension, would be of great theoretical and educational interest.

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