Native phonological processing abilities predict post-consolidation nonnative contrast learning in adults

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Abstract: This study examined the relationship between native phonological processing ability and the learning outcome of a trained nonnative (Hindi /ɖ/ - /d̪/) contrast. Participants were perceptually trained and assessed in the evening, and reassessed early the next morning. Native phonological processing ability did not predict the learning of the nonnative contrasts on Day 1. However, after a period of post-training sleep, Blending ability predicted nonnative Discrimination performance, and Nonword Repetition predicted nonnative Identification. These findings may point to similarities between processes involved in maintaining native phonological representations and that in the retention of nonnative acoustic-phonetic features in adulthood.

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1. Introduction

Proficiency in a second language is associated with mastery of *L*2 phonology (Flege, 1988), however what leads to individual differences in the ability to perceive and acquire foreign speech sounds are poorly understood. The bulk of past research into predicting the successful acquisition of *L*2 phonology has focused on differences in external factors such as the age of *L*2 onset (e.g., Abrahamsson and Hyltenstam, 2009). Recent interest has turned to how internal factors, such as differences in cognitive and/or memory processes, influence the learning of foreign speech contrasts (Francis and Nusbaum, 2002; Iverson *et al.*, 2003; Maddox and Chandrasekaran, 2014). Within this literature, the question of whether these internal factors are shared across *both* native and nonnative speech sound representations is relatively underexplored. While it is clear that there are maturational differences in learning strategies available to an infant versus a mature learner (e.g., Thomas *et al.*, 2004), there is also an intuitive logic in the hypothesis that those who are good at organizing and storing the sounds of their native language are likely to be good at doing the same for sounds in another language (Sebastián-Gallés and Díaz, 2012).

Few studies have directly investigated the relationship between native speech processing ability and learning of nonnative speech, and these have yielded mixed results. For example, Díaz *et al.* (2008) found that bilinguals who are good perceivers of *L*2 have greater electrophysiological responses to both native and nonnative speech sounds relative to poor perceivers, despite similar detection of changes in non-speech auditory stimuli. Further, Golestani and Zatorre (2004) found that relative success in nonnative contrast learning, trained over multiple days, is associated with increased efficiency in neural processing of the nonnative contrast in classical (native-like) speech regions. Based on such findings, Sebastián-Gallés and Díaz (2012) have argued for a "language-specific" capability that can explain individual differences in second language learning beyond age of exposure. However, recent work by Fuhrmeister and Myers (2017) suggests that native perceptual ability does not predict one's ability to learn a nonnative contrast over a single training session. In other words, whatever commonalities observed between native and nonnative speech (e.g., Diaz *et al.*, 2008; Golestani and Zatorre, 2004) appear to reflect the longer-term outcome of speech information retained over time, rather than the short-term gains observed immediately after training. One possibility is that native and nonnative speech may share common

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memory processes involved in retaining speech sound information over time. Following linguistic exposure, acoustic-phonetic features must be retained, integrated with pre-existing knowledge, and stored. In nonnative speech learning, previous work has shown that offline consolidation during sleep plays several important roles in this process (Earle and Myers, 2015a,b).

Therefore, the purpose of this study was to determine if native phonological processing ability would predict the learning outcome of a nonnative contrast following a period of post-training sleep. Phonological processing broadly refers to one's ability to mentally manipulate sub-lexical units of speech. Tasks that measure phonological processing ability include nonword repetition (NWR), Blending (combining discrete segments together to make a whole word), and Elision (removing segments from words). We reasoned that, if the processes involved in the retention of acoustic-phonetic information are similar between native and nonnative speech, this may be reflected in a relationship between performance on such tasks and perception on a trained nonnative contrast after a period of overnight consolidation, but not necessarily before.

2. Methods

Portions of this dataset have previously been reported elsewhere (Earle *et al.*, 2017). These reports focus on how sleep duration and a history of spoken language impairment influence nonnative speech learning. The investigation into the relationship between nonnative speech learning and native phonological processing ability is a novel contribution by the present paper.

2.1 Participants

All participants provided informed consent according to University of Connecticut (UConn) IRB guidelines. A total of 88 participants were recruited from the UConn community and enrolled. Nine participants did not complete the study. Of the remaining 79 participants, 64 [21 male, mean age 20.71, standard deviation (SD) 1.96 yrs] met the following inclusionary criteria: monolingual speakers of American English, with a self-reported history of typical gestation, hearing, and sensory-motor development, and with no neurological, attentional, or socio-emotional disorders. Participants passed a 25 dB hearing level pure tone audiometric screening (at 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 6 kHz) during the study. Data from these 64 participants are included presently.

Native phonological processing abilities are linked to language and reading ability (e.g., Ramus *et al.*, 2013). Thus, in order to ensure that our sample included a wide range of phonological processing abilities, we aimed to recruit individuals across a wide range of language and reading abilities. To this end, recruitment materials included specified wording welcoming those with a history of language and reading-based difficulties. Therefore, our sample includes a greater representation of those with language (22%) and reading difficulties (15%) than a normative sample. We will address the implications of this breakdown to our findings in Sec. 4.

2.2 Stimuli

Five unique tokens each of the target "words" (/ɖug/ - /d̪ug/) were spoken by a male native speaker of Hindi and digitally recorded in a sound-attenuated audiology booth at UConn. The tokens were rescaled to a mean amplitude of 70 dB sound pressure level (SPL) using PRAAT software (Boersma and Weenink, 2011). In order to standardize presentation timing across trials, the tokens began at the onset of the burst. Auditory stimuli were presented through Hi-Fi digital Sound Monitor headphones (SONY MDR-7506, Sony Electronics Inc., Laredo, TX) at a listening level of 70 dB SPL. Auditory tokens were paired with two novel visual objects during training ("Fribbles," stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, http://www.tarrlab.org/).

2.3 Procedures

Participants completed the nonnative phonetic training and assessments in two sessions over 2 days. In order to limit the amount of potential exposure to English between sessions, all participants were trained on the dental-retroflex /d̪/ -/ɖ/ (Hindi) contrast late in the evening (8 PM), and were assessed their ability to identify and discriminate between the trained contrast immediately after training, and again on the following morning (8 AM). Stimulus presentation and response recording for the nonnative contrast training/assessments were controlled using E-Prime 2.0 (Psychology Software Tools, Inc., Pittsburgh, PA).

Phonological processing ability was assessed through the Elision, Blending, and NWR subtests of the Comprehensive Test of Phonological Processing (CTOPP; Wagner *et al.*, 1999). In the Elision subtest, examinees are instructed to remove a specified phoneme from a presented word, and to produce the resultant word. In the Blending subtest, participants are presented with a sequence of speech segments, and then instructed to put the segments together to produce a word. In NWR, participants hear a series of nonwords and are asked to repeat the word that they hear. Items are scored in whole numbers correct (1) or incorrect (0). Because our measures all rely in varying degrees on verbal working memory, we also obtained a Digit Span composite score (Weschler Adult Intelligence Scale–IV; Wechsler, 2008) for potential inclusion as a model covariate.

Five participants completed the CTOPP and Digit Span subtests within 6 months prior to the study. The remaining completed these measures on Day 2 of the experiment, immediately after reassessment of the nonnative contrast. The measures were administered by one of two trained graduate students, and rescored by a trained undergraduate student. Discrepancies in scoring were flagged by the second scorer, and resolved by F.S.E.

Identification training/assessments. Participants were first presented with a familiarization sequence in which each token from the token set was presented simultaneously with the corresponding visual object. Participants were shown both visual objects on the screen, and instructed to choose the picture corresponding to the "word" that they hear. Participants completed 200 trials, with written feedback ("correct!" or "incorrect") after every trial. Participants were given a 2-min break halfway through training. In each of the two post-training assessments (Day 1 [immediate] and Day 2 [12-h post]), participants completed 50 trials without feedback.

Discrimination assessments. Participants completed Discrimination assessments at three time points: before training (baseline), immediately after training, and on Day 2. Participants were instructed that they will hear a sequence of two words, and that they must indicate if the two words begin with the same speech sound, or with different speech sounds. Following four practice trials, participants completed 128 trials (64 "same"/64 "different") of this task without feedback. Each "same" trial contained two different exemplars of the same sound (e.g., /ɖug$_1$/-/ɖug$_2$/), and each different trial contained one retroflex and one dental (e.g., /ɖug/-/d̪ug/), such that discrimination judgments were made on category membership rather than low-level acoustic differences. In order to further promote judgments based on phonetic identity, the two tokens were presented 1 s apart from offset to onset.

3. Analyses and results

Proportions accuracy was converted to d' scores (MacMillan and Creelman, 2004). In order to avoid infinite values, hit and false alarm rates of 0 or 1 were adjusted to a maximum z-score of 4.65. Raw number of items correct on the CTOPP subtests, and the Digit Span composite scores, were Z-normalized prior to analyses.

We first confirmed that participants were successfully trained; we determined that the immediate post-training Identification scores were above chance (d' of 0) by conducting a one-sample t-test ($t_{63} = 9.15$, $p < 0.001$, 95% confidence interval (CI): [1.91, 2.98]). We then conducted a paired t-test across the two identification scores, to determine if changes in performance took place over the time in the absence of further training. We found that Day 2 scores were higher in comparison to Day 1 ($t_{63} = -3.13$, $p = 0.003$, CI: [−1.75, −0.39]). Finally, in order to determine the effects of training and Time on Discrimination scores, we conducted a repeated measures analysis of variance (ANOVA) on the Discrimination scores. We found a significant main effect of Time ($F_{2,132} = 32.37$, $p < 0.001$, $h^2 = 0.329$), driven by significant training-induced gains ($t_{63} = -5.42$, $p < 0.001$, 95% CI: [−0.74, −0.34]) followed by a non-significant increase in performance overnight ($t_{63} = -1.44$, $p = 0.155$, 95% CI: [−0.29, 0.05]). These behavioral patterns on nonnative contrast training replicate previous findings (Earle and Myers, 2015b). Correlations and descriptive statistics on nonnative contrast training are provided in Table 1.

Next, we conducted a set of linear regression analyses to address whether or not native phonological processing abilities predict the initial learning of the nonnative contrast. First, we regressed the immediate post-training Identification scores, with NWR, Elision, and Blending, as predictors. The model did not significantly account for immediate post-training Identification scores ($F_{3,60} = 0.22$, $p = 0.88$, $r^2 = 0.01$), and

Table 1. Nonnative contrast training: Correlation matrix and descriptive statistics ($n = 64$). Means and SDs are expressed in d'. Correlations are expressed in Pearson's r-values. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. Holms-Bonferroni correction applied.

	Mean (SD)	Discrimination Baseline	Post-test 1	Post-test 2	Identification Post-test 1	Identification Post-test 2
Discrimination	Baseline 0.66 (0.51)	—				
	Post-test 1.21 (0.85)	0.39*	—			
	Post-test 2 1.33 (0.84)	0.49***	0.69***	—		
Identification	Post-test 1 2.45 (2.14)	0.34	0.49***	0.43**	—	
	Post-test 2 3.52 (2.78)	0.43**	0.59***	0.69***	0.41**	—

no individual predictor accounted for a significant portion of the variance [NWR: $\beta = 0.23$, standard error (SE) $= 0.29$, $t = 0.78$, $p = 0.44$; Elision: $\beta = -0.11$, SE $= 0.30$, $t = -0.35$, $p = 0.73$; Blending: $\beta = 0.03$; SE $= 0.30$, $t = 0.09$, $p = 0.93$]. We then regressed the immediate post-training Discrimination scores, with Elision, Blending, and NWR as predictors. Again, we found that the model was insignificant ($F_{3,60} = 0.75$, $p = 0.53$, $r^2 = 0.03$), with no predictor accounting for a significant portion of the variance (NWR: $\beta = 0.00$, SE $= 0.12$, $t = -0.03$, $p = 0.98$; Elision: $\beta = -0.06$, SE $= 0.12$, $t = -0.47$, $p = 0.64$; Blending: $\beta = 0.17$, SE $= 0.12$, $t = 1.47$, $p = 0.15$). This suggests that native phonological ability does not predict one's ability to learn a nonnative contrast, measured immediately after training.

We conducted the next set of analyses in order to address if native phonological processing abilities predict the retained (post-sleep/consolidation) learning of the nonnative contrast on Day 2 (see Fig. 1). First, we regressed the Day 2 post-training Identification scores, with NWR, Elision, and Blending as predictors. The model showed a trend toward significance ($F_{3,60} = 2.51$, $p = 0.06$, $r^2 = 0.11$). Furthermore, NWR scores independently accounted for a significant portion of the variance ($\beta = 0.73$, SE $= 0.34$, $t = 2.00$, $p = 0.05$), after adjusting for Elision and Blending ($\beta = -0.19$, SE $= 0.36$, $t = 2.00$, $p = 0.61$; $\beta = 0.51$, SE $= 0.37$, $t = 1.37$, $p = 0.17$, respectively). We then regressed the Day 2 post-training Discrimination scores, with NWR, Elision, and Blending as predictors. The model significantly accounted for variance in the Day 2 post-training Discrimination scores ($F_{3,60} = 3.30$, $p = 0.03$, $r^2 = 0.14$). Furthermore, Blending scores independently accounted for a significant portion of the variance ($\beta = 0.28$, SE $= 0.11$, $t = 2.51$, $p = 0.01$), after adjusting for Elision and NWR ($\beta = -0.05$, SE $= 0.11$, $t = -0.49$, $p = 0.62$; $\beta = 0.13$, SE $= 0.11$, $t = 1.20$, $p = 0.23$, respectively).

We further wished to determine if these relationships between Day 2 native phonological processing and nonnative speech perception were independent of, or epiphenomenal to, individual differences in verbal working memory. We therefore ran the same regression analyses as above, with Digit Span composite included as a model covariate. We found that, after adjusting for verbal working memory, the relationships between phonological processing ability and Day 2 performance on nonnative speech

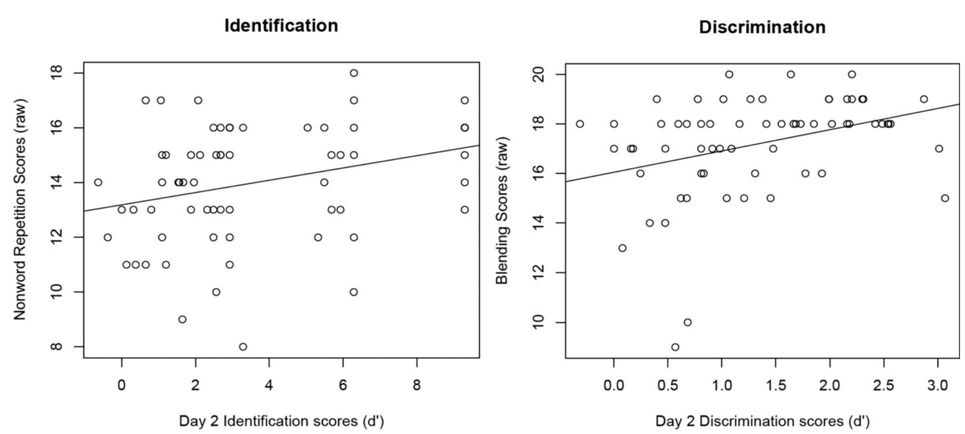

Fig. 1. Phonological processing skills plotted against outcome of nonnative contrast training on Day 2 ($n = 64$). Scatterplots and regression lines depicting the relationship between NWR and Identification, and Blending and Discrimination, on Day 2. Values for the depicted regression lines are as follows. Identification ~NWR: $F_{1,62} = 5.67$, $p = 0.02$, $r^2 = 0.08$. Discrimination ~ Blending: $F_{1,62} = 8.49$, $p = 0.005$, $r^2 = 0.12$.

Table 2. ANOVA tables for Day 2 Identification and Discrimination performance regressed with phonological processing skills as predictors. * denotes significance at 0.05 level.

Identification						Discrimination					
	df	Sum Sq	Mean Sq	F	Sig		df	Sum Sq	Mean Sq	F	Sig
NWR	1	40.86	40.86	5.61	0.02*	*NWR*	1	2.24	2.24	3.47	0.07
Elision	1	0.07	0.07	0.01	0.92	*Elision*	1	0.06	0.06	0.09	0.77
Blending	1	13.48	13.48	1.85	0.18	*Blending*	1	4.00	4.00	6.21	0.02*
Digit Span	1	3.53	3.53	0.48	0.49	*Digit Span*	1	0.14	0.14	0.22	0.64
Residual	59	7.29				*Residual*	59	38.02	0.64		

perception tasks were strengthened. These results are summarized in Table 2, and see Table 3 for a correlation matrix that summarizes the relationships between tasks.

In summary, we found that native phonological processing skills do not predict nonnative contrast learning when assessed immediately after training. Following a period of sleep, we found that NWR skills predicted nonnative Identification performance, and Blending predicted nonnative Discrimination performance. This may suggest that native and nonnative speech sounds may be similarly represented, but only after sleep has taken place between training and assessment of the new (nonnative) speech information.

4. Discussion

Interpretation of the particular relationships between phonological processing tasks (i.e., NWR as predictive of Identification, and Blending as predictive of Discrimination) requires further discussion. We have previously argued that Identification and Discrimination likely recruit speech information encoded by different memory systems (for details on this proposal, see Earle and Myers, 2014). Speech Identification, in that it requires the explicit recall of the mapping between the auditory token and a category label, resembles a declarative memory task akin to word learning. In contrast, Discrimination does not necessitate awareness of the category label, but rather requires the implicitly acquired skill of attending selectively to the acoustic-phonetic features that are relevant for disambiguating the contrast. While perceptual task abilities are likely to be correlated (Table 1), our proposal is broadly consistent with reports that different sources of linguistic information influence speech Identification and Discrimination performance (e.g., Antoniou *et al.*, 2013).

Blending, Elision, and NWR tasks are all used to measure aspects of phonological processing, however each of these tasks relies on subtly different underlying knowledge. NWR, which requires participants to repeat a set of phonotactically legal nonwords, is thought to be supported by lexical knowledge (Metsala and Chisolm, 2010) that influences the efficiency with which constituent syllables are maintained in phonological short-term memory (Gathercole *et al.*, 1994). The finding that this phonological processing ability, which relies on underlying lexical knowledge, predicts Identification skill is consistent with our consideration of the Identification task as broadly analogous to a measure of word learning.

In contrast, Elision and Blending are considered measures of phonological awareness, or an individual's ability to recognize, isolate, and manipulate the sound

Table 3. Phonological processing and nonnative contrast tasks: Correlation matrix and descriptive statistics ($n = 64$). Means and SDs are expressed in raw items correct. Correlations are expressed in Pearson's r-values. *$p < 0.05$, Holms-Bonferroni correction applied.

	Discrimination			Identification	
Mean(SD)	Baseline	Post-test 1	Post-test 2	Post-test 1	Post-test 2
Elision 17.84(2.60)	0.19	0.01	0.11	−0.01	0.08
Blending 17.19(2.07)	0.13	0.18	0.35*	0.02	0.23
NWR 13.97(2.16)	0.2	0.03	0.22	0.1	0.29*

structure of his or her oral language (Torgesen *et al.*, 1997). Blending requires recognition more so than manipulation of phonological units, as participants are asked to combine individually presented segments into whole words. While this task also requires storage of phonological segments, it is greatly influenced by the ease with which the participant can match features of isolated sounds to a preexisting lexical item. Such skills would be particularly relevant in a speech Discrimination task, in which participants are asked to match relevant phonetic features across tokens. This differs starkly from the task requirements of Elision. In this task, participants are asked to manipulate aurally presented words by subtracting component parts of those words (e.g., "say *bold* without saying /b/"). This requires simultaneous storage and processing of increasingly isolated units as the task progresses from subtraction of full syllables, to syllable onsets, to individual phonemes within blends. Elision therefore requires robust, meta-linguistic phonological awareness, likely beyond the sound representation that one is able to establish through a single session of perceptual training.

There are certain limitations to the current data that warrant caution in interpretation. First, while our results are statistically significant, the magnitude of these effects is small. One factor we are unable to account for is whether or not the duration and quality of sleep during the experiment period is representative of a given participant's habitual sleep behavior. In other words, the relatively small effects may reflect additional variability relating to potential differences between sleep obtained during the experiment period and day-to-day sleep involved in the regular maintenance of native phonological representations. Future work, taking into account habitual sleep behavior in relation to sleep obtained during the experiment period, will determine if this is the case.

Finally, our sample included a greater-than-normal distribution of individuals with difficulties associated with poor native phonological processing abilities. Thus, our associations between native and nonnative speech abilities may be driven, in part, by relative weaknesses in both by those with language disabilities. Considering this, it is particularly interesting that the relationships between native and nonnative speech abilities do not emerge until Day 2. This may suggest that relative weaknesses on nonnative speech processing in those with language difficulties are not apparent until after consolidation.

The current study adds to a sparse, yet growing literature that points to native phonological representations as a predictor of eventual foreign speech learning success (e.g., Diaz *et al.*, 2008). Previous authors who have identified relationships between native phonology and nonnative speech outcomes have proposed that such findings reflect individual differences in a "language-specific" capacity for learning (Sebastián-Gallés and Díaz, 2012). The current observations neither support nor refute this claim. However, we note that the nuance of our account is consistent with a domain-general memory consolidation mechanism. Specifically, the present contribution highlights the delayed emergence of a predictive relationship between native speech ability to nonnative speech learning following post-training sleep. This may suggest an overnight change in nonnative speech representations as to render them more "native-like." Broadly interpreted, native and nonnative speech information may undergo similar processes in order to establish long-term representations.

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