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Distributional training of speech sounds can be done with continuous distributions

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Abstract: In previous research on distributional training of non-native speech sounds, distributions were always discontinuous: typically, each of only eight different stimuli was repeated multiple times. The current study examines distributional training with continuous distributions, in which all presented tokens are acoustically different. Adult Spanish learners of Dutch were trained on either a discontinuous or a continuous bimodal distribution of the Dutch vowel contrast /aː/–/a/:. Both groups improved their perception of the contrast; this shows that continuous training works equally well as discontinuous training. Using the more natural continuous distributions is therefore recommended for future distributional learning experiments.

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1. Introduction
Earlier research has shown that adult learners can improve their discrimination or classification of a non-native speech sound contrast simply by listening for a few minutes to a bimodal distribution representing this contrast (Maye and Gerken, 2000, 2001; Hayes-Harb, 2007; Gulian et al., 2007; Escudero et al., 2011; Wanrooij et al., 2013). This phenomenon is called “distributional learning.” The stimuli differ from one another in steps along an acoustic continuum. For a bimodal distribution, two stimuli with acoustic properties near the end points of the continuum (e.g., the two stimuli with F1 values of 11.9 and 14.0 ERB in Fig. 1; left) are presented more often than the other stimuli (as represented by the varying line lengths in the figure). Through the differences between the stimuli in their frequency of presentation, listeners supposedly start to treat these two most frequently presented stimuli (and their acoustic neighbors, which are presented slightly less often) as exemplars of two different speech sounds.

1.1 Discontinuous and continuous distributions
In all previous studies on distributional learning, bimodal distributions were based on stimuli with 8 or 10 different values for voice onset time (e.g., Maye and Gerken, 2000, 2001; Hayes-Harb, 2007; Maye et al., 2002; Maye et al., 2008; Yoshida et al., 2010), vowel formants (e.g., Gulian et al., 2007; Escudero et al., 2011; Wanrooij et al., 2013), or fricative frequencies and formant transitions (Cristià et al., 2011), and these stimuli were repeated in certain proportions. In Fig. 1 (left), for instance, the eight stimuli (the thin vertical lines) are spaced at equal distances along the F1 continuum, and some stimuli are presented more often than others (the height of the vertical lines), while acoustic values in between those of the eight stimuli are never presented. We therefore label such distributions “discontinuous.”

In a natural environment, however, acoustic values are never repeated exactly. Rather, naturally occurring speech tokens can have any value (between certain bounds)
along the relevant acoustic dimension. When applying this idea to a bimodal stimulus distribution for distributional training, we obtain Fig. 1 (right), where the stimuli (the thin vertical lines) are spaced more densely around 12.2 and 13.7 ERB and more sparsely elsewhere, and each stimulus is presented only once. We therefore label such distributions “continuous.”

In the current study, we aimed to examine whether previous observations obtained with discontinuous distributions might have been artifacts of the unnatural sampling method. After all, it is known that input variability can influence category formation and discrimination (Lively et al., 1993; Rogers and Davis, 2009), so that one could hypothesize that the observed changes in participants’ behavior after training were due to the artificially sparse (eightfold) sampling of the acoustic space. To find out whether the effects reported in the distributional learning literature have not been methodological artifacts, one would have to test whether adult listeners also improve classification performance through listening to a more ecologically valid continuous distribution, with more variation in acoustic values, and without stimulus repetition. This is done in the present article, which compares three groups of participants: one group was presented with a discontinuous training (hence, the Discontinuous group), another group with a continuous training (hence, the Continuous group), and the third group was a control group that listened to classical music (the Music group). As explained in Sec. 2.1, the Discontinuous and Music groups were taken from Wanrooij et al. (2013).

1.2 A vowel contrast and its appropriate participant group

For the acoustic continuum we chose the Dutch vowel contrast /a/-/aː/. For this contrast, appropriate listeners are native speakers of Spanish. This group is known to have difficulty classifying the two Dutch vowels when the durational difference (/aː/ is longer; Adank et al., 2004) is eliminated, so that only the spectral difference (/a/ has higher first and second formants; Pols et al., 1973; Adank et al., 2004) can be used to classify the vowels correctly (Escudero and Wanrooij, 2010; Escudero et al., 2011; Wanrooij et al., 2013). To train the Spanish listeners on this spectral difference only, the manipulated acoustic dimensions in both distributions (i.e., discontinuous and continuous) were the first and second formant values (F1 and F2), and the duration of the training vowels was kept constant (see also Escudero et al., 2011; Wanrooij et al., 2013). Note that Fig. 1 shows the discontinuous and continuous distributions of the F1 values only; because F2 values varied linearly with those of F1, the pictures for the discontinuous and continuous F2 distributions look identical.

2. Method

The method was identical to that of Escudero et al. (2011) and Wanrooij et al. (2013). Participants performed a pre-test (Sec. 2.3), a training phase (Sec. 2.2) and a post-test (Sec. 2.3).
2.1 Participants

Participants were adult native speakers of Spanish who were learning Dutch. Only the Continuous group was new, and it consisted of 50 participants. The Discontinuous group was taken from an earlier study as follows. To ensure a high-level benchmark for the Continuous group, we chose for our Discontinuous group the group that had shown the most improvement of all four groups that received discontinuous distributional training in two recent studies in our lab (Escudero et al., 2011; Wanrooij et al., 2013). These two studies used identical pre- and post-tests and an identical procedure as those used for the Continuous group in the present study, and in both studies the results were the same. Specifically, in both studies three groups of Spanish listeners participated, one presented with a discontinuous bimodal distribution representing the Dutch contrast /a/-/æ/ (the Bimodal group), one exposed to a discontinuous enhanced bimodal distribution of the same contrast (the Enhanced group), and one, the control condition, presented with classical music (the Music group). In the enhanced bimodal distribution, the perceptual distance between the end point acoustic values of the training stimuli was larger than that in the non-enhanced bimodal distribution. Accordingly, the difference between the two speech sounds was “exaggerated” and thus presumably easier to perceive (Kuhl et al., 1997; Liu et al., 2003).

With new Spanish participants in the Bimodal and Enhanced groups (50 in each group), Wanrooij et al. (2013) replicated the results obtained for the participants (53 in each group) in Escudero et al. (2011), i.e., that (1) the Enhanced group improved significantly in accuracy of classification of Dutch /a/ and /æ/, (2) the Music group did not show significant progress, and (3) the Enhanced group improved significantly more than the Music group. Table 1 shows the difference scores (i.e., post-test minus pre-test classification accuracy in percentages) for each group (i.e., Enhanced, Bimodal, Music) in both studies.

It can be observed that the Enhanced group in Wanrooij et al. (2013) had the highest absolute improvement after training of all four groups, with a 95% confidence interval (CI) that appeared narrower and further from zero than in Escudero et al. (2011). Therefore we used this group as a stringent standard against which to compare our Continuous group. In addition, we compared the results of the Discontinuous and Continuous groups to the Music group’s results as obtained in Wanrooij et al. (2013). In Escudero et al. (2011) and Wanrooij et al. (2013), a music condition was preferred over a unimodal control condition for ethical reasons, because all participants were learners of Dutch and previous research had shown that a unimodal distribution may reduce discrimination performance (Maye et al., 2002; Wanrooij et al., 2012). Table 2 lists the mean age, age range, and length of residence in the Netherlands as a measure of previous exposure to Dutch, for the Discontinuous (12 male, 38 female), Continuous (15 male, 35 female), and Music (6 male, 44 female) groups separately.

2.2 Training: Stimuli and procedure

The stimuli in the continuous and discontinuous training distributions were made with the Klatt synthesizer in the computer program PRAAT (Boersma and Weenink, 2011). Each stimulus in both distributions had a fundamental frequency (F0) contour that fell from 150 to 100 Hz. Also the stimulus duration was 140 milliseconds (ms), and the inter-stimulus interval was 750 ms. Total training time was nearly 2 minutes.

Table 1. Difference score (= post-test minus pre-test percentage correct) for groups of Spanish listeners presented with enhanced, bimodal and musical training phases in two previous studies. Ninety-five percent confidence intervals are given between parentheses.

<table>
<thead>
<tr>
<th>Previous study</th>
<th>Enhanced</th>
<th>Bimodal</th>
<th>Music</th>
</tr>
</thead>
<tbody>
<tr>
<td>Escudero et al. (2011)</td>
<td>6.04 (+2.76…+9.31)</td>
<td>0.80 (−2.22…+3.83)</td>
<td>−0.15 (−3.50…+3.21)</td>
</tr>
<tr>
<td>Wanrooij et al. (2013)</td>
<td>6.63 (+4.05…+9.20)</td>
<td>3.83 (+0.97…+6.68)</td>
<td>2.00 (−0.50…+4.50)</td>
</tr>
</tbody>
</table>
The stimuli in the discontinuous distribution are described in detail in Escudero et al. (2011) and Wanrooij et al. (2013). The F1 values (range: 11.5–14.4 ERB) and F2 values (range: 15.3–18.2 ERB) varied in eight steps of approximately 0.4 ERB apart. Stimuli 1 through 4 with the lower F1 and F2 values can be thought of as representing the Dutch vowel /a/, and stimuli 5 through 8 with the higher F1 and F2 values can be thought of as representing the Dutch vowel /a/. Stimuli 1, 4, 5, and 8 in the tails (see Fig. 1, left) were each presented eight times, stimuli 2 and 7 at the peaks each occurred 32 times, and stimuli 3 and 6 were each presented 16 times. Thus the total number of presentations was 128.

To make a continuous distribution that would correspond as closely as possible to the discontinuous one, we first had to match the shapes of the distributions. For this, we approximated the ratio of the least to most frequent stimuli; i.e., this ratio is 1 to 4 in earlier studies with discontinuous distributions and is approximately 1 to 4 in the current continuous distribution (see Fig. 1). Further, we created the underlying continuous distribution as the sum of two Gaussian curves the means of which were positioned at 25% and 75% of the F1 range (and consequently also of the F2 range), and the standard deviations of which were set to 11% of the total F1 (or F2) range. This distribution is the probability density function shown in Fig. 1 (right).

The next step was the determination of the F1 and F2 values for each stimulus. We created the same total number of stimuli (128) as for the discontinuous distribution. This time none of the stimuli was repeated, so that each stimulus had a unique combination of F1 and F2 values. As the procedure for the calculation of the F2 values is the same as that for the F1 values, we restrict the description to the F1 values, as follows.

After determining the precise shape of the underlying continuous distribution (the gray curve in Fig. 1, right), the F1 values of the 128 stimuli (the thin vertical lines in Fig. 1, right; for the purpose of clarity only 64 stimuli are shown) were calculated in the following way. First, the area under the curve was normalized, i.e., it was set to 128, the number of stimuli. Then the distribution was sampled evenly, i.e., the F1 values were chosen in such a way that the area between consecutive F1 values under the curve was always 1. Thus there were 127 unit areas between the 128 F1 samples. The additional leftmost area (running from the left edge of the F1 continuum to the first F1 sample) and rightmost area (running from the last F1 sample to the right edge of the F1 continuum) were 0.5 each.

The task of the participants in the training phase was merely to listen. Participants in the Discontinuous and Continuous groups were instructed to listen to the vowels carefully because they would perform a post-test afterward. Participants in the Music group were asked to relax while listening to the music and were informed that they would perform a post-test afterward.

2.3 Pre- and post-tests: Stimuli and procedure
The pre- and post-tests, which were equal to those used in Escudero et al. (2011) and Wanrooij et al. (2013), were identical classification tasks, which were the same for all participants. Listeners heard an X-stimulus and two subsequent response options.
A and B. They were forced to choose which option was from the same vowel category as X.

The X-stimuli were chosen to be natural vowels to promote classification rather than discrimination; they were a subset of the vowels reported in the corpus by Adank et al. (2004), which were produced by male and female speakers of standard Northern Dutch. The response options A (F1 = 12.5 ERB, F2 = 16.1 ERB) and B (F1 = 13.3 ERB, F2 = 17.4 ERB) were chosen to be synthetic; they were created with the computer program Praat (Boersma and Weenink, 2011) and had an equal duration of 140 ms to prevent participants from resorting to durational differences between /a/ and /a/ (recall Sec. 1.2).

In each test, participants were asked to classify 80 X-stimuli. Listeners were told that the next trial would only appear after their response, but they were encouraged to answer as quickly as possible and to guess if they were unsure. To test hearing and understanding of the test, the participants performed a practice test before the pre-test and before the post-test.

### 3. Results

Table 3 gives the pre- and post-test percentages correct (i.e., the percentage of correct classifications of the 80 test stimuli) and the difference (i.e., the post- minus pre-test percentage correct) for the Music, Discontinuous, and Continuous groups. An ANOVA on pre-test accuracy did not display a significant difference between the three groups \[ F(2,147) = 0.40, p = 0.67 \]. This supports the equality of the groups before training.

The difference between pre- and post-test accuracy is a measure of improvement after training. For the Continuous group, this difference was 9.68% (95% CI = +6.80%...+12.55%), which was significantly different from zero [one-sample \( t(49) = 6.75, p < 0.001 \)]. As reported in Wanrooij et al. (2013), the difference score also differed from zero significantly for the Discontinuous group [one-sample \( t(49) = 5.17, p < 0.001 \], and it did not for the Music group [one-sample \( t(49) = 1.61, p = 0.12 \] (95% CIs: see Table 1). This confirmed that both the Discontinuous and the Continuous groups improved their accuracy percentages robustly after training. An ANOVA with difference scores as the dependent variable revealed a significant difference between groups \[ F(2,147) = 8.54, p < 0.001 \]. Post hoc tests on the difference scores using Tukey’s HSD for multiple-comparison corrections showed a significant difference between the Music and Discontinuous groups of +4.63% (CI = +0.20%...+9.05%, \( p = 0.04 \)) and between the Music and Continuous groups of +7.68% (CI = +3.25%...+12.10%, \( p < 0.001 \), and no significant difference between the Discontinuous and Continuous groups (difference = +3.05%, CI = −1.38%...+7.48%, \( p = 0.24 \)). Thus participants who received distributional training improved more than participants who listened to music instead, although we cannot say with confidence that the progress of the Continuous group (9.68%) was larger than that of the Discontinuous group (6.63%).

### 4. Conclusion

We showed that listeners’ performance in classifying a non-native phoneme contrast can be improved not only by training them with a discontinuous distribution but also...
by training them with a continuous distribution. We can therefore erase the fear that earlier results demonstrating an effect of training with discontinuous distributions (e.g., Maye and Gerken, 2000, 2001; Maye et al., 2002, 2008; Hayes-Harb, 2007; Gulian et al., 2007; Yoshida et al., 2010; Escudero et al., 2011; Cristiá et al., 2011; Wanrooij et al., 2013) could have been artifacts of the discontinuous sampling method; after all, these results have now been replicated with the arguably more natural continuous distributions, so it has become more likely that the observed perceptual improvements are a realistic result of bimodal training. However, as both types of sampling have now been shown to exhibit distributional learning effects and continuous distributions can be considered more ecologically valid than discontinuous distributions, we recommend for future distributional learning experiments not to artificially reduce the variation in the stimuli to 8 or 10 auditory values but to solely employ continuous distributions.

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References and links


