Development of voicing categorization in deaf children with cochlear implant

Victoria Medina, Willy Serniclaes

Laboratoire Psychologie de la Perception, Université Paris Descartes, CNRS
medina_vicky@yahoo.fr, willy.serniclaes@parisdescartes.fr

Abstract

Cochlear implant (CI) is an electronic device that can improve the hearing of a person with profound or severe deafness. In children, cochlear implant enables the acquisition of oral language. However, there are important cross-individual variations in the perceptual performance of implanted children.

Categorical perception (CP) is the phenomenon by which differences between stimuli are not perceptible except if they belong to different categories [1]. CP filters acoustic variations that are not pertinent to speech communication, facilitating the storage and transport of information to superior levels of linguistic processing.

CP is assessed using two different tasks: identification and discrimination. The difference between observed and expected discrimination (from the identification task) is often used as the evaluation criterion. Phoneme boundary precision, otherwise "boundary precision" is another categorical property used to measure the size of the observed and expected discrimination peaks. The observed discrimination peak is equivalent to the Phoneme Boundary Effect (PBE; [2]) and the expected discrimination peak is equivalent to the slope of the identification function.

Developmental studies showed that CP is predisposed to voicing [3]. CP changes in the first year of life and is adapted to the phonemic oppositions present in the native language [4], [5]. Boundary precision continues to develop later, at least up to some 9 years old [6], [7], [8].

Communication abilities in deaf children might depend on their CP and boundary precision performances. The cochlear implant improves hearing although communication abilities also depend on other factors, mainly on deafness duration without implant and implantation age [9]. These factors seem to act on the development of the phonological level before implantation. This is suggested by the effect of the size of the phonemic repertory before implantation on the rate of development after implantation [10]. Therefore, they might affect the development of either categorical perception or boundary precision, or both.

The aim of the present study is to examine the development of voicing categorization in deaf children with cochlear implant via CP and boundary precision performances.

2. Method

2.1. Participants

Five groups of native French speakers took part in this study. Four of these groups were the normal-hearing children: 11 control children of four years of age; 14 control children of six years of age; 13 control children of eight years of age and 17 control children of 10 of ten years of age.

The fifth group involved implanted children: 22 deaf children with cochlear implant from six to twelve years old with a minimum of two years of implantation, 19 with a congenital profound hearing loss and 3 with acquired profound hearing loss. These children had an "Auditory Age" (length of implant usage) of: three years (N=3), four years (N=8), six years (N=9), and eight years (N=2).

2.2. Stimuli

2.2.1. Minimal Pairs Discrimination. Evaluation protocol with standardized stimuli (PEPS)

This protocol was a modified version of the "Evaluation Test of Speech Production and Perception" (Test d'Evaluation de la Production et de la Perception de la Parole, TEPPP; [11]). This protocol included simplified and complete lists. We used consonant lists based on CV syllables recorded by a French speaker. These lists assessed 16 consonants in /a, u, i/ context. The complete list contained 16 different pairs and 16 same pairs to assess the four consonant features: manner, place, voicing and nasality.
to the stable part of the vowel were fixed at 500, 1500 and 2500 Hz respectively for F1, F2, F3. A friction noise of 10 ms preceded the beginning of transitions. The F0 was fixed to 120 Hz, the transition duration and stable vocalic duration were set to 24 ms and 180 ms respectively.

Figure 1: Voicing continuum from /ds/ to /ts/. Stimuli from left to right: -45ms of VOT, -15ms of VOT, +15ms of VOT and +45ms of VOT.

2.3. Procedure

The procedure consisted in three successive stages: a minimal pairs test, a identification/discrimination training session using the endpoints of the continuum and a CP test using the whole continuum. The stimuli were played back through loudspeakers.

The identification and discrimination answers were given by pressing one out of two different coloured keys on the computer keyboard. In the identification task, each stimulus was presented 10 times in a pseudo-random order and the participants had to answer either /ds/ or /ts/. In the discrimination task, the stimuli were presented pairwise (AX format) involving either different stimuli (in two different orders, e.g. -45 ms VOT followed by -15 ms VOT, or -15 ms VOT followed by -45 ms VOT) or the same stimuli presented twice (e.g. two times -45 ms VOT, or two times -15 ms VOT). Each pair was presented 5 times in a pseudo-random order and the participants had to answer “same” or “different”. We modified the procedure for 4 years old control children who gave oral answers.

2.3.1. Data processing

Categorical perception was measured by comparing the magnitudes of the expected and observed discrimination peaks. The peaks were calculated as the difference between across- and within-category discrimination scores. The expected discrimination scores were derived from the identification data using classical formulas [12]. Boundary precision was assessed using the values of either the expected or the observed discrimination peaks.

3. Results

3.1.1. Minimal Pairs Discrimination

All control children discriminated minimal pairs with over 98% of correct answers whereas implanted children obtained 75.2%. The control children showed near perfect performance. For this reason only the results of implanted children are presented in Figure 2. For implanted children, the best discriminated feature was the manner (69% correct discrimination) and the worst was the place (51% correct discrimination). A Feature X Auditory Age interaction in a repeated measures ANOVA showed that the feature discrimination did not depend on auditory age (F(3,18)=2.10, p=.14). Although, the feature effect was not significant (F(3,54)=2.53, p=.07). The examination of discrimination scores indicates that discrimination performances are lower for place (Figure 2) and contrast analysis showed significant differences between place and manner (F(1,18)=5.29, p<.05) and between place and voicing (F(1,18)=4.31, p=.05). Further, the Feature X Group interaction was significant (F(9,54)=2.57, p<.05). This interaction arisen from weaker performance in nasality perception by the children of only three years of auditory age. They presented relatively low discrimination scores for nasality vs. other features comparing to the other groups.

Figure 2: Discrimination scores of consonant features on minimal pairs in implanted children.

3.1.2. Categorical perception and boundary precision

Figures 3 and 4 show the expected and observed discrimination peaks of control and implanted children in relation to auditory age (corresponding to length of implant usage in implanted children and to chronological age in control children). As can be seen, the two discrimination peaks progressed in a similar way as a function of age for both groups.

Figure 3: Expected discrimination peak. Implanted children (N=22) in black triangles and control children (N=55) in gray.
CP (the difference between expected and observed peaks) did not depend on either age or group. In order to assess differences in boundary precision, the effect of age on the expected and observed discrimination peaks was analyzed using linear regressions for both the control and implant children. The results are presented in Table 1. For the control children, the expected discrimination peak was significantly correlated with the auditory age. There was also some correlation between the observed discrimination peak and auditory age, but it failed to reach significance. For the implanted children, the expected discrimination peak was significantly correlated with auditory age, but not with implantation age. The observed discrimination peak was not significantly correlated with the auditory age and not implantation age either. These results show that for both groups only the identification capacities depend on the auditory age. However, the observed discrimination peak does not depend on the auditory age.

Table 1. Linear Regressions of expected and observed discrimination peak with different factors for control and implanted children

<table>
<thead>
<tr>
<th>Discrimination Peak</th>
<th>Control Group</th>
<th>CI Group</th>
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<tbody>
<tr>
<td>Expected discrimination peak (Same-different answer)</td>
<td>Explained Variance: 18% F(1,54)=13.31; p=.001*** Auditory Age: p=0.01***</td>
<td>Explained Variance: 31% F(2,21)=5.77; p=0.05** Auditory Age: p&lt;.01** Implantation Age: p=.39</td>
</tr>
<tr>
<td>Observed discrimination peak (Same-different answer)</td>
<td>Explained Variance: 4% F(1,54)=3.27; p=.08 Auditory Age: p=.08</td>
<td>Explained Variance: 1% F(2,21)=1.6; p=.34 Auditory Age: p=.22 Implantation Age: p=.95</td>
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</table>

We compared the discrimination peaks of control children with those of implanted children using an analysis of covariance (ANCOVA) with the Group (implanted or normal-hearing) and Task (expected vs. observed discrimination) as factors and the Auditory Age as covariable. The relationship between the expected and observed discrimination peaks and auditory age did not depend on the group (Group X Auditory Age interaction: F<1).

Table 1. Results of ANCOVA test of Discrimination peaks of control and implanted children by auditory age and group (control vs. implanted)

<table>
<thead>
<tr>
<th></th>
<th>Control and IC Groups</th>
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<tbody>
<tr>
<td>Expected Discrimination Peak (Same-different answer)</td>
<td>Auditory age: F(1,74)=21.45; p&lt;.001*** Group: F=1</td>
</tr>
<tr>
<td>Observed Discrimination Peak (Same-different answer)</td>
<td>Auditory age: F(1,74)=5.24; p=.05* Group: F&lt;1</td>
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4. Discussion

The results of the minimal pairs discrimination test showed that implanted children discriminated consonantal pairs with less accuracy than normal-hearing children. We found for implanted children that the best discriminated features were manner and voicing and the worst discriminated was place. These results are consistent with those found for perception in noise by normal-hearing subjects, the performances decreasing in the following order: voicing, nasality, manner, place [13].

Categorical perception (measured by the difference between expected and observed peaks) did not depend on either age or group. Boundary precision (measured by the magnitude of the observed and expected discrimination peaks) showed that implanted children categorize the voicing continuum in much the same way as the control children of the same auditory age. This suggests that implanted children don’t present a deficit when the amount of auditory experience is taken into account. They only present a delay when compared to normal-hearing children of the same chronological age and which is due to the absence of auditory stimulation between birth and implantation. When this period of deprivation is taken into account, the performances are quite similar.

Voicing is a robust feature and children with cochlear implant perceive and categorize this feature as the normal-hearing children of same auditory age. We also collected data on the perceptual development of place of articulation using the same methodology and the same groups of children as those used for voicing [14]. The results showed that place of articulation perception was very difficult for the implanted children and did not progress as a function of age. This can be explained by the nature of this feature and the technology of cochlear implant. The cochlear implant transmits information of temporal envelop and eliminates information of fine structure. While the perception of the place feature mainly depends on fine structure information, the voicing feature depends on both envelop and fine structure information whereas the place features only depends on fine structure information [15].
While the discrimination performances of the implanted children were similar to those of the control children of same auditory age for the synthetic stimuli, their performances were lesser for the minimal pairs of voicing. These minimal pairs were recorded by a French speaker. This suggests that implanted children could not use all voicing cues present in natural speech. Some of these cues were constant in our synthetic continuum, in particular the F0, which provides an important voicing cue and is fairly reliable in French natural stops [16]. The fact that F0 is conveyed by spectral fine structure [17], which is not properly transmitted by the cochlear implant [18], might explain the low performance of implanted children versus normal-hearing controls, for voicing perception with natural stimuli.

5. Conclusions
As a whole, these results suggest that the development of speech perception in CI children is fairly similar to the one in normal-hearing controls when the relevant auditory features are correctly transmitted by the implant (i.e. for voicing but not for place of articulation). The age at implantation does not seem to impose major constraints on the development of phonological categorization performances.

6. References