Production of the /t/-/k/ Contrast in Children with Cochlear Implants and Children with Normal Hearing

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In the U.S., cochlear implants (CIs) are the standard of care for children over 12 months who have a severe-to-profound sensorineural hearing loss. Despite a relatively early age of implantation, phonological development is delayed for children with CIs compared to their peers with normal hearing (NH). This is not surprising, because CIs do not transmit a rich acoustic signal. The signal is degraded spectrally, which may critically impact a pediatric CI user's acquisition of contrasts that depend on spectral cues, such as place-of-articulation contrasts. This study focuses on the acquisition of a specific place contrast, the /t/-/k/ contrast.

Normative data suggest that English-speaking children master the /t/-/k/ contrast between ages three and four. Well-established error patterns occur during this period of typical development, such as pre-vocalic voicing (e.g., “gat” for cat) and velar fronting (e.g., “tup” for cup). While there is considerable evidence that young children with CIs demonstrate delays in phonological development, there is less information on whether acquisition of specific spectral contrasts, such as the /t/-/k/ contrast, also differs qualitatively from children with NH. This study collected many productions of word-initial /t/ and /k/ sounds, and will use mixed-effects modeling to analyze accuracy and error patterns in children with CIs compared to age-matched peers with NH.

Participants included 26 children with CIs and 26 children with NH who were matched in terms of age, sex, and maternal education. As part of a larger longitudinal project, 11 of the pairs returned for a second visit and three pairs returned for three visits, resulting in 40 sessions of data. Standardized, norm-referenced assessments of vocabulary and articulation were administered. Scores indicated that both groups exhibited age-appropriate expressive and receptive vocabulary skills. Children with NH also had age-appropriate articulation skills, but the mean articulation score for children with CIs was more than 1.5 standard deviations below the age-referenced norm.

Children participated in a word-repetition task inside a sound-treated lab setting. Stimuli included 15 different /t/-initial words (e.g., “tummy”) and 21 different /k/-initial words (e.g., “kitty”). Select words were presented based on familiarity given the child’s age, and some words were repeated to achieve a balanced number of tokens across front- and back-vowel contexts for each consonant. A picture stimulus appeared on a computer screen in front of the child while the corresponding word was presented over speakers. Children repeated the word into a microphone, and responses were recorded for later analysis.

Each response was transcribed and coded in terms of voicing, manner, and place of articulation. Productions were coded as voiced if the voice-onset time (VOT) was less than 20ms. Place of articulation for stops was transcribed as [t], [k], intermediate between [t] and [k], or ‘other’. For intermediate productions, the code [t:k] was used if the sound was intermediate but closer to /t/, and [k:t] was used if it was closer to /k/. ‘Other’ places of articulation included bilabial and glottal stops.

Overall, children with CIs produced /t/ and /k/ accurately 67% of the time, and children with NH produced /t/ and /k/ accurately 92% of the time. This difference was significant for both target /t/ and target /k/ in front- and back-vowel contexts. Figure 1 shows the results of two mixed-effects logistic regression models that predict phonemic accuracy based on: fixed effects of group (CI, NH), target consonant (/t/, /k/), and their interaction; and random effects of the intercept and the slope for target consonant, with participant (at a given timepoint) as the grouping factor. To control for the effects of anticipatory coarticulation, separate models were run for productions in back-vowel context and front-vowel context.

Statistical analyses of error patterns for both groups are underway. Table 1 shows the percentage of total errors within each group that contained a voicing, place, or manner error, and the percentage of errors within each category that occurred for target /t/ and target /k/.
Figure 1. Overall accuracy of word-initial /t/ and /k/ productions in back- and front-vowel contexts for children with CIs and children with NH. Asterisks (***) indicate differences that were significant at alpha-level 0.0001.

Table 1. Voicing, Place, and Manner Errors for Children with CIs and Children with NH

<table>
<thead>
<tr>
<th>Group</th>
<th>Voicing Errors (% of total errors)</th>
<th>Place Errors (% of total errors)</th>
<th>Manner Errors (% of total errors)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># productions = 1288</td>
<td>/t/ 66% /k/ 31% /t/ 5%</td>
<td>/t/ 32% /k/ 68% /t/ 20% /k/ 80%</td>
<td></td>
</tr>
<tr>
<td># inaccurate = 97</td>
<td>56% 44%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CI</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># productions = 1255</td>
<td>/t/ 29% /k/ 53% /t/ 32% /k/ 68% /t/ 55% /k/ 45%</td>
<td></td>
<td></td>
</tr>
<tr>
<td># inaccurate = 411</td>
<td>53% 47%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The majority of errors for children with NH were voicing errors, followed by place errors, and then a very small percentage of manner errors. By contrast, the majority of errors for children with CIs were place errors, followed by manner errors, and then voicing errors. Children with NH produced proportionally more voicing errors than children with CIs. However, children with NH produced longer VOTs (mean VOT: 11.0ms) in their voiced stop substitutions compared to shorter VOTs produced by children with CIs (mean VOT: 0.61ms).

While the distribution of place errors across /t/ and /k/ was equivalent between groups, children with CIs produced proportionally more place errors overall than children with NH. When place errors occurred, children with NH produced clearly incorrect substitutions 50% of the time (including 17% transcribed as ‘other’ place of articulation), and intermediate productions between /t/ and /k/ 50% of the time. In contrast, children with CIs produced clearly incorrect substitutions 77% of the time (with 25% transcribed as ‘other’ place of articulation) and intermediate productions only 23% of the time.

For children with CIs, 31% of manner errors produced for target /t/ and 19% produced for /k/ were transcribed as affricate substitutions. For children with NH, manner errors were exceptionally rare. Of those produced, 100% that occurred on /t/ and none that occurred on target /k/ were transcribed as affricate substitutions.

These results suggest that acquisition of the /t/-/k/ contrast for children with CIs is not just delayed, but qualitatively different from that of children with NH. The children with NH showed evidence of progression towards correct articulations (e.g., greater VOTs, more intermediate productions, and very few manner errors), but the children with CIs did not show these same trends. Inaccurate productions for children with NH also typically contained only one type of error, whereas those for children with CIs often contained more than one type of error. The relatively higher percentage of place errors and lower percentage of voicing errors for children with CIs compared to their peers with NH is consistent with the limitations of cochlear implants, which preserve temporal information much better than spectral information. Understanding how phonological development for children with CIs is different from their peers with NH will help us develop more focused, effective treatment approaches for young children with CIs.

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