Speech and sign perception in deaf children with cochlear implants
Giezen, M.R.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
5 THE RELATIONSHIP BETWEEN SOUND PERCEPTION AND RAPID WORD LEARNING

The findings of the previous chapter raise interesting questions with respect to the ability of the children to learn novel minimal pairs that differ in these four phonological contrasts. In this chapter\textsuperscript{26}, we will present the results from two rapid word learning tasks described in §3.2.2. In addition, we will examine the relation between sound perception (as measured by the sound categorization task from Chapter 4), rapid word learning and phonological short-term memory. The chapter starts with the discussion of relevant previous research (§5.1), followed by a discussion of the research methodology (§5.2). The results are presented in §5.3 and discussed in §5.4.

5.1 BACKGROUND

As already mentioned in §2.1.2, studies have shown that early speech perception and lexical abilities develop in parallel, but that occasionally developmental discontinuities occur. On the one hand, Kuhl et al. (2005), for instance, showed that native speech-language phonetic discrimination at 7 months of age correlated positively with expressive vocabulary size at 18 months of age. On the other hand, experimental word learning studies have shown that early in the second year of life, infants have difficulty learning minimal pairs that differ in contrasts they can nevertheless discriminate (Stager & Werker, 1997; Werker et al., 1998). Importantly, infants at this age and even younger have no difficulty perceiving phonetic detail in familiar words (Swingley, 2007). Interestingly, the ability to learn novel minimal pairs is itself related to concurrent expressive vocabulary size (Werker et al., 2002).

With respect to older children, a strong relationship between sound perception and lexical development is expressed in the lexical restructuring model (see also §2.1.2). In this model the emergence of phonemes as units in perceptual processing is strongly associated with vocabulary growth and with increasing phonological neighborhood density in the mental lexicon (Metsala & Walley, 1998; Storkel, 2002; Storkel & Morrisette, 2002; Walley, 1993; Walley et al., 2003).

Recent studies with adult second language learners have also provided insight into the relation between speech perception and lexical development. Adult second

\textsuperscript{26} An adapted version of this chapter has been submitted for publication as Giezen, M.R., Escudero, P., & Baker, A.E. Rapid learning of minimally different words by 5- to 6-year-old children with cochlear implants. Journal of Speech, Language and Hearing Research.
and third language learners have been shown to have considerable difficulty learning novel minimal pairs if these involve phonological contrasts not present in their previously learned languages (Escudero et al., 2008; Simon, Escudero, & Broersma, 2010). Moreover, introducing a lexical contrast to adult second language learners during training of a novel phonological contrast resulted in more accurate perception of that contrast (Hayes-Harb, 2007).

Together, these findings are suggestive of a strong relationship between the development of sound perception and lexical development. As discussed in §2.1.2, this relationship raises important questions for children with a CI, given the reduced spectrotemporal resolution of sound processing with a CI and frequently observed difficulties in speech perception (Pisoni et al., 1999; Tyler et al., 1997; Wang et al., 2008). Indeed, performance on standardized speech perception tests has been found to predict other spoken language outcomes in children with a CI including expressive and receptive vocabulary knowledge (e.g. Blamey et al., 2001; DesJardin et al., 2009). However, as explained in §2.1.1, their speech perception abilities are typically assessed by means of standardized word recognition tests that provide only limited insight into their strengths and weaknesses in speech perception (Pisoni, 2005). Examining the underlying linguistic and cognitive processes involved in their speech processing, as well as the interactions between such processes, will help in obtaining a better understanding of the observed inter-individual variation in spoken language outcomes (Pisoni, 2000).

In that respect, Frisch and Pisoni (2000) modeled spoken word recognition performance in children with a CI using their phoneme identification scores on a two-alternative forced-choice word identification test with minimal pairs. They found that an interactive model of lexical access best predicted their spoken word recognition scores, as it does for children and adults with normal hearing. In addition, Eisenberg, Martinez, Holowecy and Pogorelsky (2002) compared recognition of lexically “easy” words (high frequency and low neighborhood density) and lexically “hard” words (low frequency and high neighborhood density) in children with normal hearing, with acoustic hearing aids, and with a CI. The combined effects of word frequency and neighborhood density on spoken word recognition were similar for all three groups and suggest underlying similarities in lexical organization. Finally, Burkholder-Juhasz et al. (2007) showed that spoken word recognition scores and forward digit spans correlated with non-word repetition scores for children with a CI as well as for adults with normal hearing listening to CI simulations, suggesting that they used similar component processes to perceive, store and recall non-words.

Although speech perception has been relatively well-studied in children with a CI, few studies have been done on word learning. Lexical development is usually assessed through standardized expressive and receptive vocabulary measures (Schauwers et al., 2005). As is the case with many clinically used speech perception
The relationship between sound perception and rapid word learning

In infants with cochlear implants, early-implanted infants (<15 months) performed like infants with normal hearing within six months after activation of the CI and learned the sound-event associations, whereas later-implanted children (16-25 months) did not learn the sound-event associations, even after more than one year of CI use. Tomblin et al. (2007) taught 14 children with a CI (mean age 3;8) three novel words and tested their receptive and expressive knowledge in comparison with that of 14 age-matched children with normal hearing. They found that the children with a CI performed more poorly than the children with normal hearing, but it should be noted that the scores for both groups of children showed substantial overlap. Finally, Houston et al. (2005) taught 24 2- to 5-year old children with a CI two sets of four or eight (depending on the age of the child) names for stuffed animals. The names referred to salient perceptual attributes of the animals (e.g., teeth for a shark, or fuzzy for a bear). Receptive and expressive knowledge of the names was tested immediately after exposure and following a two-hour delay. The children with a CI performed more poorly than age-matched children with normal hearing in both the immediate and delayed test conditions. In a second analysis, the authors separated the words that according to the parents were familiar to each child from those that were not. The unfamiliar words presented more difficulty for the children with a CI than the familiar words, presumably because for these words they had to encode a novel phonological form as well as a novel word-object association.

To our knowledge, only one study has directly examined the relation between speech perception and word learning in children with a CI. Willstedt-Svensson et al. (2004) administered a rapid word learning task to a group of 15 Swedish 5- to 11-year old children with a CI, together with tests of expressive and receptive language, verbal working memory, non-word repetition, non-word discrimination and speech production. The children were taught four novel words in the rapid word learning task. Receptive and expressive knowledge of the words was tested immediately after exposure and following a 30-minute delay. Correlation analyses showed that rapid word learning performance correlated significantly with non-word repetition, verbal working memory, speech production and expressive and receptive grammar, but not with non-word discrimination, a measure of speech perception. It should be noted though that overall performance on the non-word discrimination task was very poor, which might explain the absence of a correlation with rapid word learning.

To summarize, although a few studies have investigated word learning processes in children with a CI, only one study has looked at the relationship between their
speech perception and word learning. The age of the children in that study varied substantially (5-11 years old) and all had been implanted relatively late (at 2-6 years of age). To obtain further insight into this relationship, we designed two rapid word learning tasks in which the children were taught novel minimal pairs that differed in the same phonological contrasts as had been tested in the sound categorization task discussed in §4.2. The two rapid word learning tasks differed in cognitive demands, which made it possible to consider the effect of task demands on the performance of the children. By relating the perception of specific phonological contrasts to the ability to create new lexical representations that differed minimally in the same contrasts, we aimed to provide insight into the relationship between the development of sound perception and lexical development in children with a CI. Moreover, because at the age of six years sound perception in typically developing children is not yet adult-like (§4.4.1) and lexical restructuring is assumed to be still ongoing (e.g. Garlock, Walley, & Metsala, 2001; Storkel, 2002, 2004), it is also interesting to investigate this relationship in children with normal hearing. Importantly, in this respect, tasks that involve the learning of minimal pairs have been used extensively with younger, typically developing children to investigate phonetic detail in newly created phonological-lexical representations (see e.g. Escudero & Benders, 2010; Fikkert, 2010; Nazzi, 2005; Swingley, 2009; Werker et al., 2002; Werker & Yeung, 2005; Yoshida et al., 2009), but not yet with older children.

Besides sound perception, we also related phonological short-term memory (pSTM) to word learning. Children with a CI have been shown to score lower on pSTM tasks than age-matched children with normal hearing, and pSTM scores in children with a CI have been found to correlate with spoken language outcomes, including speech perception and receptive vocabulary (Burkholder-Juhasz et al., 2007; Dawson et al., 2002; Pisoni et al., 1999; Willstedt-Svensson et al., 2004).

### 5.2 Methodology

#### 5.2.1 Participants

Participants in the experiments reported in this chapter were 15 children with a CI (mean age: 5;8), 20 children with normal hearing (mean age: 5;10) and 21 young adults with normal hearing (mean age: 22;3). They were the same participants as in the acoustic cue weighting experiment reported in the previous chapter (§4.2.1, see also §3.1).
The relationship between sound perception and rapid word learning

5.2.2 MATERIALS

5.2.2.1 PICTURE-MATCHING

As an on-line measure for rapid word learning, a picture-matching task was designed that consisted of a familiarization and a testing phase. The stimuli were monosyllabic minimal non-word pairs and black-and-white drawings of novel objects. Familiar mono-syllabic words and drawings of familiar objects were included as filler stimuli. The auditory stimuli consisted of a target word (either a non-word or a familiar word) embedded in a carrier phrase: ‘Kijk, een X!’ (look, a X!) during familiarization, and ‘Waar is de X?’ (where is the X?) during testing. The auditory stimuli for the on-line picture-matching task were recorded by the same male adult native speaker of Dutch as the stimuli for the sound categorization task using the same recording equipment (see §4.2.2). Emphasis was always on the first word (i.e., ‘kijk’, look or ‘waar’, where) and the target word. All target words conformed to a monosyllabic consonant-vowel-consonant frame.

Non-words were generated with WordGen© (Duyck, Desmet, Verbeke, & Brysbaert, 2004), a (non-)word generator program based on the CELEX database (Baayen, Piepenbrock, & Van Rijn, 1993) and non-word status was also checked by two native speakers of Dutch, a speaker of Northern Standard Dutch and a speaker of Southern Standard Dutch. Minimal non-word pairs were formed differing either in vowel (/ɑ/-/a/ and /ɛ/-/e/) or initial consonant (/l/-/l/ and /b/-/b/). These phonological contrasts were chosen because they had also been used in the sound categorization task (see §4.2.2). Including both vowel and consonant contrasts is also important because it is still a matter of debate in the infant literature whether learning novel minimal pairs is more successful when the words involve vowel or consonant contrasts. While Curtin, Fennell and Escudero (2009) showed that infants succeeded at learning novel minimal pairs that involve some vowel contrasts at an earlier age than has been reported for consonant contrasts (cf. Mani & Plunkett, 2008), Nazzi and colleagues (e.g. Nazzi, 2005) have shown more successful performance for consonant contrasts.

In total, 12 non-word pairs were formed; three pairs for each phonological contrast (see Table 5.1). One of these pairs for each contrast was presented in the picture-matching task; the two remaining pairs were presented in the object-matching task (see §5.2.2.2 and §6.2.2.3). Presentation of non-word pairs for each contrast was counterbalanced across participants in each group such that subsets of participants were presented with different non-word pairs in the same task, but never with the same non-word pair twice across tasks. In addition, eight monosyllabic familiar words were selected as filler stimuli in the picture-matching and object-
matching tasks. These words were judged to be known to typically developing six-year old children (Schaerlaeken, Kohnstamm, & Lejaegere, 1999).

**Table 5.1.** List of non-word pairs and familiar words included in the picture-matching task and the object-matching task.

<table>
<thead>
<tr>
<th>non-word pairs</th>
<th>familiar words</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>orthographic</strong></td>
<td><strong>phonetic</strong></td>
</tr>
<tr>
<td><strong>forms</strong></td>
<td><strong>forms</strong></td>
</tr>
<tr>
<td>kig - kieg</td>
<td>/kig/ - /kig/</td>
</tr>
<tr>
<td>gik - giek</td>
<td>/gikl/ - /gikl/</td>
</tr>
<tr>
<td>tig - tieg</td>
<td>/tigl/ - /tigl/</td>
</tr>
<tr>
<td>kag - kaag</td>
<td>/kagl/ - /kagl/</td>
</tr>
<tr>
<td>tag - taag</td>
<td>/tagl/ - /tagl/</td>
</tr>
<tr>
<td>tat - taat</td>
<td>/tatl/ - /tatl/</td>
</tr>
<tr>
<td>buuk - puuk</td>
<td>/bykl/ - /bykl/</td>
</tr>
<tr>
<td>beet - peet</td>
<td>/betl/ - /betl/</td>
</tr>
<tr>
<td>beeg - peeg</td>
<td>/beɡl/ - /peɡl/</td>
</tr>
<tr>
<td>suuk - fuuk</td>
<td>/sykl/ - /fykl/</td>
</tr>
<tr>
<td>soot - foot</td>
<td>/soɬl/ - /fyɬl/</td>
</tr>
<tr>
<td>seet - feet</td>
<td>/ʃeɬl/ - /ʃeɬl/</td>
</tr>
</tbody>
</table>

The pictures that were presented together with the auditory stimuli were black-and-white drawings of novel objects and familiar objects. They were selected from the same database of drawings of novel objects as used by Shatzman and McQueen (2006), Escudero et al. (2008) and Simon et al. (2010). Two example pictures are given in Figure 5.1. Pictures for the familiar words were taken from a publicly available database of black-and-white drawings designed for reading instruction in classrooms. An example picture is also given in Figure 5.1.
The relationship between sound perception and rapid word learning

Figure 5.1. Example pictures from the picture-matching task of two novel objects labeled /tɑt/ and /tat/ (left and middle) and one familiar object /dør/ ‘door’ (right).

The experiment was divided into four blocks, corresponding to four stimulus sets of two novel words/objects (e.g., the novel minimal pair /tɑt/-/tat/ paired to the two novel objects from Figure 5.1) and one familiar word/object (e.g., /dør/ paired to the familiar object from Figure 5.1). Each block consisted of a familiarization phase and a testing phase. In the familiarization phase, one of the objects was presented in the center of the screen and remained visible for 4000 milliseconds during which period an auditory stimulus was presented once (e.g., Look, a /tɑt/). The auditory stimuli averaged about 3000 milliseconds. Stimuli were randomly presented until each word/object had been presented three times. During testing, which followed immediately, an auditory stimulus (e.g., Where is the /tɑt/?) was presented, and followed immediately by the presentation of two of the objects the children had been familiarized with, one at the left and one at the right side of the screen that remained visible until the participant had given a response. Left and right response keys on the laptop were indicated by stickers. The next auditory stimulus was presented immediately following the participant’s response. The testing phase consisted of ten trials that were presented in random order. They were either target trials (4) or filler trials (6). A target trial contained two novel objects, e.g., the /tɑt/ and the /tat/, while a filler trial had a novel and the familiar object. In the four target trials, each novel object was tested twice. In the six filler trials, the novel and familiar object were each tested twice. Presentation on the screen (left or right side) was counterbalanced for both novel and familiar objects.

Of the six filler trials, four trials were congruent and two trials were incongruent. In the congruent trials, the presented non-word was the correct name for the novel object presented on the screen (e.g., the auditory stimulus where is the /tɑt/? followed by pictures of /tɑt/ and /dør/ on the screen). In the incongruent trials, the presented non-word was the name for the novel object not presented on the screen, i.e., a switch in non-word-object mapping had taken place (e.g., the auditory stimulus where is the /tɑt/? followed by pictures of /tɑt/ and /dør/ on the screen). Participants were not told beforehand that some of the trials were incongruent. If they overtly noticed the switch and objected that the correct answer was not on the
screen, they were encouraged by the experimenter to still choose one of the two objects.

These trials were included as an additional measure of word learning based on reaction times. It was adapted from the Switch task (Stager & Werker, 1997; Werker & Fennell, 2004), which has been used in many infant word learning studies (Werker & Yeung, 2005; Yoshida et al., 2009). In the standard version of this task, infants are habituated to two novel word-object pairings, e.g., word A with object A and word B with object B. Two test trials follow habituation, a ‘same’ trial, in which word A and object A or word B and object B are presented, and a ‘switch’ trial, in which word A is presented with object B or word B with object A. Looking times for both types of trials are compared. If infants have learned the word-object pairings they will look longer at the screen in the switch trial, which presents a violation of these pairings. We expected participants in our task to choose the picture of the novel object rather than the picture of the familiar object in incongruent trials, given the phonological similarity of both non-words as opposed to the phonological dissimilarity between the non-words and the familiar words. However, if participants noticed the switch, a delay in reaction time was expected for the incongruent trials compared to the congruent trials, similar to the longer looking times for infants on switch trials.

The task took children approximately 15 minutes and adults 10 minutes. They were told that they would be presented with novel and familiar words together with pictures of novel and familiar objects, and that they had to remember which word was associated with which picture. Presentation of the four blocks was counterbalanced across participants within each group. The blocks were separated by a brief pause to prepare the participants for the next block and to provide non-specific feedback to stimulate the children. The task was preceded by a practice block with two phonologically dissimilar non-words (/wɔt/ and /wɔd/) and a familiar word (/rɔk/, ‘skirt’) as the stimuli. Familiarization was identical to that of the experimental blocks, but testing was limited to three trials, two target trials and one filler trial, presented in random order. The practice block was completed successfully by all children with normal hearing and 11 out of 13 children with a CI. These two children received additional instructions before proceeding with the experiment.

E-Prime 2.0® (Psychology Software Tools, Pittsburgh PA) was used to present the stimuli and to record responses and reaction times. We included reaction times as a measure because these might give an indication of difficulties with learning novel minimal pairs for children with a CI, even when they are accurate. For instance, slower reaction times on target trials for children with a CI than children with normal hearing could indicate that their newly created lexical representations are less robust.
Accuracy was defined as the number of trials correctly answered. The incongruent trials (two out of ten testing trials) were excluded from the accuracy analysis since no errors could be made on these trials. For each block, i.e., each phonological contrast, the minimum score that could be obtained in the current study was 0 and the maximum score was 8. As a result, the maximum score for the entire task was $4 \times 8 = 32$. Reaction times were measured from the offset of the auditory stimulus to the overt response, i.e., the key press. The offset rather than the onset of the auditory stimuli was chosen as the starting point to avoid an effect of differences in length between auditory stimuli and differences in the position of the discriminating phoneme, i.e., initial consonant or medial vowel. Reaction times were analyzed separately for the trials with two novel objects, the congruent filler trials and the incongruent filler trials. Only trials correctly answered were analyzed. Furthermore, trials with reaction times more than 2.5 standard deviations above and below the mean reaction time for each participant were excluded, resulting in the exclusion of 3.4% of the trials for the children with a CI, 2.9% for the children with normal hearing and 3.0% for the adults.

The difference in reaction times for the congruent and incongruent filler trials was used as a measure of sensitivity to a switch in word-object mappings. For this purpose, a difference ratio was calculated to account for inter-individual variation in reaction time within and between groups. For each block of test trials, the reaction times for the incongruent trials for each participant were divided by the sum of the reaction times for the congruent and incongruent trials for the same participant. The ratio thus obtained provides a number between 0 and 1. If $< 0.5$, then reaction times are lower for the incongruent trials than for the congruent trials, suggesting the switch was not noticed. If $> 0.5$, then reaction times are higher for the incongruent trials than for the congruent trials, suggesting the switch was noticed.

### 5.2.2.2 Object-matching

An object-matching task was designed as an off-line measure of rapid word learning and administered only to the children. Its purpose was to control for potential performance differences between the children with a CI and the children with normal hearing related to some of the task demands of the picture-matching task. This was accomplished by making the rapid word learning task more interactive and by reducing the length of the task. More specifically, 1) colorful tangible novel objects that the child could pick up and touch, were used instead of black-and-white drawings of novel objects; 2) audiovisual cues were available to the child because the novel words were presented live by the experimenter instead of using pre-recorded audio strings; 3) the number of testing trials was only three in the object-matching task as opposed to ten in the picture-matching task; and 4) the testing trials
in the object-matching task included only congruent trials, whereas the picture-matching task also included incongruent trials.

The object-matching task was therefore an interactive rapid word learning task presented live to the child by the experimenter. The child and the experimenter were seated next to or opposite one another depending on the set-up of the room where testing took place. The novel objects presented in the task were mainly uncommon kitchen utensils that the children would most probably be unable to name (e.g., a water dispenser, a scouring pad or a fruit juice extractor). Familiar objects (e.g., a fork) were included as filler stimuli. The task consisted of three subtests: a novel word learning test, a generalization test and a rapid word learning test (cf. Lederberg & Spencer, 2009; Lederberg et al., 2000). The novel word learning test examined whether the children would associate a novel word with an unfamiliar object without explicit labeling. Three objects were placed in random order on the table in front of the child, two familiar objects (a bowl, /kɔp/ in Dutch, and a clock, /klɔk/ in Dutch) and one novel object. Next, the experimenter asked the child for /lʏk/. The word /lʏk/ is a novel word in Dutch. Because the child knew the names of the two familiar objects, he was expected to choose the novel object to pass this test. The generalization test subsequently examined whether the children generalized the novel word to other exemplars of the novel object by repeating the novel word learning test with a different exemplar of the novel object and one of the familiar objects.

The rapid word learning test involved three objects, two novel objects referred to as, e.g., /fyk/ and /syk/, and one familiar object, referred to as, e.g., /vɔrk/ ‘fork’. These three objects were placed in random order on the table in front of the child and the experimenter pointed at the objects and named them with the phrase ‘Kijk, een X’ (Look, a X!). They were then pointed at and named again with the phrase ‘Dus, een X’ (So, a X). Familiarization was followed by three testing trials in which the children were asked to point to one of the objects in response to the question ‘Waar is de X?’ (Where is the X?). Emphasis was always placed on the first word and the target word. The words presented together with the objects were taken from the same set of monosyllabic non-words and familiar words as used in the picture-matching task (see Table 5.1).

In the first two testing trials, the experimenter asked the child for one of the novel objects, e.g., the /fyk/, and the familiar object, namely the /vɔrk/, in random order. In the final testing trial, the experimenter either asked the child for the remaining novel object, namely the /syk/ or for the novel object that had already been asked for, namely the /fyk/. This was done in order to prevent the children from simply guessing what the answer to the final testing trial was, given the two preceding testing trials. After completion of the first stimulus set, the objects were removed and a new set of objects was placed on the table. The procedure for the
rapid word learning test was then repeated. All children completed the task in the same order with alternated presentation of vowel and consonant contrasts. The task took approximately ten minutes for children. They were told that they would be presented with novel and familiar words together with novel and familiar objects, and that they had to remember which word belonged to which object.

A sheet was used for on-site scoring. In addition, the task was videotaped for off-line validation of the on-site scoring. Children could either pass or fail the novel word learning test and the generalization test depending on whether they successfully associated a novel word with a novel object and whether they showed generalization to new exemplars, respectively. All children passed these tests and their scores were therefore not further analyzed. The number of testing trials on which the child pointed out the correct novel object in the rapid word learning test was used as the dependent variable in the analyses. Because there were four stimulus sets with each two relevant testing trials, the maximum score was 8.

5.2.2.3 DIGIT SPAN

Participants were presented with 15 digit sequences of five different lengths (i.e., three sequences for each length), ranging from two to six digits. Inter-stimulus interval (time between onsets of two subsequent digits) was set at 2000 milliseconds. The digits 7 (l7ezvn7) and 9 (l9ezvn9) were excluded from the spoken stimuli set because they are the only two disyllabic digits in Dutch. The digit sequences were randomly generated by a publicly available digit sequence generator. Digits were allowed to occur twice in the same sequence but only in non-adjacent positions (i.e., the sequence 52835 was allowed, but the sequence 55283 was not allowed). The auditory stimuli for the digit span task were recorded by the same male adult native speaker of Dutch as for the sound categorization and picture-matching tasks using the same recording equipment (see §4.2.2). Windows Media Player 9 (OS MS Windows XP) was used to present the recorded digit sequences one by one in a fixed order, starting with the two-digit sequences and increasing the difficulty by increasing the sequence length. The task continued as long as participants correctly repeated at least two out of the three sequences for any particular list length (up to a maximum of six digits). The task took children and adults approximately five minutes. They were told that they would hear sequences of digits that they had to memorize and then recall in the same order as they were presented. The task was preceded by a two-digit practice sequence. The score for each participant was the longest list length that was correctly repeated for at least two out of the three sequences, i.e., the maximum score was 6.
5.2.3 Statistical Analysis

Parametric statistical techniques were used to analyze the data from the rapid word learning and digit span tasks. More specifically, univariate analyses of variance were used to examine main effects and independent and paired samples $t$-tests were used for post hoc comparisons. In the independent samples $t$-test, the $t$ statistic for unequal variances was adopted in case of a significant Levene’s test for equality of variances. In all group wise post hoc comparisons, a correction was applied to adjust for multiple comparisons and the significance cut-off was .02 ($\alpha/n=.05/3=.02$). Raw scores were used in the accuracy analysis of the rapid word learning tasks, but are expressed as percentage correct scores in the text. In correlation analyses, Pearson product moment correlation coefficients are reported when two normally-distributed variables were correlated, while Spearman rho rank-based coefficients are reported when at least one of the two variables was non-normally distributed, i.e., in correlations with dependent variables from the sound categorization task reported in Chapter 4.

5.3 Results

All children provided data for the analyses for most of the tasks, but it will be mentioned when less data was available. Additionally, it should be noted that not all children completed all four blocks of the picture-matching and object-matching tasks. Across both tasks, this was the case for four children with a CI and three children with normal hearing. The children that had completed at least one vowel and one consonant contrast were included in the analyses, resulting in the exclusion of two children. They were also among the three children who were excluded from the analysis of the sound categorization task (S6 and J8 in Table 3.1, see §4.3).

Results for the picture-matching task are presented first (§5.3.1), followed by the object-matching task (§5.3.2) and the digit span task (§5.3.3). The correlation analyses are given in §5.3.4. Individual results for the children with a CI are provided in Appendix C.

---

27 As in §4.4.1, the effect of regional phonetic variety on performance was examined in a 2 x 2 MANOVA with Group (CI vs. normal hearing) and Regional phonetic variety (Northern Standard Dutch vs. Southern Standard Dutch) as two-level independent variables and performance in the rapid word learning and digit span tasks as dependent variables. No main effect of Regional phonetic variety was found for any of the outcome measures (all $p>.30$). A significant Group x Regional phonetic variety interaction was found only for digit span ($F(1,30)=21.67$, $p<.01$; other outcome measures all $p>.10$). This significant interaction will be further discussed in §5.3.3.
5.3.1 PICTURE-MATCHING

Data from the picture-matching task were available from 13 children with a CI, 20 children with normal hearing and 21 adults. Descriptive statistics for this task are provided in Table 5.2. Figure 5.2 shows the mean percentage correct scores on both target trials (two novel objects) and filler trials (one novel, one familiar object) averaged across sound contrasts for both child groups and the adults. The children clearly scored more poorly than the adults on target trials and thus had difficulties in learning the novel minimal pairs. A 3 (Group) x 2 (Trial) repeated measures ANOVA revealed a main effect of Group (F(2,51)=116.50, p<.01). Independent samples t-tests showed that, overall, the children with a CI scored significantly lower than the children with normal hearing (t(15)=3.87, p<.01) and that the children scored significantly lower than the adults (children with a CI: t(12)=-10.59, p<.01; children with normal hearing: t(24)=-16.35, p<.01). In addition, a main effect of Trial (F(1,51)=231.09, p<.01) was found: scores were higher on filler trials than target trials. Importantly, however, these main effects were qualified by a Group x Trial interaction (F(2,51)=36.73, p<.01). Paired samples t-tests confirmed that all three groups scored significantly higher on filler trials than target trials (children with a CI: t(12)=-5.29, p<.01; children with normal hearing: t(19)=-21.68, p<.01; adults: t(20)=-9.65, p<.01). Independent samples t-tests further showed that the children with a CI made significantly more errors than the children with normal hearing on both target and filler trials (target trials: t(31)=2.73, p<.01; filler trials: t(12)=2.43, p<.05). Both child groups made significantly more errors than the adults on target trials (children with a CI: t(13)=-13.55, p<.01; children with normal hearing: t(26)=-17.62, p<.01). In addition, the children with a CI made significantly more errors than the adults on filler trials (children with a CI: t(12)=-2.65, p<.05, children with normal hearing: t(19)=-1.37, p=.19).

Relative performance on consonant and vowel contrasts was also examined. Paired samples t-tests showed that the children with a CI obtained significantly higher scores on the vowel contrasts than the consonant contrasts (t(12)=2.23, p<.05). Performance on the consonant and vowel contrasts was similar for the children with normal hearing and the adults (children with normal hearing: t(19)=.72 p=.48; adults: t(20)=1.24, p=.23).

The results from the accuracy analysis show that both child groups had difficulty in learning novel minimal pairs. As shown in Figure 5.2, children with a CI even seemed to score close to chance on target trials (50%), which was confirmed by a one-sample t-test (t(12)=1.67, p=.12). By contrast, the children with normal hearing clearly scored above chance on these trials (t(19)=8.00, p<.01). The difficulties for the children with a CI appeared to be especially profound for novel minimal pairs that differed in a single consonant. Furthermore, their overall lower scores resulted...
from errors on the relatively easy filler trials as well as on the relatively difficult target trials.

Table 5.2. Descriptive statistics of the picture-matching task for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

<table>
<thead>
<tr>
<th>Measure</th>
<th>Trial type</th>
<th>CI (n=13)</th>
<th>NH (n=20)</th>
<th>A (n=21)</th>
<th>Total (n=54)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>M (SD)</td>
<td>M (SD)</td>
<td>M (SD)</td>
<td>M (SD)</td>
</tr>
<tr>
<td>Accuracy (% correct)</td>
<td>Target</td>
<td>54.6 (10.0)</td>
<td>62.8 (7.1)</td>
<td>93.5 (3.1)</td>
<td>72.8 (18.2)</td>
</tr>
<tr>
<td></td>
<td>Filler</td>
<td>87.3 (17.3)</td>
<td>99.1 (3.1)</td>
<td>100.0 (0.0)</td>
<td>96.6 (9.9)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>71.0 (8.7)</td>
<td>80.9 (4.0)</td>
<td>96.7 (1.6)</td>
<td>84.7 (11.5)</td>
</tr>
<tr>
<td>Reaction time (msec)</td>
<td>Target</td>
<td>2594 (1129)</td>
<td>3155 (892)</td>
<td>1246 (170)</td>
<td>2278 (1150)</td>
</tr>
<tr>
<td></td>
<td>Filler</td>
<td>2337 (1150)</td>
<td>2167 (451)</td>
<td>1047 (172)</td>
<td>1772 (854)</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>2466 (1052)</td>
<td>2661 (628)</td>
<td>1147 (160)</td>
<td>2025 (953)</td>
</tr>
<tr>
<td>Difference ratio</td>
<td></td>
<td>.52 (.03)</td>
<td>.53 (.04)</td>
<td>.60 (.05)</td>
<td>.56 (.06)</td>
</tr>
</tbody>
</table>

Note. M=mean, SD=standard deviation

Figure 5.2. Mean percentage correct scores on the target and filler trials in the picture-matching task for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).
In the analysis of overall reaction times the incongruent trials were excluded and will be discussed separately below. Figure 5.3 shows the mean reaction times on target and filler trials averaged across sound contrasts for both child groups and the adults. A 3 (Group) x 2 (Trial) repeated measures ANOVA revealed a main effect of Group \((F(2,51)=32.14, \ p<.01)\). Independent samples \(t\)-tests showed that, overall, the children responded slower than the adults (children with a CI: \(t(12)=4.49, \ p<.01\); children with normal hearing: \(t(21)=10.46, \ p<.01\) and that the reaction times for the two child groups did not differ significantly \((t(31)=.67, \ p=.51)\). In addition, a main effect of Trial was found \((F(1,51)=34.75, \ p<.01)\): reaction times were faster on filler than target trials. Importantly, these main effects were qualified by a Group x Trial interaction \((F(2,51)=10.81, \ p<.01)\). Independent samples \(t\)-tests showed that both child groups responded slower than the adults on target trials (children with a CI: \(t(12)=4.28, \ p<.01\), children with normal hearing: \(t(20)=9.41, \ p<.01\)). They also responded slower on filler trials (children with a CI: \(t(12)=4.02, \ p<.01\), children with normal hearing: \(t(24)=10.40, \ p<.01\)). Reaction times for the two child groups did not differ significantly on either target or filler trials (target trials: \(t(31)=1.59, \ p=.12\), filler trials: \(t(14)=-.51, \ p=.62\)). However, paired samples \(t\)-tests showed that whereas the children with normal hearing and the adults responded faster on filler trials than on target trials (children with normal hearing: \(t(19)=6.81, \ p<.01\), adults: \(t(20)=7.51, \ p<.01\)), this was not the case for the children with a CI \((t(12)=1.06, \ p=.31)\).

In summary, the analysis of the overall reaction times mainly revealed differences between children and adults, namely faster reaction times for the latter. Both adults and children with normal hearing responded faster to filler than target trials, which was not the case for the children with a CI. This divergence could be a direct result of their chance-level performance on target trials. The children with a CI might have randomly chosen the two response keys on these trials, resulting in reaction times more comparable to filler trials.
In order to examine sensitivity to a switch in word-object mappings in the three groups of listeners, absolute differences between reaction times in congruent and incongruent trials were expressed as a difference ratio by dividing the reaction times in the incongruent trials by the sum of the reaction times in the congruent and incongruent trials (§5.2.2.1). Difference ratios were averaged across sound contrasts and compared between groups. In addition, for each group the difference ratio was examined to see if it was significantly different from 0.5 (the value expected when the reaction times for the congruent and incongruent trials are similar). The mean difference ratio for the children with a CI was 0.52, for the children with normal hearing 0.53 and for the adults 0.60 (see Table 5.2). A one-way ANOVA with Group as independent variable and difference ratio as dependent variable revealed a significant main effect of Group ($F(2,50)=17.22, p<.01$). Independent samples $t$-tests showed that the difference ratio for the adults was significantly higher than the difference ratio for the children (children with a CI: $t(31)=-4.86, p<.01$; children with normal hearing: $t(39)=-4.68, p<.01$), who did not differ significantly from each other ($t(30)=.67, p=.51$). One-sample $t$-tests showed that the reaction times on the incongruent trials were significantly higher than 0.5 for all three groups (children with a CI: $t(11)=2.53, p<.05$; children with normal hearing: $t(19)=3.39, p<.01$; adults: $t(20)=9.26, p<.01$). Thus, all three groups showed some sensitivity to a
switch in word-object mappings, but the sensitivity was most pronounced for the adults.

The results from the picture-matching task were unexpected for two reasons. Firstly, although scores on target trials were significantly lower for the children with a CI than the children with normal hearing, both clearly had difficulty with learning the novel minimal pairs. The scores of the children with a CI did not exceed chance-level. It is important to note that the analysis of the reaction times on the incongruent trials shows that the children with a CI were sensitive to a switch in word-object mappings, suggesting that some learning of the words and their referents had taken place. Secondly, the children with a CI made an unexpectedly large number of errors on filler trials, resulting in a significant difference between the two child groups in scores on these trials. Importantly, however, both unexpected findings may be explained by the relatively high processing demands of the picture-matching task. We will now turn to the results from the object-matching task where the task demands were reduced (see §5.2.2.2).

5.3.2 OBJECT-MATCHING

Data from the object-matching task were available for 13 children with a CI and 20 children with normal hearing. The mean percentage correct scores on the rapid word learning test in the task were 55.8% (SD=22.0%) for the children with a CI and 80.6% (SD=17.9%) for the children with normal hearing. This difference was significant ($t(31)=3.56$, $p<.01$). As in the picture-matching task, relative performance on consonant and vowel contrasts was also examined. Paired samples $t$-tests showed a trend towards higher scores for the vowel contrasts than for the consonant contrasts in both groups, but these differences did not reach significance (children with a CI: $t(12)=1.85$, $p=.09$; children with normal hearing: $t(19)=1.88$, $p=.08$).

Comparing the performance in the object-matching task to the performance in the picture-matching task, performance was higher in the former only for the children with normal hearing (see Figure 5.4). This difference was confirmed in a 2 (Group) x 2 (Task) repeated measures ANOVA on arcsine transformed percentage correct scores. In addition to a main effect of Group ($F(1,31)=15.68$, $p<.01$) and of Task ($F(1,31)=7.43$, $p<.01$), a significant Group x Task interaction ($F(1,31)=4.44$, $p<.05$) was found. Paired samples $t$-tests showed that scores were significantly higher in the object-matching task than in the picture-matching task for the children with normal hearing ($t(19)=3.95$, $p<.01$), but not for the children with a CI ($t(12)=.38$, $p=.71$).
The results from the object-matching task indicate that the relatively high processing demands of the picture-matching task appeared to have affected the performance of the children with normal hearing. By contrast, the children with a CI showed substantial difficulty in learning novel minimal pairs even in a rapid word learning task with reduced processing demands. It is possible, however, that phonological short-term memory difficulties affected the performance of the children with a CI on the two rapid word learning tasks. Both tasks require the child to (temporarily) store the form and meaning of a novel word after only a few exposures. This possibility will be addressed in the next section.

![Figure 5.4](image)

**Figure 5.4.** Mean percentage correct scores in the picture-matching task and the object-matching task for the children with a CI (CI) and the children with normal hearing (NH).

### 5.3.3 Digit Span

Data from the digit span task were available for 10 children with a CI, 20 children with normal hearing and 19 adults. A one-way ANOVA revealed a main effect of Group ($F(2,46)=86.18, p<.01$). The mean digit span obtained by the children with a CI

28 In addition to the two children already excluded from the analyses, an additional three children did not pass the first level of the digit span task, i.e., repeating a two-digit sequence. Although this could imply a very poor phonological short-term memory capacity, it is also possible that they did not understand the task. Therefore, they are not included in the analysis here.
CI was 3.2 (SD=.63), compared to 3.8 (SD=.84) for the children with normal hearing and 6.0 (the maximum score, SD=.23) for the adults. Independent samples t-tests showed that the children had significantly smaller digit spans than the adults (children with a CI: t(10)=-13.29, p<.01; children with normal hearing: t(22)=-11.09, p<.01). The difference in digit spans for the two child groups did not reach significance (t(28)=2.00, p=.06).

In contrast to the other outcome measures in this chapter, a significant interaction with regional phonetic variety was found for performance on the digit span task (F(1,30)=21.67, p<.01). This interaction is illustrated in Figure 5.5. The Dutch children with normal hearing clearly had a higher digit span than the Flemish children with normal hearing, whereas this was not the case for the Dutch and Flemish children with a CI. The reason for this observed difference in digit span within the group of children with normal hearing is unclear.

Figure 5.5. Mean digit spans for the children with a CI (CI) and the children with normal hearing (NH) split according to region (NL=Netherlands, FL=Flanders).

The results from the digit span task, namely a trend towards smaller digit spans for the children with a CI in comparison to the children with normal hearing, raise the possibility that limitations in pSTM have contributed to the difficulties of the children with a CI in the two rapid word learning tasks. In addition, limitations in pSTM may have contributed to their relatively poor performance on the sound categorization task (see §4.3). Alternatively, the lower scores in the rapid word
learning tasks may be directly related to their phonological perceptual difficulties. We will therefore next examine the correlations between the different outcome measures.

### 5.3.4 Correlations

To examine the relationship between sound categorization, rapid word learning and pSTM, correlation analyses were performed for the children with normal hearing and the children with a CI separately (Table 5.3 and Table 5.4, respectively). In addition, chronological age was included in the correlation analysis for the children with normal hearing, and chronological age, age at implantation and length of CI use for the children with a CI. Correlations are not reported for the adults, given near-ceiling performance on most measures. The outcome measures included in the correlation analyses were phoneme endpoint identification and classification slope for sound categorization; scores, reaction times and difference ratio for picture-matching; scores for object-matching; and digit span for pSTM. In this analysis, outcome measures of the sound categorization and rapid word learning tasks were averaged across all sound contrasts.

Among the children with normal hearing, no significant correlations were observed between performance in the sound categorization task and the picture-matching task. However, both phoneme endpoint identification and classification slope correlated positively with each other ($R=.80, p<.01$) and with scores in the object-matching task ($R=.49, p<.05$ and $R=.65, p<.01$, respectively). In addition, reaction times in the picture-matching task correlated negatively with scores in the object-matching task ($r=-.45, p<.05$) and with chronological age ($r=-.49, p<.05$).
The relationship between sound perception and rapid word learning

Table 5.3. Correlations between sound categorization, rapid word learning and pSTM for the children with normal hearing.

<table>
<thead>
<tr>
<th></th>
<th>age mo</th>
<th>XAB %</th>
<th>PICT %</th>
<th>PICT msec</th>
<th>PICT ratio</th>
<th>OBJ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>% (XAB)</td>
<td>.27</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (XAB)</td>
<td>.23</td>
<td>.80**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% (PICT)</td>
<td>.21</td>
<td>.23</td>
<td>.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>msec (PICT)</td>
<td>-.50*</td>
<td>-.03</td>
<td>.04</td>
<td>-.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ratio (PICT)</td>
<td>-.02</td>
<td>-.13</td>
<td>-.10</td>
<td>.23</td>
<td>.01</td>
<td></td>
</tr>
<tr>
<td>% (OBJ)</td>
<td>.40</td>
<td>.49*</td>
<td>.65**</td>
<td>-.06</td>
<td>-.47*</td>
<td>-.14</td>
</tr>
<tr>
<td>span</td>
<td>.09</td>
<td>.10</td>
<td>-.04</td>
<td>-.26</td>
<td>-.24</td>
<td>-.12</td>
</tr>
</tbody>
</table>

*p < .05  
**p < .01

Note. XAB = sound categorization (% = phoneme endpoint identification), PICT = picture-matching (% = accuracy, msec = reaction time, ratio = difference ratio), OBJ = object-matching (% = accuracy), span = digit span, mo = months

Among the children with a CI, pSTM correlated with classification slope in the sound categorization task (R = .70, p < .05) and with length of CI use (r = .79, p < .05). In fact, the correlation between pSTM and classification slope was no longer significant when length of CI use was statistically controlled for, suggesting that this correlation was mediated by length of CI use. Chronological age correlated positively with phoneme endpoint identification in the sound categorization task (r = .63, p < .05). Interestingly, in contrast to the children with normal hearing, sound categorization did not correlate significantly with rapid word learning performance for the children with a CI. No significant correlations were observed between age at implantation and any of the outcome measures.
### Table 5.4. Correlations between sound categorization, rapid word learning and pSTM for the children with a CI.

<table>
<thead>
<tr>
<th></th>
<th>C-age</th>
<th>I-age</th>
<th>H-age</th>
<th>XAB</th>
<th>PICT</th>
<th>OBJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mo</td>
<td>mo</td>
<td>mo</td>
<td>%</td>
<td>slope</td>
<td>%</td>
</tr>
<tr>
<td>I-age</td>
<td>.34</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H-age</td>
<td>.45</td>
<td>-.69*</td>
<td>.29</td>
<td>-1.5</td>
<td>.40</td>
<td>.25</td>
</tr>
<tr>
<td>% (XAB)</td>
<td>.62*</td>
<td>.17</td>
<td>.29</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>slope (XAB)</td>
<td>.45</td>
<td>-.15</td>
<td>.40</td>
<td></td>
<td>.25</td>
<td></td>
</tr>
<tr>
<td>% (PICT)</td>
<td>.41</td>
<td>-.10</td>
<td>.37</td>
<td>.14</td>
<td>.02</td>
<td></td>
</tr>
<tr>
<td>msec (PICT)</td>
<td>-.33</td>
<td>-.38</td>
<td>.14</td>
<td>-.11</td>
<td>.08</td>
<td>-.33</td>
</tr>
<tr>
<td>ratio (PICT)</td>
<td>-.23</td>
<td>.01</td>
<td>-.25</td>
<td>.10</td>
<td>-.23</td>
<td>.12</td>
</tr>
<tr>
<td>% (OBJ)</td>
<td>.12</td>
<td>.45</td>
<td>-.33</td>
<td>.01</td>
<td>.25</td>
<td>-.32</td>
</tr>
<tr>
<td>span</td>
<td>.56</td>
<td>-.32</td>
<td>.79**</td>
<td>.11</td>
<td>.70*</td>
<td>.02</td>
</tr>
</tbody>
</table>

*\(p<.05\)

**\(p<.01\)

Note. C-age=chronological age, I-age=age at implantation, H-age=length of CI use (mo=months), XAB=sound categorization (%=phoneme endpoint identification), PICT=picture-matching (%=accuracy, msec=reaction time, ratio=difference ratio), OBJ=object-matching (%=accuracy), span=digit span

### 5.4 DISCUSSION

From the results reported it is possible to discuss the relationship between sound categorization, rapid word learning and phonological short-term memory (pSTM) in 5- to 6-year-old children with a CI and age-matched children with normal hearing. Sound categorization in the children with normal hearing correlated with their ability to learn novel minimal pairs containing the same sound contrasts. In addition, their rapid word learning performance was dependent on the complexity of the task, but was not associated with pSTM. Children with a CI had poorer sound categorization abilities and greater difficulties when learning novel minimal pairs in rapid word learning tasks than their peers with normal hearing, with a small advantage for minimal pairs that were distinguished by a vowel compared to a consonant contrast. Neither sound categorization nor pSTM correlated with their rapid word learning performance, but pSTM did correlate with their sound categorization performance. The discussion of the results will first address differences between the children with normal hearing and the adults, i.e., age effects (§5.4.1). The effects of reduced auditory input are discussed in §5.4.2.
5.4.1 Sound Categorization and Rapid Word Learning in Typically Developing Children

The results of the present study confirm that the relationship between speech perception and word learning is complex. At age six, children are still developing their perception and production of phonemes (e.g. Gerrits, 2001; Hazan & Barrett, 2000; Lee, Potamianos, & Narayanan, 1999) and are in the process of restructuring lexical representations in their mental lexicon (e.g. Garlock et al., 2001; see also Rispens et al., in preparation, for Dutch; Storkel, 2002, 2004). This means that, at this age, both phonological and lexical representations are not yet fully adult-like. Consistent with this previous research, the typically developing children showed poorer phoneme identification and shallower classification slopes in a sound categorization task (§4.3) and had more difficulty with learning novel minimal pairs in rapid word learning tasks than young adults (§5.3).

This study was specifically designed to test the interrelation between the development of phonological representations and lexical representations. To that end, the same phonological contrasts were used in the sound categorization and rapid word learning tasks. Moreover, the sound perception task involved categorization rather than discrimination, as had been the case in most previous studies (e.g. Kuhl et al., 2005; Werker et al., 2002). A sound categorization task is likely to probe phonetic perception rather than only auditory discrimination (see §4.2.2). The former is a linguistic ability that can be more easily compared to word recognition. Indeed, phoneme endpoint identification and classification slope in the sound categorization task correlated positively with scores in the off-line rapid word learning task (object-matching). Unexpectedly, however, neither phoneme endpoint identification nor classification slope correlated with performance in the on-line rapid word learning task (picture-matching). However, a substantial discrepancy between scores on the object-matching task and the target trials of the picture-matching task was observed for the children with normal hearing (81% and 60% correct, respectively, see Figure 5.4). Moreover, scores in the two rapid word learning tasks did not correlate significantly, although a significant negative correlation was observed between reaction times in the picture-matching task and accuracy in the object-matching task (see Table 5.3).

The disparity in accuracy between the two rapid word learning tasks may be explained by the relatively high task demands of the picture-matching task. Recall that the picture-matching task used more challenging materials than the object-matching task: 1) drawings rather than tangible objects; 2) audio recordings rather than live voice; 3) more testing trials; and 4) both congruent and incongruent trials as opposed to only congruent trials. Any of these aspects might have imposed larger cognitive demands on the children. It should be noted, however, that their scores on filler trials approached ceiling, which excludes the possibility that attention demands...
were too high in the picture-matching task. In addition, the absence of a correlation between pSTM and picture-matching scores makes it unlikely that limited pSTM can explain the discrepancy between performance in the picture-matching and the object-matching tasks. Alternatively, the presence of incongruent trials in the picture-matching task might have negatively affected the performance of the children in this task. That is, the participants were not told beforehand that they would be presented with congruent as well as incongruent trials and all trials were presented in random order. Although only two out of ten trials were incongruent, it is possible that some children who were presented with an incongruent trial immediately after familiarization became unsure about the word-object mappings they had just established. The relatively poor performance in the picture-matching task might thus indicate that novel lexical representations in these children are still fragile and are easily altered by conflicting information.

Although the performance of the children with normal hearing improved substantially in the object-matching task compared to the picture-matching task, it did not approach ceiling (81% correct on average). Therefore, regardless of the discrepancy in performance between tasks, they clearly have difficulty learning minimal pairs in rapid word learning tasks. The adults in the present study did perform at ceiling-level. However, Simon et al. (2010) found that adult native speakers of Dutch scored significantly lower on minimal pairs than non-minimal pairs in a more complex rapid word learning task with multiple non-word pairs. The authors also showed that adult second and third language learners have considerable difficulty learning minimal pairs if they are distinguished by sound contrasts not present in their previously learned languages (cf. Escudero et al., 2008). Thus, phonological neighbors appear to have a special status in the development of phonological and lexical representations in both children and adults (see also Storkel et al., 2006).

In previous word learning studies, infants, children or adults had to learn words from either low or high phonological neighborhoods. In contrast, the participants of the present study were explicitly exposed to two novel words that were phonological neighbors of each other (cf. Escudero et al., 2008; Simon et al., 2010; Werker et al., 2002). Although the advantage of the paradigm adopted here is that the two

---

29 In order to shed some light on this matter, we reanalyzed the data from the picture-matching task for the children with normal hearing. Specifically, we divided the children into two groups according to whether they were exposed to both incongruent trials in the first half of the testing phase (i.e. in the first five trials) or not and compared their scores on target trials in independent samples t-tests. Indeed, some support was found for the possibility that the incongruent trials had confused the children, but only for the /f/-/s/ contrast. Children who were exposed to the incongruent trials early on in the testing phase scored more poorly on this contrast than those who were not (t(17)=−2.73, p<.05).
The relationship between sound perception and rapid word learning

Phonological neighbors refer to two distinct novel objects, it may place a larger burden on working memory because two novel word-object pairings have to be learned. However, our finding that pSTM did not correlate with rapid word learning performance suggests that limitations in pSTM were not the cause of the observed difficulties in learning the novel minimal pairs (cf. Gray, 2006). Alternatively, as already mentioned in §2.1.2, Storkel and colleagues have argued that a high neighborhood density makes it more difficult for learners to detect the novelty status of words they have not heard before (Hoover et al., 2010; Storkel et al., 2006). For this reason, it may be particularly difficult for children to in a very short time learn two novel words that are phonological neighbors of each other, such as the minimal pairs in our study. This possibility needs to be investigated in future research.

The ability of children with normal hearing to learn novel minimal pairs in a rapid word learning task was related to their categorization abilities for the same sound contrasts. Unfortunately, the direction of the relationship between sound categorization and rapid word learning cannot be determined. One possibility is that ongoing developmental changes in acoustic cue weighting sharpen phonological representations and by extension lexical representations. In this scenario an important remaining question concerns the force driving developmental changes in cue weighting (see also §4.1). Alternatively, it may be that the growing mental lexicon and the resulting need for detailed lexical representations drive developmental changes in cue weighting and sharpen phonological representations (e.g. Jusczyk, 1993; Metsala & Walley, 1998; Walley, 1993; Walley & Flege, 1999). Here the exact nature of the mechanism underlying the reorganization of lexical and phonological representations still needs to be determined.

5.4.2 Sound Categorization and Rapid Word Learning in Children with a CI

The results from the children with normal hearing show that phonetic categorization is still developing at age six and that sound categorization correlates with the ability to learn minimal pairs. In addition, the ability to learn minimal pairs in a rapid word learning task was related to their categorization abilities for the same sound contrasts. Unfortunately, the direction of the relationship between sound categorization and rapid word learning cannot be determined. One possibility is that ongoing developmental changes in acoustic cue weighting sharpen phonological representations and by extension lexical representations. In this scenario an important remaining question concerns the force driving developmental changes in cue weighting (see also §4.1). Alternatively, it may be that the growing mental lexicon and the resulting need for detailed lexical representations drive developmental changes in cue weighting and sharpen phonological representations (e.g. Jusczyk, 1993; Metsala & Walley, 1998; Walley, 1993; Walley & Flege, 1999). Here the exact nature of the mechanism underlying the reorganization of lexical and phonological representations still needs to be determined.

5.4.2 Sound Categorization and Rapid Word Learning in Children with a CI

The results from the children with normal hearing show that phonetic categorization is still developing at age six and that sound categorization correlates with the ability to learn minimal pairs. In addition, the ability to learn minimal pairs in a rapid word learning task was related to their categorization abilities for the same sound contrasts. Unfortunately, the direction of the relationship between sound categorization and rapid word learning cannot be determined. One possibility is that ongoing developmental changes in acoustic cue weighting sharpen phonological representations and by extension lexical representations. In this scenario an important remaining question concerns the force driving developmental changes in cue weighting (see also §4.1). Alternatively, it may be that the growing mental lexicon and the resulting need for detailed lexical representations drive developmental changes in cue weighting and sharpen phonological representations (e.g. Jusczyk, 1993; Metsala & Walley, 1998; Walley, 1993; Walley & Flege, 1999). Here the exact nature of the mechanism underlying the reorganization of lexical and phonological representations still needs to be determined.

In addition to vocabulary growth, lexical restructuring has also been related to the development of phonological awareness (e.g. Metsala, 1999; Metsala, Stavrinos, & Walley, 2009). In addition, Mayo et al. (2003) showed that the development of phonological awareness affects acoustic cue weighting strategies in young children. Given that the majority of the children in the current study were just starting to learn to read, limited levels of phonological awareness might also have contributed to their difficulties with learning novel minimal pairs in the rapid word learning tasks. Additionally, phonological awareness might have mediated the observed relationship between sound categorization and rapid word learning.
learning task strongly depends on task demands (cf. Yoshida et al., 2009 for similar findings with infants). These findings raise concerns for children with a CI who perceive and acquire spoken language through spectrotemporally degraded auditory input. Indeed, they showed more difficulties than age-matched children with normal hearing when they had to learn novel minimal pairs containing such contrasts, both in the picture-matching and object-matching tasks. These difficulties appeared to be more pronounced for words differing in a single consonant than a single vowel contrast, which is consistent with studies that reported more accurate vowel than consonant perception in children with a CI (e.g. Kishon-Rabin et al., 2002; Pisoni et al., 1999). Furthermore, consistent with previous studies, a trend was observed towards smaller digit spans for the children with a CI (e.g. Pisoni et al., 1999). However, the two groups of children did not differ significantly in their overall reaction times in the picture-matching task nor in their sensitivity to incongruent trials based on reaction times.

Novel minimal pairs appear to present even more difficulty to children with a CI than to children with normal hearing most likely because of their poorer speech perception abilities. However, unlike for the children with normal hearing, neither phoneme endpoint identification nor classification slope correlated significantly with rapid word learning for the children with a CI. That is, although they had lower performance in both word learning tasks than the children with normal hearing, no relation could be shown between these difficulties and their difficulties in categorizing the consonant and vowel contrasts that distinguished the minimal pairs. One possible explanation for this unexpected result is that the present sample of children with a CI may have been too small to detect such a relationship. Alternatively, it may be that their sound categorization and rapid word learning performance was too low to find significant correlations. In fact, despite substantial inter-individual variation, as a group they tended to cluster at the low end of the distribution of scores in the tasks. Specifically, their performance varied between 50% and 75% correct on the sound categorization task, 53% and 84% correct on the picture-matching task, and 25% and 100% correct on the object-matching task (see Appendix C). To further illustrate this inter-individual variation, consider the children with the steepest and the shallowest slope in the sound categorization task. Child X5, implanted at 0:7, had the steepest classification slope among the children with a CI, which was still below the mean of the children with normal hearing. Child K3, implanted at 2;1, had the shallowest classification slope. However, both children performed similarly on the rapid word learning tasks. Child X5 scored 75% correct on picture-matching and 50% on object-matching. These percentages were 72% and 50%, respectively, for child K3.

As in the children with normal hearing, pSTM did not correlate with rapid word learning performance. In contrast to the children with normal hearing, however, pSTM correlated with classification slope in the sound categorization task, as did
chronological age. This probably reflects the relatively long inter-stimulus intervals that were used to avoid pure auditory discrimination (see §4.2.3 and §4.4.1) as well as the relatively high processing demands associated with sound categorization tasks. In contrast to our findings, Willstedt-Svensson et al. (2004) found that the performance of children with a CI in a novel word learning task was significantly correlated with both non-word repetition, often used as a measure of pSTM, and complex verbal working memory (sentence completion with word recall). The ages of the children in that study varied substantially, however (5-11 years old) and they had all been implanted relatively late (at 2-6 years of age). The majority of the children in our study were implanted before their second birthday. It is possible that pSTM is more strongly related to rapid word learning performance in later-implanted children. The relation between pSTM and vocabulary acquisition has been found to decline with age in typically developing children (Gathercole, 2006). Later-implanted children with a CI may thus rely until a later age than earlier-implanted children on pSTM to support developing phonological and lexical representations. Alternatively, non-word repetition as a measure of pSTM might be more strongly related to rapid word learning than digit span, because both involve the short-term storage of non-words (Gathercole, 2006).

Previous word learning studies (Houston et al., 2005; Tomblin et al., 2007; Willstedt-Svensson et al., 2004) measured the ability to rapidly learn words through both receptive and productive tests, whereas only receptive tests were used in the present study. Receptive word learning scores are usually higher than expressive word learning scores, because less detailed representation of the novel word is necessary for providing the correct answer in a receptive test than in an expressive test (e.g. Gray, 2003b, 2005, 2006). In addition, Willstedt-Svensson et al. (2004) and Tomblin et al. (2007) taught one novel word at a time rather than two. It is unlikely, however, that the children in our study were generally unable to learn two novel words after only three exposures, because 11 out of 13 children successfully completed the practice block of the picture-matching task in which they had to learn a pair of phonologically different non-words (§5.2.2.1). Nevertheless, experimental control was not as rigorous for the practice block as for the experimental blocks, and therefore this evidence should be interpreted with caution. Although using different methodologies, all previous studies on word learning in children with a CI showed that they are in principle able to learn novel words after only a limited amount of exposure to the words and referents, even if their performance is lower than that of their peers with normal hearing.

Age at implantation unexpectedly did not correlate with sound categorization, rapid word learning or pSTM. Length of CI use also did not correlate with sound categorization or rapid word learning, but did correlate with pSTM, suggesting that the latter is strongly dependent on auditory experience. The absence of significant correlations with age at implantation might be related to the relatively small sample
and the fact that the majority of the children were implanted at a relatively young age. Houston et al. (2005) also did not find a strong correlation between rapid word learning performance and age at implantation, length of CI use or chronological age in their early-implanted children. Tomblin et al. (2007) did find a significant correlation with age at implantation, but only when length of CI use was not controlled for in the analysis. They also reported a significant correlation with chronological age. Finally, Willstedt-Svensson et al. (2004) reported a significant correlation with age at implantation, but not with length of CI use or chronological age.

Another unexpected result was that the children with a CI made more errors on the filler trials in the picture-matching task than the children with normal hearing (13% and 1%, respectively). One possible explanation for the increased error rate on filler trials is that children with a CI may have problems maintaining (auditory) attention to tasks that involve high cognitive demands. Unfortunately, independent evidence for this explanation is not available from this study because sustained auditory attention was not explicitly assessed. Other work has shown that infants with a CI show less interest in speech stimuli than infants with normal hearing (Horn et al., 2007b) and that children with a CI are delayed in the development of sustained visual attention (Horn et al., 2005; Quittner et al., 2007). Additionally, they are rated differently than their peers with normal hearing on several scales of executive functioning, including attention scales (Pisoni et al., 2008). Clearly, more research is needed to determine the role of attentional demands in explaining attested performance difference between children with a CI and children with normal hearing.

To conclude, the children with a CI were clearly delayed in their ability to learn novel minimal pairs in a rapid word learning task. This delay was evident despite the fact that the majority of them had received their CI at a relatively early age. However, in contrast to their peers with normal hearing, we were unable to establish a clear relationship between their sound perception and rapid word learning.