

File ID	uvapub:89769
Filename	Thesis
Version	unknown

SOURCE (OR PART OF THE FOLLOWING SOURCE):

Type	PhD thesis
Title	Speech and sign perception in deaf children with cochlear implants
Author(s)	M.R. Giezen
Faculty	FGw: Amsterdam Center for Language and Communication (ACLC)
Year	2011

FULL BIBLIOGRAPHIC DETAILS:

<http://hdl.handle.net/11245/1.343475>

Copyright

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 licence (like Creative Commons).

Marcel Giezen

Speech and Sign Perception in Deaf Children with Cochlear Implants

Although a cochlear implant (CI) restores access to sound and speech for profoundly deaf children, there is substantial inter-individual variation in outcomes and many children with a CI continue to be delayed in their spoken language development. This suggests that they may benefit from alternative modes of communication such as sign language. However, the role of signed input in the education of children with a CI is much debated.

The aim of the present thesis was two-folded: to explore underlying processes in speech perception that may help to explain inter-individual variation in outcomes, and to obtain insight into the effects of signed input on spoken language abilities. To that end, this thesis investigates speech and sign perception in 5- to 6-year old children with a CI. More specifically, it examines and interrelates the use of acoustic and visual cues in phonetic categorization and the representation of phonetic contrasts in novel words and signs. Additionally, it investigates the effects of bimodal (i.e., simultaneously spoken and signed) input on speech perception.

The analyses show that children with a CI have fuzzy boundaries between sound categories and have difficulties to represent phonetic detail in novel words. Weakly-specified auditory phonological-lexical representations likely negatively impact speech processing. Importantly, signing experience did not negatively affect their speech perception and bimodal input seemed to even facilitate spoken word recognition. Together, these findings form an argument for bilingualism in a spoken and a signed language as the ultimate goal in the rehabilitation and education of children with a CI.



Netherlands
Graduate
School of
Linguistics

ISBN 978-94-6093-058-4

Marcel Giezen

Speech and Sign Perception in Deaf Children with Cochlear Implants



AMSTERDAM CENTER
FOR LANGUAGE AND
COMMUNICATION



Netherlands
Graduate
School of
Linguistics

Landelijke Onderzoekschool Taalwetenschap

Speech and Sign Perception in Deaf Children with Cochlear Implants

Published by
LOT
Trans 10
3512 JK Utrecht
The Netherlands

phone: +31 30 253 6006

e-mail: lot@uu.nl
<http://www.lotschool.nl>

Cover illustration: Illustration of a cochlear implant, from the National Institute of Deafness and Other Communication Disorders at the National Institutes of Health, part of the United States Department of Health and Human Services.

ISBN: 978-94-6093-058-4
NUR 616

Copyright © 2011: Marcel Giezen. All rights reserved.

SPEECH AND SIGN PERCEPTION IN DEAF CHILDREN WITH COCHLEAR IMPLANTS

ACADEMISCH PROEFSCHRIFT

ter verkrijging van de graad van doctor
aan de Universiteit van Amsterdam
op gezag van de Rector Magnificus
prof. dr. D.C. van den Boom
ten overstaan van een door het college voor promoties
ingestelde commissie,
in het openbaar te verdedigen in de Agnietenkapel
op vrijdag 29 april 2011, te 14:00 uur

door

Marcel Raymond Giezen

geboren te 's-Gravenhage

Promotiecommissie

Promotor: Prof. dr. A.E. Baker

Co-promotor: Dr. P. Escudero

Overige Leden: Prof. dr. P.P.G. Boersma

Prof. dr. K. Emmorey

Prof. dr. S. Gillis

Prof. dr. G. Szagun

Dr. R. Pfau

Faculteit der Geesteswetenschappen

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	IX
1 INTRODUCTION	13
1.1 THE TOPIC AND GOAL OF THIS THESIS	13
1.2 COCHLEAR IMPLANTATION	15
1.2.1 COCHLEAR IMPLANT TECHNOLOGY	15
1.2.2 CURRENT PRACTICE IN PEDIATRIC COCHLEAR IMPLANTATION	18
1.3 OUTCOMES OF PEDIATRIC COCHLEAR IMPLANTATION	21
1.3.1 EFFECTS ON SPOKEN LANGUAGE ABILITIES	21
1.3.2 EFFECTS ON OTHER COGNITIVE ABILITIES	24
1.3.3 LONG-TERM OUTCOMES	25
1.4 EFFECTS OF AGE AT IMPLANTATION AND COMMUNICATION MODALITY ON SPOKEN LANGUAGE	25
1.4.1 AGE AT IMPLANTATION	25
1.4.2 COMMUNICATION MODALITY	27
1.5 THE ORGANIZATION OF THIS THESIS	29
2 SPEECH AND SIGN PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS: THE PRESENT STUDY	31
2.1 THE PERCEPTION OF SOUNDS AND WORDS BY CHILDREN WITH A CI	31
2.1.1 BACKGROUND	31
2.1.2 LEARNING TO PERCEIVE SPEECH SOUNDS: ACOUSTIC CUE WEIGHTING	33
2.1.2 THE INTERRELATION BETWEEN SOUNDS AND WORDS	35
2.2 RELATIONSHIP AND INTERACTION BETWEEN SIGN AND SPEECH PERCEPTION IN CHILDREN WITH A CI	40
2.2.1 BACKGROUND	40
2.2.2 THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION	43
2.2.3 THE INTERACTION BETWEEN SIGN AND SPEECH PERCEPTION	45
3 METHODOLOGY	47
3.1 PARTICIPANTS	47
3.1.1 CHILDREN WITH A CI	47
3.1.2 CHILDREN WITH NORMAL HEARING	51
3.1.3 ADULTS WITH NORMAL HEARING	51
3.2 TASKS	52
3.2.1 THE PERCEPTION OF SPEECH SOUNDS: ACOUSTIC CUE WEIGHTING	52
3.2.2 THE RELATIONSHIP BETWEEN SOUND PERCEPTION AND RAPID WORD LEARNING	53
3.2.2.1 PICTURE-MATCHING	53
3.2.2.2 OBJECT-MATCHING	54
3.2.2.3 PHONOLOGICAL SHORT-TERM MEMORY	54

3.2.3	THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION	55
3.2.4	THE EFFECTS OF BIMODAL INPUT ON SPEECH PERCEPTION	56
3.3	PROCEDURE	56
3.4	STATISTICAL ANALYSES	58
4	THE USE OF ACOUSTIC CUES	59
4.1	BACKGROUND	59
4.2	METHODOLOGY	62
4.2.1	PARTICIPANTS	62
4.2.2	STIMULI	62
4.2.2.1	VOWEL CONTRASTS	63
4.2.2.2	CONSONANT CONTRASTS	65
4.2.3	TASK	66
4.2.4	DEPENDENT VARIABLES	67
4.2.4.1	PHONEME ENDPOINT IDENTIFICATION	67
4.2.4.2	INDIVIDUAL CUE RELIANCE, CUE WEIGHTING AND CLASSIFICATION SLOPE	68
4.2.5	STATISTICAL ANALYSIS	69
4.3	RESULTS	69
4.3.1	PHONEME ENDPOINT IDENTIFICATION	70
4.3.2	INDIVIDUAL CUE RELIANCE	71
4.3.3	CUE WEIGHTING	73
4.3.4	CLASSIFICATION SLOPE	74
4.4	DISCUSSION	79
4.4.1	AGE EFFECTS IN ACOUSTIC CUE WEIGHTING	79
4.4.2	USE OF ACOUSTIC CUES BY CHILDREN WITH A CI	81
5	THE RELATIONSHIP BETWEEN SOUND PERCEPTION AND RAPID WORD LEARNING	85
5.1	BACKGROUND	85
5.2	METHODOLOGY	88
5.2.1	PARTICIPANTS	88
5.2.2	MATERIALS	89
5.2.2.1	PICTURE-MATCHING	89
5.2.2.2	OBJECT-MATCHING	93
5.2.2.3	DIGIT SPAN	95
5.2.3	STATISTICAL ANALYSIS	96
5.3	RESULTS	96
5.3.1	PICTURE-MATCHING	97
5.3.2	OBJECT-MATCHING	101
5.3.3	DIGIT SPAN	102
5.3.4	CORRELATIONS	104
5.4	DISCUSSION	106
5.4.1	SOUND CATEGORIZATION AND RAPID WORD LEARNING IN TYPICALLY DEVELOPING CHILDREN	107
5.4.2	SOUND CATEGORIZATION AND RAPID WORD LEARNING IN CHILDREN WITH A CI	109

6	THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION	113
6.1	BACKGROUND	114
6.2	METHODOLOGY	117
6.2.1	PARTICIPANTS	117
6.2.2	MATERIALS	117
6.2.2.1	SIGN CATEGORIZATION	117
6.2.2.2	PICTURE-MATCHING	119
6.2.2.3	OBJECT-MATCHING	121
6.2.2.4	DIGIT SPAN	122
6.2.3	STATISTICAL ANALYSIS	123
6.3	RELATIVE PERFORMANCE IN BOTH LANGUAGE MODALITIES	123
6.3.1	SIGN AND SOUND CATEGORIZATION	124
6.3.2	PICTURE-MATCHING	129
6.3.3	OBJECT-MATCHING	132
6.3.4	DIGIT SPAN	134
6.3.5	SUMMARY	135
6.4	CORRELATIONS BETWEEN LANGUAGE MODALITIES	136
6.5	THE ROLE OF SIGNING EXPERIENCE	137
6.6	CONCLUSION	140
7	EFFECTS OF BIMODAL INPUT ON SPEECH PERCEPTION	141
7.1	BACKGROUND	141
7.1.1	THE ROLE OF THE VISUAL MODALITY IN LANGUAGE PROCESSING	141
7.1.2	CHILDREN WITH A CI AND THE VISUAL MODALITY IN LANGUAGE PROCESSING	143
7.2	METHODOLOGY	145
7.2.1	PARTICIPANTS	145
7.2.2	MATERIALS	147
7.2.2.1	TASK	147
7.2.2.2	STIMULI	149
7.2.3	PROCEDURE	150
7.2.4	STATISTICAL ANALYSIS	151
7.3	RESULTS	152
7.3.1	ADULTS	152
7.3.2	CHILDREN WITH A CI	153
7.3.3	CORRELATIONS	156
7.4	DISCUSSION	157
7.4.1	CROSS-MODAL FACILITATION	157
7.4.2	CROSS-MODAL INTERFERENCE	158
7.4.3	CONCLUSION	159
8	CONCLUSIONS	161
8.1	UNDERLYING PROCESSES IN SPEECH PERCEPTION	161
8.1.1	SUMMARY OF MAIN FINDINGS	161
8.1.2	IMPLICATIONS	162

8.2	INTERACTIONS BETWEEN LANGUAGE MODALITIES	165
8.2.1	SUMMARY OF MAIN FINDINGS	165
8.2.2	IMPLICATIONS	167
8.3	AGE EFFECTS	169
8.4	METHODOLOGICAL CONSIDERATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH	170
8.4.1	SAMPLE REPRESENTATIVENESS	170
8.4.2	ECOLOGICAL VALIDITY	171
8.4.3	MOVING TARGETS	171
8.4.4	INTER-INDIVIDUAL VARIATION IN PERFORMANCE	172
APPENDICES		175
BIBLIOGRAPHY		181
SUMMARY IN ENGLISH		209
SAMENVATTING IN HET NEDERLANDS		213

ACKNOWLEDGEMENTS

Evidently, at the end of a scientific journey of almost four years many people deserve to be thanked who made this research possible, contributed to the outcomes or shared their ideas and concerns with me.

I owe my deepest gratitude to Anne and Paola, for supervising this project from its formulation in a research proposal four years ago until its completion. Your endless interest, support and patience is reflected in every page of this dissertation and I have the greatest appreciation for all your efforts. In other words, you have been absolutely amazing! I would also like to express my gratitude to Steven Gillis, Gisela Szagun, Karen Emmorey, Paul Boersma and Roland Pfau. In the midst of end-of-year stress they found the time to read the manuscript and provide valuable comments on its content and structure.

This project would not have been possible without the cooperation and continuous support of the *Koninklijk Instituut voor Doven en Slechthorenden* in Hasselt and the *Nederlandse Stichting voor het Dove en Slechthorende Kind* in Amsterdam. In this respect I particularly wish to thank Leo de Raeve, Noëlle Uilenburg and Gerard Spaai for granting me permission to approach parents, sharing relevant information with me and facilitating testing of the children. I would also like to acknowledge the *Amsterdam Center for Language and Communication* for funding the project. In particular, I would like to express my gratitude to current academic director Kees Hengeveld, previous academic director Anne Baker, and Josep Quer and Paul Boersma in the role of ACLC representatives in progress meetings for their confidence and support, as well as to managing director Els Verheugd and office manager Marijke Vuijk for their assistance in practical matter of all sorts.

It is beyond any doubt that, in addition to the above-mentioned institutes, this project would not have succeeded without the cooperation of many children and their parents, teachers and school principals. Also, I wish to sincerely thank all those who participated in the experiments as adult controls. Their important role in research projects that involve children is often underestimated.

Furthermore, Jan de Jong, Beppie van den Bogaerde, Mieke Beers and Ellen Gerrits supervised this project at a distance and their insightful comments and suggestions along the way have been extremely helpful. Judith Rispens, although not officially a member of the supervising committee, was my sparring partner during the past three years and endured endless discussions with me on neighborhood density, phonotactic probability, non-words, fuzzy phonological representations and many other topics. Dirk-Jan Vet provided technical advice and assistance in designing the

experiments and Marijke Scheffener and Myriam Vermeerbergen helped with the construction of non-signs.

Of course, I also have many colleagues and friends to thank who shared their ideas and opinions with me during conferences, workshops, symposia, summer schools, winter schools, research group meetings, lab meetings, and in the office, hallways, coffee room or canteen. Many of you unfortunately remain anonymous. A few people I would like to mention individually are Marjolein Cremer, Josefien Sweep and Wieneke Wesseling, for being awesome roommates throughout these years, and Elly ten Berge and Gerdien Kerssies, for being the most assistant and sociable neighbors I could have hoped for! Furthermore, Suzanne Aalberse, Titia Benders, Catherine van Beuningen, Akke de Blauw, Bart de Boer, Marian Erkelens, Jan Hulstijn, Irene Jacobi, Kino Jansonius, Petra Jongmans, Marije Michel, Antje Orgassa, Esther Parigger, Daniela Polišenská, Louis Pols, Margot Rozendaal, Rob Schoonen, Joke Schuit and Jeannette van der Stelt, for being tremendously involved ACLC colleagues throughout the years. Also, Elise de Bree, Desiree Capel, Iris Duinmeijer, Patricia Gulpen and Caroline Junge, for being just as much involved, although not ACLC colleagues.

Marjolein, Wieneke, Akke, Marian, Petra, Marije, Antje, Esther, Daniela, Margot, Iris, Patricia and Caroline joined me in activities for the *Werkverband Amsterdamse Psycholinguïsten* (WAP) at one time or another in the past few years and have proven to be exceptional friends as well as colleagues. Editing the WAP newsletter has been a highly enjoyable and recurring passtime throughout my years as a PhD student and for that reason I would also like to thank Marieke Kolkman, Floor Landa, Anneriet Nubé, Ruth Timmer and Annemarie van de Zande for sharing that experience with me.

Last, but not least, I would like to acknowledge the *Fulbright Center* for providing me with the opportunity and means to spend four months in the Laboratory for Language and Cognitive Neuroscience in San Diego as part of the Fulbright Visiting Scholar Program. These four months have been an amazing and invaluable experience that I once hope to renew and extend. Karen, Ally, Brenda, Shannon, Jill, Heather, Jenn, Amy, Bean, Cindy, Steve, Jonathan, Christiana, Ashley, Danielle and Alisha, thank you so much for sharing your knowledge, expertise and, not to forget, company with me! You rock! I also owe many thanks to Matt Hall and Rachel Mayberry for giving me a taste of the fantastic research that is carried out at the Laboratory for Comparative Language Acquisition at UCSD by inviting me to their lab meetings and sharing their work and thoughts with me. I sure hope to see you again sometime soon!

In loving memory of my sister,
Thera

1 INTRODUCTION

1.1 THE TOPIC AND GOAL OF THIS THESIS

As of January 2010, more than 150.000 patients with severe-to-profound sensorineural hearing loss worldwide had received a cochlear implant (CI), more than half of which were children (De Raeve et al., 2009). The majority of the operations were successful, restoring some sense of hearing. Each year, over 350 cochlear implant operations are performed in the Netherlands and it is estimated that at least between 70-75% of congenitally deaf children in the Netherlands use a CI (De Raeve et al., 2009).

For pre-lingually deaf children, one of the most important functions of a CI is to support spoken language development. As a result, research in pediatric cochlear implantation mainly focuses on spoken language outcomes (Thoutenhoofd et al., 2005). When the first pre-lingually deaf children received a CI in the 1980s, it was unknown whether they would be able to acquire a spoken language from the relatively poor auditory input provided by the implant (Svirsky, Robbins, Kirk, Pisoni, & Miyamoto, 2000). In the meantime, several studies have shown that some children with a CI show similar, or even faster, rates of spoken language development compared to children with normal hearing of the same age (Schauwers, Gillis, & Govaerts, 2005). That is, despite initial delays in language development, some children with a CI are able to catch up with their peers with normal hearing within a few years after implantation. However, individual outcomes are highly variable and many different factors affect the benefits a child will obtain from the CI (Geers, Nicholas, & Moog, 2007).

Within the domain of spoken language outcomes, speech perception has received much attention for several reasons. Firstly, compared to the human ear, auditory processing through a CI is characterized by relatively poor spectrotemporal resolution (Shannon, 2002), thus posing a challenge for language acquisition. Secondly, as an index of auditory functioning, speech perception tests are frequently used in the clinical assessment of children with a CI (Mendel, 2008). Thirdly, speech perception abilities have been found to be a strong predictor of their expressive and receptive language abilities (DesJardin, Ambrose, Martinez, & Eisenberg, 2009; Sarant, Blamey, Dowell, Clark, & Gibson, 2001). Speech perception outcomes also have been shown to depend on a range of factors including factors related to the hearing loss such as age at onset of hearing loss, degree of hearing loss and age at implantation, but also more general factors such as nonverbal IQ (Geers, Brenner, & Davidson, 2003a; Sarant et al., 2001; Wie, Falkenberg, Tvete, & Tomblin, 2007).

Most studies of speech perception in children with a CI have included standardized word and sentence recognition tests and have not focused on the underlying processes in speech perception. Nevertheless, understanding how the nature of the auditory input affects the linguistic and cognitive processes relevant to speech perception will contribute substantially to explaining why some children do particularly well with their CI, whereas others do not (Pisoni, 2000). The first goal of this thesis is to enhance the understanding of speech perception in children with a CI by examining underlying processes in their perception of sounds and words. More specifically, we will examine whether they use acoustic cues in consonant and vowel perception differently from children with normal hearing and how such differences, if found, affect word learning.

The second goal of this thesis is directly related to another, more controversial, topic in the pediatric cochlear implantation literature, namely the effect of signed input on spoken language development (Geers, 2006; Nicholas & Geers, 2003; Spencer & Tomblin, 2006; Yoshinaga-Itano, 2006)¹. Given that the main function of a CI in pre-lingually deaf children is to support spoken language development, it is not surprising that the majority of time and effort in their rehabilitation and education is aimed at fostering spoken language abilities. However, a CI does not restore normal hearing and the child is again deaf if the device is switched off or not functioning properly. Moreover, as already mentioned, not all children benefit from the CI to the same extent. Signed input has been suggested to have positive effects on spoken language development (e.g. Connor, Hieber, Arts, & Zwolan, 2000; Delore, Robier, Bremond, Beutter, & Ployet, 1999; Yoshinaga-Itano, 2006) as well as negative effects (e.g. Cullington, Hodges, Butts, Dolan-Ash, & Balkany, 2000; Geers et al., 2002; Pisoni, Cleary, Geers, & Tobey, 1999; Svirsky et al., 2000). Most of these studies compared children in different educational settings (usually ‘Oral Communication’ versus ‘Total Communication’) and, as will become clear in §1.4.2, their findings are often difficult to interpret. Only a few studies have adopted the more valid approach of comparing spoken and signed language abilities in the same children (Cassandro, Nicastrì, Chiarella, Genovese, & Gallo, 2003; Coerts, Mills, Van den Broek, & Brokx, 1994; De Raeve et al., 2009; Nordqvist & Nelfelt, 2004; Yoshinaga-Itano, 2006). This thesis will therefore provide more insight into the effects of signed input on spoken language abilities by examining speech perception and sign perception in the same sample of children.

In sum, this thesis contributes to understanding how children with a CI use the implant to perceive and learn spoken language as well as understanding their

¹ The term ‘signed input’ is preferred to ‘sign language’ since many children with a CI are exposed to artificial sign systems or sign-supported speech, but not to the natural sign language used in the deaf community.

potential strengths and weaknesses in perceiving language in different modalities. A group of 15 children with a CI, 02 age-matched children with normal hearing and 21 young adults with normal hearing participated in a series of experiments targeting pre-lexical and lexical perception in speech and sign. Before we turn to a discussion of the research questions (Chapter 2) and the research methodology (Chapter 3), the remaining part of this chapter provides an overview of the technology, process, and outcomes of (pediatric) cochlear implantation.

1.2 COCHLEAR IMPLANTATION

Both children and adults with severe-to-profound sensorineural hearing loss are candidates for a CI. Details of the implantation procedure are different for children and adults, but more importantly their outcomes can be different given that onset and duration of deafness are strong predictors of implant benefit (Dunham & Limb, 2007; Fallon, Irvine, & Shepherd, 2008; Peterson, Pisoni, & Miyamoto, 2010). More specifically, speech recognition performance achieved by children who lost their hearing before the age of four or five years (i.e., pre-lingually) is often quite good and comparable to that achieved by post-lingually deaf adults who received a CI at a later age (e.g. Dowell, Dettman, Blamey, Barker, & Clark, 2002). In contrast, pre-lingually deaf children and adults who have experienced a long period of auditory deprivation (i.e., more than eight years) before implantation typically perform poorly (e.g. Teoh, Pisoni, & Miyamoto, 2004a; Waltzman, Roland, & Cohen, 2002b). This is due to the lack of plasticity in auditory cortical structures after the long period of auditory deprivation (Fallon et al., 2008; Teoh, Pisoni, & Miyamoto, 2004b). Similarly, age-related differences in auditory cortical plasticity explain why age at implantation is an important predictor of spoken language outcomes in congenitally deaf children (see §1.4.1).

Pediatric cochlear implantation is a multifaceted and multidisciplinary topic covering areas of research as diverse as engineering, neurobiology, medicine, audiology, psychology, clinical linguistics, education and ethics. Here, two main topics will be addressed: cochlear implant technology (§1.2.1) and current practice in pediatric cochlear implantation (§1.2.2).

1.2.1 COCHLEAR IMPLANT TECHNOLOGY

A CI is an electronic hearing prosthesis that consists of an external component and a surgically implanted internal component (see Figure 1.1). The external component consists of a microphone, a speech processor, a magnetic radio frequency transmitter

and a power source. The speech processor and power source are either integrated with the microphone in a behind-the-ear processor or worn on the body. Externally fitted or built-in electromagnets allow wireless coupling to other devices such as assistive listening devices, cell phones and MP3 players, which feed output directly into the speech processor. The surgically implanted internal component consists of a magnetic radio frequency receiver and an electrode array that is inserted in the cochlea. Sound is received by the microphone and relayed to the speech processor, where the input signal is digitized, compressed and filtered. The signal is then transmitted transcutaneously via radiofrequencies to the internal component, where the signals are converted into electrical discharges at assigned electrodes through induction of an electrical field between the assigned electrode and a reference electrode placed usually on the outside of the cochlea. The electrodes directly stimulate the auditory nerve².

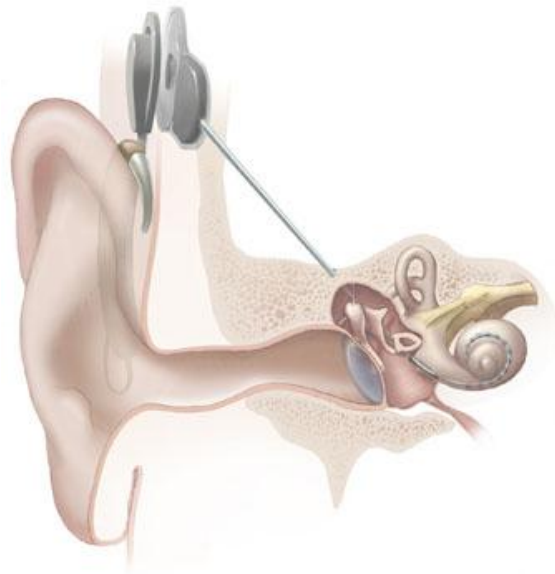


Figure 1.1. External and internal components of a CI.

² Some adults have a dysfunctional auditory nerve and some children are born without an auditory nerve. Cochlear implants do not provide benefit for these patients, but auditory brainstem implants or auditory midbrain implants might (Moore & Shannon, 2009). These implants bypass the cochlea and are inserted in the cochlea nucleus (auditory brainstem implant) or the inferior colliculus (auditory midbrain implant). Preliminary results have shown moderate success of the auditory brainstem implant in post-lingually deaf adults (Moore & Shannon, 2009) and also in pre-lingually deaf children implanted at three and a half years of age (Sennaroglu et al., 2009). Results with the auditory midbrain implant have not been very positive as yet.

There are three major manufacturers of implant devices: MED-EL[®], Cochlear[®] and Advanced Bionics[®]. CIs can vary in design, implemented speech processing algorithm, electrode array and number of electrodes (Dunham & Limb, 2007). The functioning of a CI can depend on the placement of the array inside the cochlea (depth and proximity to spiral ganglion cells) and the number of electrodes that can be used effectively. Current CIs use between 12 and 24 electrodes that span the frequency range between approximately 100 and 8000 Hz. However, the number of available electrodes far exceeds the number that are actively used, which lies between four and eight for current electrode array designs and for current positioning of the electrode array within the cochlea. This limitation may be due to interference between the electric fields from adjacent stimulating electrodes (Wilson & Dorman, 2008a). Current CIs are flexible in the number of active electrodes and stimulation rate to allow adaptation to the needs and preferences of individual users or different listening situations.

CIs have different speech processing algorithms. The most frequently used algorithms are: continuous interleaved sampling (CIS), spectral peak (SPEAK), advanced combination encoder (ACE), *n*-of-*m* and HiResolution (HiRes) strategies. CIS is the default algorithm for MED-EL[®] devices, ACE for Cochlear[®] devices and HiRes for Advanced Bionics[®] devices (Wilson & Dorman, 2008b). However, manufacturers sometimes use different algorithms.

The CIS algorithm is widely used and compatible with devices from all three manufacturers. It filters speech and other sounds using frequency band filters. After compression of the dynamic range, the algorithm directs the output of each filter to a single electrode. High frequency bands are assigned to electrodes at the beginning of the cochlea (base) and low frequency bands to electrodes at the end of the cochlea (apex), following the frequency-to-place mapping in the normal cochlea. Signals are continuously sampled by rapidly presented pulses interleaved across electrodes. The HiRes algorithm resembles the CIS algorithm, but uses higher stimulation rates and cut-off frequencies for the frequency band filters.

With SPEAK, *n*-of-*m*, and ACE algorithms, signals for the different channels are scanned before electrode stimulation. Stimulus pulses are delivered only to the electrodes that correspond to channels with the highest amplitudes. The number of chosen channels is fixed in *n*-of-*m* and ACE, but can vary in SPEAK, depending on the input signal. The main functions of channel selection in these strategies are to reduce interference between adjacent electrodes and to increase speech-to-noise ratios.

The development of new processing algorithms is largely directed at representing temporal fine structure information, that is, rapid high-frequency modulations in the acoustic signal (Wilson & Dorman, 2008b). Such information is especially important for speech perception under adverse conditions as well as for

the perception of melody in music. Current processing algorithms such as CIS, SPEAK and ACE were not designed to transmit fine structure information. Several recently developed algorithms aim to enhance the transmission of such information by, for instance, interlacing pulses for low-frequency channels and high-frequency channels or creating virtual electrodes by using multiple stimulation sites for each channel to represent intermediate frequencies. However, it is as yet unclear how much fine structure information is already provided by current algorithms and how much benefit can be gained from these new algorithms (Wilson & Dorman, 2008b).

Whatever future technological developments may bring, it is important to keep in mind that a CI does not restore normal hearing. Sound processing with a CI differs in several crucial ways from what the normal ear does, specifically in the spectral, temporal and amplitude information provided (Moore, 2003). Fortunately, speech recognition has been found to be fairly resistant to amplitude and temporal distortion in the speech signal (Dorman, Loizou, Spahr, & Maloff, 2002). However, a CI is also known to distort spectral information. This is due to a low pitch saturation limit, the limited number of effective channels and sometimes substantial shifts in frequency-to-place mapping in the cochlea (Moore, 2003). Unfortunately, spectral distortion has clear adverse effects on speech recognition (Dorman et al., 2002; Shannon, 2002; Xu & Pfingst, 2008). Furthermore, it should be noted that, although modern CIs allow fairly accurate speech recognition in quiet listening conditions, noisy environments or situations with multiple speakers talking at the same time continue to present a great challenge to users (e.g. Friesen, Shannon, Baskent, & Wang, 2001; Fu & Nogaki, 2005; Schafer & Thibodeau, 2006).

It is important to note that variation in CI technology impacts pediatric cochlear implantation practice and the study of spoken language outcomes. Depending on which manufacturer is preferred by CI centers, children will receive different CIs with different technical specifications and different implemented speech processing algorithms. However, all modern CIs have been shown to produce very good results in children and adults (Wilson & Dorman, 2008b). The role of these differences in explaining inter-individual variation in outcomes therefore appears to be limited (see e.g. Psarros et al., 2002; Skinner et al., 2002). Importantly, because all CI centers adopt the most recent techniques, it is difficult to compare children implanted today with children implanted five years ago - the so-called 'moving target' phenomenon (Geers, 2006).

1.2.2 CURRENT PRACTICE IN PEDIATRIC COCHLEAR IMPLANTATION

As a result of newborn hearing screening programs, the age of diagnosis in congenitally deaf children has decreased substantially in many countries (Gerrits, Brokx, & Rozier, 2005; Kennedy et al., 2006; Sarant, Holt, Dowell, Rickards, &

Blamey, 2009; Yoshinaga-Itano, 2003). Reliable indices of auditory functioning in infants such as oto-acoustic emissions or auditory brainstem responses have made such a screening possible. Early diagnosis has paved the way for early intervention and support, including early cochlear implantation. Early diagnosis together with converging evidence for the positive effect of early implantation on spoken language development (see §1.4.1) has resulted in a sharp decrease in the age at which pre-lingually deaf children receive a CI. Implantation within the first year of life is becoming standard practice in many countries.

Cochlear implantation requires a multidisciplinary team to provide the most supportive environment for the child as well as for the parents and siblings (Archbold & O'Donoghue, 2009). If the hearing screening indicates severe to profound hearing loss, parents are referred to a CI centre where an audiological, medical, communicational and psychological assessment is completed to determine whether a child is a potential candidate for a CI. In the meantime, acoustic hearing aids are fitted to determine the amount of benefit gained through means of acoustic amplification³. The decision to proceed with implantation is shared between the parents and the CI team.

Currently, when the implant is surgically inserted, residual hearing is often lost during the operation. For profoundly deaf children with between 90 dB and 120 dB loss in the better ear, the benefit gained from the CI outweighs the loss of any residual hearing. For children with less severe hearing loss factors other than auditory thresholds, such as the amount of benefit obtained from acoustic amplification, may determine whether they receive a CI (Fitzpatrick et al., 2009). Another important issue to consider before implantation is whether the child suffers from additional disabilities, which concerns over 30% of the profoundly deaf children. Although the number of children with complex needs that are implanted has increased substantially in recent years, the presence of additional disabilities can strongly affect the outcomes and CI candidacy for these children has to be considered on a case-by-case basis (Edwards, 2007b).

The surgical procedure involved in cochlear implantation can safely be performed in young children, even within the first year of life (Eter & Balkany, 2009; Holt & Svirsky, 2008; Waltzman & Roland Jr., 2005). Approximately four weeks after surgical insertion of the internal component, the external component is fitted and the CI is activated. Following this first familiarization session, several more sessions will be necessary to program the individual electrodes. As the child

³ Cochlear implantation will only be considered when acoustic amplification provides insufficient benefit. In relation to this, it is important to note that in parallel with cochlear implant technology, digital hearing aid technology has also significantly advanced in the past decade (Edwards, 2007a). The rapid technological progress in both cochlear implant and digital hearing aid technology makes it difficult to establish strict criteria for CI candidacy, especially for children with hearing loss in the severe to profound range.

gets used to the auditory input provided by the CI, re-programming is often required. The process of learning to interpret the signals from the CI takes time and stimulation by parents, teachers and speech therapists is important (Archbold & O'Donoghue, 2009).

Long-term electrical stimulation does not appear to have any negative consequences for the user (Waltzman, Cohen, Green, & Roland Jr., 2002a). However, Archbold and O'Donoghue (2009) note that further operations during a child's life-time will be likely, due to device failure or system upgrades, for instance to allow implementation of new processing strategies incompatible with the current internal component. Fortunately, re-implantation is usually accomplished without loss of functioning. The rates of pediatric revision surgery due to medical complications or device failure vary between 5% and 14% (Eter & Balkany, 2009).

Until a few years ago, implantation was performed only unilaterally and the non-implanted ear was sometimes fitted with an acoustic hearing aid to support some binaural hearing. However, bilateral implantation is rapidly becoming common practice, especially in children with no residual hearing⁴. Reported benefits mainly concern localization and speech perception in noise, for which binaural hearing is important (Ching, Van Wanrooy, & Dillon, 2007; Firszt, Reeder, & Skinner, 2008; Johnston, Durieux-Smith, Angus, O'Connor, & Fitzpatrick, 2009; Schafer, Amlani, Seibold, & Shattuck, 2007). Much less is known about the benefits of pediatric bilateral implantation for more general spoken language outcomes (but see e.g. Nittrouer & Chapman, 2009; Scherf et al., 2009). Similar to the advantage for early implantation of the first CI, there appears to be an advantage for early implantation of the second CI, both in absolute terms and relative to the first implant (Gordon & Papsin, 2009; Papsin & Gordon, 2008).

For children with residual hearing in the non-implanted ear, it is as yet unknown under what circumstances a second CI will provide greater benefit than an acoustic hearing aid (Ching et al., 2007; Nittrouer & Chapman, 2009). The development of the so-called hybrid CIs might be helpful in this respect. These CIs combine acoustic amplification and electrical stimulation in a single device. They are not fully inserted in the cochlea and preserve residual hearing in the low-frequency range for acoustic amplification. As of yet, only limited data is available on the effectiveness of these CIs (but see e.g. Turner, Reiss, & Gantz, 2008). They might provide benefit to those with severe sensorineural hearing loss that have too much residual hearing in the low-frequency range to be a candidate for a traditional CI.

⁴ Budgetary constraints form one of the major obstacles for bilateral cochlear implantation; health agencies do not always reimburse the second CI (as is currently the case in the Netherlands, for instance). However, as more evidence concerning the benefits of bilateral implantation relative to unilateral implantation is gathered, more health agencies will probably decide to also reimburse the second implant as was the case in 2010 in Flanders.

Thus, children with a CI not only vary in the type of CI and implemented speech processing algorithm, but also age at diagnosis and implantation, the presence of additional disabilities and the use of hearing aids or bilateral CIs. The complex interplay of these and other variables contributes to the difficulty of predicting spoken language outcomes in children with a CI. Moreover, as already mentioned in §1.2.1, due to continuously changing technology and progressive lowering of age at implantation, children with a CI represent a “moving target” and research is therefore rapidly outdated. In the next two sections we will nevertheless try to evaluate the outcomes of pediatric cochlear implantation (§1.3) and discuss in detail two factors that have been found to affect these outcomes, namely age at implantation and communication modality (§1.4).

1.3 OUTCOMES OF PEDIATRIC COCHLEAR IMPLANTATION

1.3.1 EFFECTS ON SPOKEN LANGUAGE ABILITIES

Most studies on spoken language outcomes report scores on standardized clinical assessment measures of speech perception, speech production, and expressive and receptive vocabulary and language abilities (Schauwers et al., 2005). Studies have also elicited spontaneous speech samples to analyze speech production (e.g. Ertmer et al., 2002; Flipsen Jr. & Parker, 2008 for English; Schauwers, Gillis, Daemers, De Beukelaer, & Govaerts, 2004 for Dutch) and morphosyntactic abilities (e.g. Nicholas & Geers, 2007; Spencer, Tye-Murray, & Tomblin, 1998; Svirsky, Stallings, Lento, Ying, & Leonard, 2002 for English; Szagun, 2000 for German). Furthermore, a few studies have addressed narrative and conversational abilities in children with a CI (e.g. Crosson & Geers, 2001 for English; Ibertsson, Hansson, Maki-Torkko, Willstedt-Svensson, & Sahlen, 2009 for Swedish). Importantly, the rapid decrease in age at implantation has resulted in a need for reliable clinical assessment measures that are suitable for use with very young children (Eisenberg, Martinez, & Boothroyd, 2007; Mendel, 2008; Nikolopoulos, Archbold, & Gregory, 2005).

Studies on spoken language outcomes report considerable inter-individual variation, varying from performance at age-appropriate levels within a few years after implantation to short- and long-term delays (for reviews, see e.g. Belzner & Seal, 2009; Bond et al., 2009; Peterson et al., 2010; Schauwers et al., 2005; Thoutenhoofd et al., 2005). The percentages of children that perform age-appropriately vary substantially between studies and language domains. For instance, Schorr, Roth and Fox (2008) compared 39 American children with a CI between five and fourteen years of age with age-matched children with normal

hearing on a range of language measures. They found that, as a group, the children with a CI performed within one standard deviation or less of age-equivalent scores (i.e., age-appropriately) on tests of speech production, expressive and receptive vocabulary, morphology and syntax, and phonological processing, but not auditory memory and meta-semantics. However, on all tests except speech production, the group scored significantly lower than the children with normal hearing. On average, 85% obtained age-appropriate scores for speech production, 51% for receptive vocabulary, 66% for expressive vocabulary, 36% for morphology and syntax, 26% for phonological processing and 13% for meta-semantics.

Geers et al. (2009) reported scores for 153 American 6-year old children with a CI on expressive and receptive vocabulary and language abilities, as well as verbal intelligence. 50% of the children obtained age-appropriate scores for receptive vocabulary, 58% for expressive vocabulary, 47% for receptive language, 39% for expressive language and 46% for verbal intelligence. A longitudinal follow-up study of 85 children from the same sample showed that, from eight to nine years of age until 15-18 years of age, the percentage of children that obtained age-appropriate scores for verbal intelligence increased from 60% to 77% (Geers, Tobey, Moog, & Brenner, 2008).

Niparko et al. (2010) compared expressive and receptive language development in 188 American children with a CI to 97 age-matched children with normal hearing in 6-month intervals until three years post-implantation. Through the years all children with a CI showed greater improvement than expected from their pre-implantation scores, but did not reach age-appropriate levels even three years after implantation. Importantly, individual developmental trajectories differed widely among the children with a CI in comparison to the children with normal hearing.

A range of factors has been found to predict spoken language outcomes, including age at implantation, age at onset of hearing loss, pre-implant auditory thresholds, family support, communication modality, nonverbal IQ and implant characteristics (Geers et al., 2007). The most consistent predictors appear to be age at implantation, communication modality and pre-implant residual hearing (Peterson et al., 2010). That is, positive spoken language outcomes in children with a CI are associated with earlier implantation, oral communication approaches and lower pre-implantation auditory thresholds. Even when taking all these factors into account, however, typically only slightly more than 50% of the variation in outcomes is explained (e.g. Geers, 2002), precluding reliable predictions of outcomes (Peterson et al., 2010). In an attempt to help clinicians evaluate the spoken language abilities of children with a CI, Nicholas and Geers (2008) provide expected test scores according to age at implantation for two commonly administered formal language tests in English and a widely used parent-report instrument based on a relatively homogenous sample of 76 children with a CI. These scores can be used to compare against the performance of other children with a CI at 3.5 years of age (parent-

report) and 4.5 years of age (parent-report as well as formal language tests). Such comparisons can help in determining the child's progress and in making informed educational decisions.

Reading outcomes in children with a CI have also been found to be extremely variable. Some studies report substantial delays for most children, whereas other studies report age-appropriate scores (Marschark, Rhoten, & Fabich, 2007). Unsurprisingly, the same demographic variables that affect spoken language outcomes have been found to affect reading outcomes (Connor & Zwolan, 2004). In addition, whether delays or age-appropriate scores are observed may be dependent on the skill measured (Vermeulen, Van Bon, Schreuder, Knoors, & Snik, 2007). Interestingly, Geers et al. (2008) report reading scores at eight to nine and 15-18 years of age. In this period, the percentage of children that obtained age-appropriate scores on a standardized test for reading recognition and comprehension actually decreased from 56% to 44%, whereas for verbal intelligence it increased from 60% to 77%, suggesting a discrepancy between long-term spoken language and reading outcomes.

It is important to note that standardized spoken language tests administered in clinical settings do not fully reflect communicative functioning (Lin et al., 2007; Lin et al., 2008). Furthermore, speech recognition with a CI might reach age-appropriate levels in quiet listening conditions, but be substantially poorer in the presence of noise (e.g. Schafer & Thibodeau, 2006). Unfortunately, many real-life situations are noisy, which present a particular challenge to hearing-impaired listeners (Shinn-Cunningham & Best, 2008).

In addition, a problem with most standardized spoken language tests is that they only provide the end result of a range of sensory, perceptual, cognitive and linguistic processes (Pisoni, 2000). This makes it difficult to interpret the results from such tests and determine the underlying cause of relatively good or poor performance. In an attempt to tackle this problem, several recent studies of spoken language outcomes in children with a CI have included more processing-oriented measures such as lexical access (e.g. Wass et al., 2008), non-word repetition (e.g. Burkholder-Juhasz, Levi, Dillon, & Pisoni, 2007), novel word learning (e.g. Houston, Carter, Pisoni, Kirk, & Ying, 2005) and verbal working memory (e.g. Burkholder & Pisoni, 2003; Pisoni & Cleary, 2003). Inter-individual variation in cognitive processes underlying spoken language acquisition and processing might help to explain variation in children's outcomes (Pisoni, 2000; Pisoni et al., 2008). The present thesis contributes to this "processing approach" because it examines the use of acoustic cues in sound perception and the relation between sound perception and word learning in children with a CI, topics that have not yet received much attention.

1.3.2 EFFECTS ON OTHER COGNITIVE ABILITIES

Pisoni and colleagues, besides introducing the above-mentioned processing approach, have also drawn attention to the interaction between spoken language abilities and other cognitive abilities, such as sensorimotor and visuospatial abilities, working memory abilities and executive functioning (see Pisoni et al., 2008 for a review). For instance, Pisoni et al. (1999) reported strong correlations between verbal working memory abilities and scores on standardized tests of speech production and perception as well as language comprehension in English. Furthermore, more recent studies found, for instance, slower verbal working memory processing in children with a CI compared to children with normal hearing (Burkholder & Pisoni, 2006)⁵, delays in the development of sustained visual attention (Horn, Davis, Pisoni, & Miyamoto, 2005; but see also Tharpe, Ashmead, & Rothpletz, 2002) and delays in the development of visual-motor integration abilities (Horn, Fagan, Dillon, Pisoni, & Miyamoto, 2007a).

Fagan, Pisoni, Horn and Dillon (2007) related scores on subtests of sensorimotor and visuospatial processing from a developmental neuropsychological assessment battery to scores on receptive vocabulary, reading and digit span measures in children with a CI. They found that visuospatial, but not sensorimotor abilities correlated positively with these measures. More generally, delays in the development of sustained visual attention may have consequences for early social-cognitive and communicative development, for instance, in the development of joint visual attention, an important precursor of social learning (Corina & Singleton, 2009). In addition, children with a CI might be more prone to visual distraction in the classroom, which raises important concerns regarding the provision of optimal learning environments for these children (Dye, Hauser, & Bavelier, 2008).

The relationship between spoken language and other cognitive abilities in children with a CI is further exemplified by studies that report positive effects of cochlear implantation on, for instance, the development of visual attention abilities (Quittner et al., 2007), behavioral regulation (Edwards, Khan, Broxholme, & Langdon, 2006), social abilities (Bat-Chava, Martin, & Kosciw, 2005) and social well-being (Percy-Smith, Caye-Thomasen, Gudman, Hedegard-Jensen, & Thomsen, 2008; Schorr, Roth, & Fox, 2009).

Together, these findings underline that spoken language development is only one aspect of development affected by cochlear implantation. Many neural and cognitive

⁵ For instance, subvocal rehearsal and serial scanning appear to operate more slowly in children with a CI, resulting in poorer performance on not only auditory, but also visual measures of verbal working memory (Burkholder & Pisoni, 2003; Cleary, Pisoni, & Geers, 2001; Dawson, Busby, McKay, & Clark, 2002). Children with a CI perform similarly to children with normal hearing, however, when the stimuli in the memory tasks are unlikely to be encoded verbally (Burkholder & Pisoni, 2006; Dawson et al., 2002).

changes as a consequence of auditory deprivation will already have taken place before implantation and reduced hearing abilities will continue to affect neural and cognitive development after implantation (Fagan & Pisoni, 2009). Deaf infants by necessity will be more focused on visual information in their surroundings (Fagan & Pisoni, 2009; Mitchell & Maslin, 2007), but the effects of such sensory processing biases on, for instance, the development of early speech perception abilities are not yet known (Gerrits, 2006; Houston, 2005). More generally, several decades of research have revealed both similarities and differences in cognitive processing between deaf and hearing children, adolescents and adults (Marschark & Hauser, 2008). It remains to be seen to what extent these findings also apply to children, adolescents and adults with a CI.

1.3.3 LONG-TERM OUTCOMES

Studies on the long-term outcomes of cochlear implantation have only recently become available (see e.g. Geers, Strube, Tobey, Pisoni, & Moog, 2011 and other papers in that issue). These studies suggest that spoken language abilities continue to improve well into adolescence (Geers et al., 2008) and that only a small percentage of those implanted in the countries studied no longer use their CI (Archbold, Nikolopoulos, & Lloyd-Richmond, 2009; Beadle et al., 2005; Spencer, Gantz, & Knutson, 2004; Waltzman et al., 2002a). Even less is known about the academic-occupational achievements of young adults who received a CI when they were young, but the few studies that have been published report good achievements (Beadle et al., 2005; Spencer et al., 2004). More long-term outcome studies in different countries are much needed, especially longitudinal ones with large representative samples that include outcomes for reading and academic achievements as well as for spoken language (Marschark et al., 2007).

1.4 EFFECTS OF AGE AT IMPLANTATION AND COMMUNICATION MODALITY ON SPOKEN LANGUAGE

1.4.1 AGE AT IMPLANTATION

Of all the factors that influence the outcomes of pediatric cochlear implantation, age at implantation seems to be one of the most robust factors, especially in relation to spoken language acquisition. The development of brain and behavior in humans and animals is characterized by multiple sensitive periods (Bischof, 2007; Knudsen,

2004; Thomas & Johnson, 2008), periods during which “having a certain kind of experience at one point in development has a profoundly different impact on future behavior than having that same experience at any other point in development” (Bruer, 2001, p.4). Language development has long been associated with one of these sensitive periods on the basis of different types of evidence: children reared in social isolation (Bortfeld & Whitehurst, 2001), deaf adults who had been raised and educated orally and systematically exposed to sign language only as adults (Mayberry & Lock, 2003), adult second language learning (Birdsong, 2006; Hakuta, 2001), and infant native language attunement (Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Werker & Tees, 2005).

Studies examining the effects of early implantation in congenitally deaf children are a recent contribution to the literature on sensitive periods in language development (Tomblin, Barker, & Hubbs, 2007). Sensory deprivation, such as hearing loss or sight loss, during sensitive periods in development can have profound and permanent effects on the development of cortical connections within the brain (Bavelier & Neville, 2002; Pascual-Leone, Amedi, Fregni, & Merabet, 2005). One such effect is cross-modal reorganization, when cortical areas that usually respond to input from the deprived sensory organ (e.g., the ear) start responding to input from another sensory organ (e.g., the eye). Several studies have provided evidence for cross-modal cortical reorganization in children and adults with CIs (for reviews, see Peterson et al., 2010; Sharma, Nash, & Dorman, 2009). If a CI is inserted and activated after cortical reorganization has taken place, benefit of the implant is limited because necessary neural connections within the auditory cortex can no longer be established (Kral & Eggermont, 2007). Age cut-offs reported in neurophysiological studies suggest a sensitive period for the development of normal (sub)cortical auditory processing that lasts until three to four years of age (e.g. Sharma, Gilley, Dorman, & Baldwin, 2007).

In support of these neurophysiological studies, behavioral studies have also found strong effects of early versus late implantation on spoken language outcomes. In fact, many behavioral studies report advantages for early implantation in children younger than three years (Marco-Algarra et al., 2009). That is, implantation before two years of age seems to lead to significantly better spoken language outcomes than at a later age (e.g. Anderson et al., 2004; Artieres, Vieu, Mondain, Uziel, & Venail, 2009; Chin, Svirsky, & Jester, 2007; Geers, Nicholas, & Sedey, 2003b; Kirk, Miyamoto, Ying, Perdew, & Zuganelis, 2003; Svirsky, Teoh, & Neuburger, 2004; Zwolan et al., 2004). A few recent studies even suggest that implantation before 12 months of age is advantageous (e.g. Coene, Schauwers, Gillis, Rooryck, & Govaerts, in press; Colletti, 2009; Dettman, Pinder, Briggs, Dowell, & Leigh, 2007; Holt & Svirsky, 2008; Waltzman & Roland Jr., 2005).

However, not all studies report advantages for early implantation (e.g. Geers, 2004). It has been suggested that age at implantation might differentially affect

language domains (Geers et al., 2009; Holt & Svirsky, 2008) as well as abilities within one language domain (Harrison, Gordon, & Mount, 2005). Additionally, other variables such as length of CI use, age at diagnosis, pre-implant hearing thresholds or demographic variables such as ethnicity and social-economic status can confound with age at implantation. The effect, or lack thereof, of age at implantation may thus be indirectly the result of uncontrolled variables. Early implantation does not guarantee successful spoken language outcomes, but it makes them likely.

1.4.2 COMMUNICATION MODALITY

The deaf community was long opposed to pediatric cochlear implantation, but this opposition has slowly waned (Christiansen & Leigh, 2004). It has now become a standard procedure in many countries, with the majority of congenitally deaf children receiving a CI. Around 90% of the congenitally deaf children have two hearing parents, which in part explains why so many deaf children receive a CI.

Ideally, after the diagnosis of hearing loss in their child, parents receive objective, balanced information on all available options such as acoustic hearing aids, CIs, sign language and the deaf community, so that they can make a well-founded decision (Archbold, Sach, O'Neill, Lutman, & Gregory, 2006). Unfortunately, this is not always the case. Parents in different countries often report that information about educational and communicative options was conflicting and biased towards or against cochlear implantation (Berg, Ip, Hurst, & Herb, 2007; Christiansen & Leigh, 2004; Sach & Whynes, 2005; Sorkin & Zwolan, 2008; Wever, 2002). Nevertheless, few parents regret having taken the decision to have their child implanted (Sach & Whynes, 2005) and most children, when they are older, appreciate the decision their parents took on their behalf (Wheeler, Archbold, Gregory, & Skipp, 2007). This is supported by studies that have examined their quality of life through parent report (e.g. Archbold, Sach, O'Neill, Lutman, & Gregory, 2008; Sach & Whynes, 2005; Stacey, Fortnum, Barton, & Summerfield, 2006) and through the children themselves (e.g. Leigh, Maxwell-McCaw, Bat-Chava, & Christiansen, 2008; Preisler, Tvingstedt, & Ahlstrom, 2005; Schorr et al., 2009).

Notwithstanding the wide-spread acceptance of cochlear implantation, a much discussed topic remains the role of signed input in the raising and education of children with a CI (e.g. Delore et al., 1999; Leigh, 2008; Marschark, 2007; Papsin & Gordon, 2007). Parents may decide to include signs in the child's language input at home, often after taking advice from pediatricians, educational psychologists and other parents (e.g. Christiansen & Leigh, 2004; Watson, Hardie, Archbold, & Wheeler, 2008; Wever, 2002). The type of language input at school is a more

complex question, however (e.g. Knoors, 2007; Leigh, 2008; Marschark, 2007). Countries can differ in the extent to which they stimulate mainstreaming of children with special needs. Furthermore, the role of a sign language in the educational setting differs between countries and within countries between states, provinces and districts. Schools that embrace an auditory-verbal approach do not include any sign language. Other schools might adopt a simultaneous communication approach, with sign-supported speech as the main mode of communication, or a bilingual-bicultural approach, with instruction in a spoken language as well as a sign language. Depending on national, state and local laws, parents might not be entirely free in the decision they make regarding the educational placement of their child. Adding to this complexity, children with a CI often make a transition from one educational setting to another, for instance from special education to mainstream or from a more bilingually oriented program to a more sign-supported oriented program (e.g. Watson, Archbold, & Nikolopoulos, 2006).

When they are older, children with a CI will mainly decide themselves whether they will speak or sign, possibly even depending on the communicative situation and interlocutor, and whether they switch off the implant at time or even stop using it (Wheeler et al., 2007). Parents report that changes in how they communicate with their children at home are most often driven by the preferences of the children themselves (Preisler, Tvingstedt, & Ahlstrom, 2001; Watson et al., 2008). That is, cochlear implantation entails a communication journey for both the parents and the children (Wever, 2002; Wheeler, Archbold, Hardie, & Watson, 2009). Unfortunately, it is not without obstacles due to opposition from professionals or restrictions imposed by local or national educational policies (Sach & Whynes, 2005; Sorkin & Zwolan, 2008; Wever, 2002; Wheeler et al., 2009).

Fueling the discussion on the role of signed input for children with a CI are reports of its negative effects on spoken language (Geers, 2006). Available studies mostly compared “Oral Communication” (OC) settings, where only spoken language is used, to “Total Communication” (TC) settings, where both spoken language and some form of signed communication are used, mainly in the United States or the United Kingdom. The majority of these studies report an OC advantage (Archbold et al., 2000; Geers et al., 2000; Kirk et al., 2003; Svirsky et al., 2000). However, other studies found no effect of educational setting (e.g. McConkey Robbins, Svirsky, & Kirk, 1997; Svirsky et al., 2004) or even a TC advantage (e.g. Connor et al., 2000; McConkey Robbins, Bollard, & Green, 1999). One explanation for these variable results may lie in the nature of Total Communication, which is an educational philosophy that incorporates a variety of practices that are often not described in research studies (Spencer & Tomblin, 2006). It may also be that children who show less than expected progress are the ones who start in a TC setting, remain in this setting for a longer time or transition from an OC setting to a TC setting. Another explanation may come from the fact that some studies only used

the spoken modality to administer tests, whereas others used the modality preferred by the child (for discussion, see Geers, 2006).

Regarding the effects of signed input, positive results have been explained by the suggestion that signed vocabulary acquired pre-implantation might bootstrap spoken vocabulary development (Yoshinaga-Itano, 2006). Additionally, it might provide important early language stimulation (Connor et al., 2000). In contrast, Pisoni et al. (1999) suggested that the efficiency of auditory short-term memory processes such as encoding and rehearsal might benefit from increased exposure to speech and therefore signed input may have negative effects. Moreover, simultaneously attending to two visual sources of information (i.e., manual-visual and audiovisual) might create competition for limited processing resources (Bergeson, Pisoni, & Davis, 2005). Finally, using sign language before implantation might stimulate cross-modal reorganization of the auditory cortex, which may negatively impact speech processing (Giraud & Lee, 2007).

Unfortunately, only a few studies have compared spoken and signed language abilities in the same sample of children with a CI, and most of these are case studies (but see De Raeve et al., 2009). A within-subject approach allows a more direct examination of the effects of signed input on spoken language development and controls for most confounds that may affect studies comparing children in OC and TC settings. In addition, the question of whether children with a CI benefit from seeing signs at the same time when they lip-read spoken words or whether the two sources of visual information compete has yet to be empirically tested. This thesis contributes to filling these two gaps in the literature by examining the relationship between speech and sign perception in children with a CI who varied in the amount of signed input they received at home and school.

1.5 THE ORGANIZATION OF THIS THESIS

This introductory chapter presented the goals of this thesis, namely to provide insight into the underlying processes in the perception of speech sounds and words by children with a CI, as well as the relationship between sign and speech perception abilities. In addition, it provided an introduction to pediatric cochlear implantation that will help in understanding and evaluating the research presented in this thesis. The remainder of this thesis is organized as follows.

Chapter 2 discusses the research questions of this thesis in more detail. Chapter 3 introduces the tasks that were designed to answer the research questions, as well as the different groups of participants that provided the answers. In Chapters 4 to 7, the results of the different experiments are presented. More specifically, Chapter 4 focuses on the use of acoustic cues in consonant and vowel perception. Chapter 5

examines the relation between perceiving speech sounds and learning novel words. Chapter 6 presents data on pre-lexical and lexical perception in the signed modality and addresses the *relationship* between perception in the signed and the spoken modality. Chapter 7 discusses the *interaction* between both language modalities during language perception. Finally, Chapter 8 summarizes the findings and presents the overall conclusions.

2 SPEECH AND SIGN PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS: THE PRESENT STUDY

This chapter presents the specific research questions of this thesis, together with the theoretical and empirical background for the experiments discussed in Chapters 4 to 7. In §2.1 the processes of how typically developing children learn to perceive sounds and words are explained in relation to how children with a CI might differ. In §2.2 similarities and differences between speech and sign perception are described and previous research on the relationship between the two language modalities in children with a CI is briefly discussed.

2.1 THE PERCEPTION OF SOUNDS AND WORDS BY CHILDREN WITH A CI

2.1.1 BACKGROUND

‘Speech perception’ is a rather broad term that encompasses the perception of speech sounds, words and sentences and for which the terms ‘speech recognition’, ‘speech comprehension’ or ‘speech processing’ are sometimes used without clear distinctions in meaning. Speech perception can be defined as “the set of operations that transform an auditory signal into mental representations of a type that can make contact with internally stored information (i.e., words).” (Poeppel & Monahan, 2008, p.80). Physically, speech consists of a continuously varying waveform, which is converted into mechanical vibration in the middle ear before it is converted into fluid vibration in the inner ear. In the inner ear, movement of the basilar membrane in the fluid causes movement of hair cells that excite adjacent neurons of the hearing nerve. Our brain then performs a rapid temporal and spectral analysis on the electrophysiological signal transmitted by the hearing nerve, resulting in a presumably abstract pre-lexical representation of speech sounds and words in the auditory cortex (Oblaser & Eisner, 2009; Poeppel & Monahan, 2008). These pre-lexical representations are then mapped onto lexical-conceptual representations and possibly also to articulatory-motor representations in different parts of the brain (Hickok & Poeppel, 2007). It should be emphasized, however, that the exact nature of the processes and representations involved in speech perception are not yet fully understood.

Regardless of its exact nature, human speech perception has at least two remarkable features. Firstly, it is incredibly adaptive and therefore robust. That is, adult listeners can adapt quickly to variation in the speech signal, such as changes in speaker, dialect, speaking rate and physical degradation of the speech signal (Pisoni,

1997). Precisely the physical variability in the speech signal combined with listener's apparent ease in coping with this variability has led researchers to posit speech perception models that include abstract units of representation.

Secondly, young children appear to learn to perceive speech rather effortlessly (Houston, 2005; Kuhl, 2004). By their first birthday, their perception of speech sounds is adapted to the language surrounding them, they are sensitive to transitional probabilities and prosodic regularities for segmenting words, and show signs of perceptual robustness in response to talker variability. Importantly, recent studies have shown that these early speech perception abilities correlate with later language development (e.g. Bernhardt, Kemp, & Werker, 2007; Kuhl et al., 2005; Marchman & Fernald, 2008; Newman, Bernstein Ratner, Jusczyk, Jusczyk, & Ayala Dow, 2006).

These two characteristics of human speech perception raise important questions about speech perception in pre-lingually deaf children with a CI. On the one hand, not having access to auditory input during a period of rapid neural and cognitive growth can be expected to have severe consequences for the development of early speech perception abilities and, by extension, for early language development. Moreover, because a CI provides perceptually degraded auditory input, children with sensorineural hearing loss are also at a disadvantage after hearing is partially restored with a CI. On the other hand, at least as far as speech perception in adults with normal hearing is concerned, human speech perception is adaptive and robust and might to some extent be able to adapt to the perceptual degradation that is introduced by CI processing (see also §1.2.1).

As mentioned in §1.1, speech perception in children with a CI has already received much attention in the literature. The results of many of these studies are difficult to interpret, however, because the variables studied do not reflect a single process. For instance, a common procedure is the use of standardized open-set or closed-set spoken word recognition tests (Pisoni, 2005). The ability to point to the correct picture in response to an auditory input (i.e., closed-set) or to correctly repeat spoken words (i.e., open-set) is the outcome of several preceding processes including auditory detection, acoustic-phonetic analysis, short-term memory and lexical access and retrieval. In order to understand exactly which aspects of the speech perception process present a continuing challenge to children with a CI, it is essential to examine each of these underlying processes in depth (cf. Pisoni, 2000). In this thesis, we address this matter by examining the use of acoustic cues in speech sound perception and the relationship between sound perception and word learning.

2.1.2 LEARNING TO PERCEIVE SPEECH SOUNDS: ACOUSTIC CUE WEIGHTING

Physically, speech sounds can be described as specific combinations of rapidly changing acoustic characteristics such as formant frequencies (bands of energy corresponding to the resonating frequencies of the vocal tract), duration and intensity (amount of energy produced by the vocal tract). The acoustic characteristics of speech sounds provide *cues* that listeners can use to discriminate and identify speech sounds in the speech signal. Different languages show different distributions of speech sounds and thus acoustic characteristics. As a result, listeners discriminate and identify speech sounds on the basis of language-specific combinations of acoustic cues. Learning to perceive speech, therefore, consists not only of learning to identify the relevant acoustic cues in the speech signal, but also of learning to combine and weigh them appropriately (Boersma, Escudero, & Hayes, 2003; Jusczyk, 1993; Nittrouer, 2002a; Werker & Curtin, 2005).

In fact, one of the first steps in learning to perceive speech sounds for infants is adapting their perception to the language surrounding them. Initially, infants are able to acoustically discriminate all contrasts that occur in natural languages. However, in their first year of life infants maintain only the ability to discriminate phonetic contrasts that occur in the language(s) surrounding them. This perceptual attunement to the native language occurs slightly earlier for vowel contrasts than for consonant contrasts (Polka & Werker, 1994; Werker & Tees, 1983). The exact mechanisms underlying these developmental changes are unknown, but there is some evidence that suggests an important role for distributional learning (Maye, Weiss, & Aslin, 2008; Maye, Werker, & Gerken, 2002). Because different languages use different distributions of speech sounds and thus acoustic characteristics, the input to the infant will show specific distributional patterns in acoustic characteristics that match the phonetic contrasts used in that language: frequently occurring (combinations of) acoustic features in the input tend to match phonetic categories in the language and infrequently occurring (combinations of) acoustic features tend to match the boundaries between phonetic categories in the language.

Notwithstanding these early accomplishments of infants in learning to perceive speech, it can take eight years or longer before adult-like cue weighting is attained by typically developing children, especially for consonant contrasts (e.g. Gerrits, 2001; Hazan & Barrett, 2000; Nittrouer, 2002b). Children with a CI seem to face an extra challenge in this process because, even if the implant provides sufficient acoustic information to support spoken language development, it does not restore normal hearing. More specifically, as we have seen in §1.2.1, sound processing with a CI is characterized by poor spectrotemporal resolution. Spectral and temporal cues are important for phoneme recognition, with spectral cues being especially important for vowel recognition and temporal cues for consonant recognition

(Dorman et al., 2002; Xu & Pfingst, 2008). However, it should be noted that spectral and temporal cues are often integrated, for instance in rapidly changing spectral patterns such as formant transitions, and that they can sometimes be used in a trade-off relationship (Xu & Pfingst, 2008).

The reduced spectrotemporal resolution of sound processing with a CI thus raises the question as to whether children with a CI use acoustic cues in speech perception differently from children with normal hearing. Several studies have investigated the use of acoustic cues by post-lingually deaf adult implant users and adults with normal hearing listening to implant simulations (e.g. Hedrick & Carney, 1997; Iverson, 2003; Iverson, Smith, & Evans, 2006; Munson & Nelson, 2005; Nie, Barco, & Zeng, 2006; Rogers, Healy, & Montgomery, 2006; Xu, Thompson, & Pfingst, 2005; Xu & Zheng, 2007). However, findings obtained with post-lingually deaf adult CI users cannot be generalized to deaf children for whom the onset of deafness occurred before they had acquired a spoken language and who were implanted at a much younger age. Furthermore, Eisenberg et al. (2000) found that young children with normal hearing (5-7 years of age) needed more spectral resolution to obtain the same levels of recognition as older children (10-12 years of age) and adults. These findings suggest developmental changes in the ability to adapt to spectrally reduced speech⁶. To our knowledge, only two studies have examined the use of acoustic cues by younger CI users (Bahng, 2008; Summerfield et al., 2002) and neither of these studies included vowel contrasts⁷. Including both consonant and vowel contrasts is important because vowel perception might be more difficult for them. As mentioned in §1.2.1, spectral information, which is especially important in vowel recognition, is distorted relatively more by a CI than temporal and amplitude information. The latter are more important for consonant recognition. Alternatively, consonant contrasts might be more difficult given that in typically developing children adult-like cue weighting usually takes longer to develop for consonant contrasts (Gerrits, 2001). Moreover, there is some evidence that vowels are perceived more accurately than consonants by young typically developing children as well as children with a CI (e.g. Kishon-Rabin et al., 2002).

⁶ Schvartz, Chatterjee & Gordon-Salant (2008) investigated the perception of spectrally degraded phonemes in younger, middle-aged and older listeners with normal hearing and found the opposite effect, namely that with increasing age the ability to recognize spectrally degraded speech became worse. Besides age, verbal memory and speed of processing abilities contributed to the observed performance differences.

⁷ In addition, a few studies are available on acoustic cue weighting in hearing-impaired children wearing acoustic hearing aids (Jerger, 2007). However, sound processing with an acoustic hearing aid is radically different from sound processing with a CI (and probably more similar to normal hearing). Findings from these studies therefore cannot be generalized to children with a CI.

The first research question in this thesis is therefore: do children with a CI use acoustic cues differently in consonant and vowel perception than children with normal hearing of the same age? More specifically, do they use the same cues and if so, do they use such cues as effectively?

2.1.2 THE INTERRELATION BETWEEN SOUNDS AND WORDS

Extracting speech sounds or phonemes from the continuous speech signal is just a first step in speech perception. Usually, the next step is to recognize words. Because there are no reliable word boundaries in continuous speech, listeners have to start with the process of word recognition as soon as input is perceived. As a result, spoken word recognition is a dynamic process that includes activation and competition of candidates as the input unfolds (see e.g. McMurray, Samuelson, Lee, & Tomblin, 2010).

Besides these core properties, different perspectives have been adopted with respect to the nature of pre-lexical processes and representations (Cutler, 2008; Gaskell, Quinlan, Tamminen, & Cleland, 2008; McMurray, Tanenhaus, & Aslin, 2009) as well as to the availability of feedback from the lexical to the phonological level during speech perception (McClelland, Mirman, & Holt, 2006; Norris, McQueen, & Cutler, 2000). Nevertheless, all models of spoken word recognition assume a strong relationship between the perception of speech sounds and the recognition of words.

Surprisingly, however, studies on adult sound perception and word recognition have mainly progressed independently of one another, which has resulted in theories of speech perception that account for one of these aspects but rarely both (Cutler, 2008). Similar to adult speech perception, the relationship between sounds and words has only recently started to be addressed in developmental studies (Stoel-Gammon, 2011; Storkel & Morrisette, 2002). Studies of sound perception and word recognition are gradually moving closer together, however, and the resulting fruitful exchanges have made it clear that the mapping from sounds onto words is not always straightforward. For instance, Weber and Cutler (2004) found that adult Dutch second language learners of English had stored the distinction between the initial syllables /pen/ and /pæn/ in the words *pencil* and *panda*, although they were unable to reliably hear the difference between the vowels /e/ and /æ/ (cf. Escudero, Hayes-Harb, & Mitterer, 2008). In contrast, Norris, McQueen and Cutler (2003) provide a rather extreme example of continuity between sound perception and word recognition. In that study, adult listeners first completed a lexical decision task in which in some words the final /t/ or /s/ was replaced by an ambiguous sound in between these two sounds. They then completed a task in which they had to

categorize ambiguous sounds on an /t/-/s/ continuum as /t/ or /s/. Listeners who had heard the ambiguous sound in /t/-final words were more likely to categorize ambiguous sounds as /t/ than those who had heard the ambiguous sounds in /s/-final words. Apparently, listeners use lexical information to rapidly adjust their phonetic boundaries when presented with distorted speech. Crucially, phonetic boundaries were not shifted if the ambiguous phonemes were embedded in non-words in the lexical decision task, which prevented mapping of the ambiguous phoneme onto its unambiguous counterpart in the mental lexicon.

One of the few linguistic models that attempts to explicitly capture both pre-lexical and lexical perception and representation is the Linguistic Perception model (Boersma, 1998; Escudero, 2005). This model distinguishes three levels of representation and two levels of processing in spoken word recognition. The three levels of representation are auditory form, phonological form and lexical form⁸. The two levels of processing are perception and recognition. The auditory form is the result of the analysis of the acoustic signal by the ears and the brain. The phonological form is a pre-lexical representation of a word in phonemes. This pre-lexical phonological representation is the outcome of a perception grammar that categorizes auditory forms in phonemes by integrating and weighting acoustic cues. The recognition of a word is established by means of a recognition grammar that maps a pre-lexical representation of a word onto a representation in the mental lexicon.

Boersma et al. (2003) have proposed a developmental account of the Linguistic Perception model. In their view, the auditory form is the result of perceptual warping of the acoustic input the child receives, a form of distributional learning (see §2.1.2). The resulting categories are initially based on single acoustic cues. That is, different acoustic cues are not yet integrated in perception. Only when infants reach the age of nine months will they start integrating acoustic cues and multi-dimensional categories will be the result⁹. Once a lexicon is further developed, the child will reorganize its perception grammar until “optimal listening” is established. This occurs by means of trial-and-error learning on the basis of feedback from the lexicon: if the child constructs an incorrect pre-lexical phonological representation, the mental lexicon will provide the correct representation according to the semantic-pragmatic context in which the word was uttered. In response to this feedback, the perception grammar is reorganized. This developmental account of infant speech processing resembles the one proposed in PRIMIR (Werker & Curtin, 2005), a more extensive developmental model that assumes multidimensional layers of information

⁸ Apoussidou (2006) added another level of representation to the model, namely meaning.

⁹ The shift from one-dimensional to multi-dimensional categories is estimated to be around nine months of age because similar shifts in speech segmentation and object categorization have been observed around that age (Boersma et al., 2003).

in the speech input available to the child and developmentally changing filters imposed on the input by the child (see Escudero & Benders, 2010 for discussion of the differences between the two models). Both models share some characteristics with WRAPSA (Jusczyk, 1993, 1997), an early developmental model of speech perception and word recognition.

Importantly, many of the processes underlying word recognition in young children also underlie word learning. That is, when children are unable to match a word in the input to a representation in the mental lexicon, they will assume that it is a novel word and will form a new lexical representation (Gupta & MacWhinney, 1997). In a sense then, word learning is a consequence of failed word recognition. In recent years a rapidly growing body of literature has emerged on infant word learning (see e.g. Hall & Waxman, 2004). Many studies have been stimulated by the findings of Stager and Werker (1997), who showed that 14-month old infants could not learn the novel minimal pair /bi/-/di/, while they could clearly discriminate between /b/-/d/ in a discrimination task (cf. Werker, Cohen, Lloyd, Casasola, & Stager, 1998)¹⁰. Apparently, infants are not always sensitive to the same amount of phonetic detail at the word level as they are at the sound level. Infants' ability to learn novel minimal pairs has been found to be related to their concurrent expressive vocabulary size (Werker, Fennell, Corcoran, & Stager, 2002), suggesting that the ability to encode phonetic detail in novel words is mediated by a growing mental lexicon (cf. Beckman & Edwards, 2000; Swingley & Aslin, 2007).

This latter idea strongly resembles the 'lexical restructuring model', proposed for older children (Metsala & Walley, 1998; Walley, 1993; Walley, Metsala, & Garlock, 2003). According to this model, the emergence of phonemes as units in perceptual processing is associated with vocabulary growth, more specifically with changing familiarity and similarity relations between words in the developing lexicon. Initially, words are represented holistically in the mental lexicon, but representations gradually become more fine-grained when more words are acquired resulting in a need for more phonetic detail. An important notion in this model is therefore 'phonological neighborhood density', the number of words that differ from each other in a single phonological segment either by substitution, addition or deletion (Vitevitch & Luce, 1998, 1999). For example, the word *mouth* has five neighbors and can be considered of low-density, whereas the word *tooth* has 14 neighbors and may be considered of high-density¹¹. Phonological neighborhood density has been

¹⁰ It should be noted that the nature of the stimuli, the task and the referential context can affect the ability of 14-month old infants to learn minimal pairs (e.g. Fennell & Waxman, 2010; Werker & Fennell, 2004; Yoshida, Fennell, Swingley, & Werker, 2009).

¹¹ Adult neighborhood density for these two words were calculated using the online neighborhood density calculator developed at the Washington University in St. Louis, available at <http://128.252.27.56/Neighborhood/Home.asp>. The examples are taken from

found to affect spoken word production, recognition and learning in children as well as adults (Storkel, Armbruster, & Hogan, 2006). For instance, children and adults repeat words from high-density neighborhoods better than words from low-density neighborhoods, but recognize words from high-density neighborhoods more slowly than words from low-density neighborhoods¹². Importantly, neighborhood density effects may be mediated by the presence or absence of language impairment (Rispen, Baker, & Duinmeijer, in preparation, for Dutch children; Storkel & Hoover, 2010b).

Corpus studies have shown that children tend to acquire words from high-density neighborhoods before words from low-density neighborhoods (Storkel, 2004, 2009). Presumably, this is because dense neighborhoods are already restructured and novel words in these neighborhoods can thus be represented with more phonetic detail. It should be noted, however, that recent experimental word learning studies with children and adults have shown that phonological neighborhood density effects in word learning are dynamic and dependent on the time course of word learning (Hoover, Storkel, & Hogan, 2010; Leach & Samuel, 2007; Storkel et al., 2006). For instance, initially, a low neighborhood density appears to help learners to correctly detect the novelty status of words they have not heard before. However, once the novelty status of the word is detected, words from high-density neighborhoods are represented more robustly in phonological short-term memory because they activate more lexical and phonological representations in the mental lexicon (Storkel et al., 2006).

The processes involved in word recognition and word learning suggest that early speech perception abilities are important abilities when acquiring a language. Indeed, several recent studies have shown that early speech perception abilities correlate with later language development. For instance, Kuhl et al. (2005) found a strong positive correlation between the ability to discriminate native speech sound contrasts at seven months of age and word production and sentence complexity at 24 months of age (as measured by the MacArthur-Bates Communicative Developmental Inventory (Fenson et al., 1993; Fenson et al., 1994)). Newman et al. (2006) showed that speech segmentation abilities, but not language discrimination abilities, before 12 months of age predicted expressive vocabulary at 24 months of age. Bernhardt et al. (2007) showed that the ability to learn novel minimal pairs at 17 and 20 months of age was related to language comprehension and production up to two and a half years later. Finally, Marchman and Fernald (2008) showed that

Storkel and Hoover (2010a) on the development of an online neighborhood density calculator based on child corpora (resulting in five neighbors for *mouth* and ten for *tooth*).

¹² However, in a recent study using eye-tracking, Magnuson, Dixon, Tanenhaus and Aslin (2007) found early facilitatory but late inhibitory effects of phonological neighborhood during spoken word recognition in adults.

speed of spoken word recognition and expressive vocabulary knowledge at 25 months of age were related to language and cognitive abilities at eight years of age.

The strong, yet complex, relation between sound perception and word recognition, and even more importantly, the relation between early speech perception abilities and later language development raise important questions for children with a CI. Few studies have been done on their early speech perception abilities. Horn et al. (2007b) found that 17-month old infants with a CI can discriminate between the non-words *boodup* and *seepug* three months post-implantation. Furthermore, Grieco-Calub, Saffran and Litovsky (2009) showed that spoken word recognition in two-year old toddlers with a CI was less accurate and slower compared to their peers with normal hearing. Studies with older children have revealed large inter-individual variation in speech perception outcomes (for a review, see Pisoni, 2005), with some high-performers showing near-typical speech perception in quiet listening conditions and some low-performers benefiting only minimally from the CI (e.g. Pisoni et al., 1999; Tyler et al., 1997; Wang et al., 2008). Child, family, implant and educational factors account for some, but not all, of this inter-individual variation (e.g. Geers et al., 2003a; Sarant et al., 2001; Wie et al., 2007).

Given the reduced spectrotemporal resolution of sound processing with a CI and observed inter-individual variation in speech perception abilities of children with a CI, their lexical development may also differ from that of children with normal hearing. Indeed, several studies have shown that many children with a CI have smaller expressive and/or receptive vocabularies than their peers with normal hearing (e.g. Duchesne, Sutton, & Bergeron, 2009; Geers, 2004; Geers et al., 2009; Schorr et al., 2008; Svirsky et al., 2000). Of course, they have had less spoken language experience because of their auditory deprivation and therefore delays in vocabulary development are not unexpected. Studies looking at growth rates in expressive and receptive vocabulary development are more informative in that respect. These have reported rates lower than, equal to or even higher than 1.0 (the norm for children with normal hearing of the same age), suggesting that even if some children with a CI are catching up with their hearing peers, many others are not (e.g. Bollard, Chute, Popp, & Parisier, 1999; Connor, Craig, Raudenbush, Heavner, & Zwolan, 2006; El-Hakim et al., 2001; Kirk et al., 2003).

An alternative to looking at growth rates is to experimentally investigate word learning abilities in novel word learning tasks. A few studies have investigated rapid word learning, the ability to learn words after only a few exposures to the word and referent, in children with a CI (range 2-11 years old), who had more difficulties than children with normal hearing (Houston et al., 2005; Tomblin et al., 2007; Willstedt-Svensson, Lofqvist, Almqvist, & Sahlen, 2004). In this thesis we examine the relation between sound perception and rapid word learning in children with a CI, which to our knowledge has not yet been systematically investigated.

More specifically, in this thesis children were taught novel minimal word pairs in two different rapid word learning tasks. We were interested in whether the children with a CI were able to learn minimal pairs given their different auditory input and how their performance in the word learning tasks related to their performance in a sound perception task. Crucially, the same consonant and vowel contrasts included in the sound perception task distinguished the novel words in the rapid word learning tasks to allow a more specific assessment of the relation between sound perception and rapid word learning. We also included a measure of phonological short-term memory, the capacity to temporarily store sequences of phonemes for further processing. This capacity has been associated with word learning abilities in typically and atypically developing populations as well as adults (Baddeley, 2003; Gathercole, 1999, 2006; Gupta, 2003; Gupta & MacWhinney, 1997). Furthermore, children with a CI have been shown to score lower on phonological short-term memory measures than age-matched children with normal hearing, and their phonological short-term memory capacity has been found to correlate with spoken language outcomes (Burkholder-Juhasz et al., 2007; Dawson et al., 2002; Pisoni et al., 1999; Willstedt-Svensson et al., 2004).

Therefore, the second research question in this thesis is: a) are children with a CI able to learn novel minimal word pairs after a limited amount of exposure to the novel words and their referents, and b) how do sound perception and phonological short-term memory relate to their rapid word learning?

2.2 RELATIONSHIP AND INTERACTION BETWEEN SIGN AND SPEECH PERCEPTION IN CHILDREN WITH A CI

2.2.1 BACKGROUND

Sign languages are natural languages in the visual-spatial modality. Signs consist of a *hand configuration* with a specific selection of fingers and orientation of the hand, a *location* where the sign is articulated, and a path or hand-internal *movement*. In addition, many signs are accompanied by a non-manual component such as a particular facial expression or mouthing. These internal components of signs are similar to consonants and vowels because they are the building blocks of lexical forms and are for that reason also called phonemes (e.g. Brentari, 1990, 1998; Corina & Sandler, 1993; Sandler, 1989). Signs can be one-handed and two-handed; in the latter, the configuration, location and movement of both hands are symmetrical or the non-dominant hand is passive and acts as a ground for the

dominant hand (Battison, 1978). Sign languages make use of space to express grammatical relations between signs and therefore may be said to have a spatial (morpho)syntax (e.g. Klima & Bellugi, 1979; Liddell, 1980, 1990; Padden, 1990). Even if at first sight they appear to be radically different from spoken languages, research since the second half of the twentieth century has revealed striking similarities in structure at the phonological, morphological and syntactic level (Baker, Van den Bogaerde, Pfau, & Schermer, in preparation; Meier, Cormier, & Quinto-Pozos, 2002; Sandler & Lillo-Martin, 2006).

Parallels have also been found in signed and spoken language processing (Emmorey, 2007). For instance, it has been shown that speakers and signers use similar segmentation strategies (Orfanidou, Adam, Morgan, & McQueen, 2010), that signs are incrementally recognized (Emmorey & Corina, 1990) and that sign production is affected by phonological and semantic priming (e.g. Baus, Gutierrez-Sigut, Quer, & Carreiras, 2008; Corina & Hildebrandt, 2002). Furthermore, signers sometimes produce slips of the hands and experience “tip of the fingers” phenomena (Hohenberger, Happ, & Leuniger, 2002; Newkirk, Klima, Pedersen, & Bellugi, 1980; Thompson, Emmorey, & Gollan, 2005). Of particular relevance to this thesis are findings that just as speakers become auditorily tuned to perceive the sound contrasts of their spoken language, signers become visually tuned to perceive sign contrasts in their sign language (Baker, Isardi, Golinkoff, & Petitto, 2005b; Best, Mathur, Miranda, & Lillo-Martin, 2010; Emmorey, McCullough, & Brentari, 2003; Morford, Grieve-Smith, MacFarlane, Staley, & Waters, 2008). Furthermore, as in spoken language processing, sign recognition is characterized by competitive activation of sign candidates (Carreiras, Gutierrez-Sigut, Baquero, & Corina, 2008) and phonological information in signs is temporarily stored and rehearsed for further processing (Wilson & Emmorey, 1997, 1998, 2003).

Part of the evidence for similarities between signed and spoken language processing comes from neuro-imaging and lesion studies. Early studies showed that right-handed deaf native signers with damage to the perisylvian regions in the left hemisphere suffered from language production and/or comprehension problems in their sign language similar to those described for speakers suffering from damage to the same regions (i.e., sign language aphasia, Poizner, Klima, & Bellugi, 1987). This overlap in neural organization between spoken and signed language processing has also been shown in neuro-imaging studies with healthy signers (Campbell, MacSweeney, & Waters, 2008; MacSweeney, Capek, Campbell, & Woll, 2008)¹³.

¹³ Sign language comprehension does seem to be more bilaterally organized in the brain than spoken language comprehension, however, presumably due to the fact that sign language comprehension relies strongly on spatial processing, which is considered to be right hemisphere dominant (Hickok, Bellugi, & Klima, 1998). In addition, parts of the parietal cortex appear to play a special role in sign language processing, possibly due to

For instance, Capek et al. (2009) found typical N400 effects in response to semantic violations in signed sentences and typical Left Anterior Negativity and P600 effects in response to syntactic violations in an EEG (electroencephalography) study with deaf native signers¹⁴. In addition, in a recent fMRI (functional Magnetic Resonance Imaging) study, Capek et al. (2010) compared deaf native signers that were also proficient speech readers and hearing non-signers and showed that activation in the posterior superior temporal cortex was modulated by language proficiency, irrespective of the language modality.

Sign language acquisition studies have indicated similarities in the stages of acquisition that deaf children acquiring a sign language and hearing children acquiring a spoken language go through, such as babbling, phonological simplification of early signs or words, increases in utterance length and complexity, overgeneralization of words or signs and overregularization of rules, as well as similarities in the timing of these stages (Emmorey, 2002; Schick, Marschark, & Spencer, 2005). This is not surprising, given the similarities in language structure and processing in the two modalities. It should be noted, however, that most of what we know about sign language development comes from studies of acquisition in deaf children of deaf, signing parents. This context resembles most closely the context in which hearing children with hearing parents acquire a spoken language, but it is not the context experienced by the majority of deaf children (Marschark, Schick, & Spencer, 2005). As already mentioned in §1.4.2, over 90% of the deaf children are born to hearing parents who have very little knowledge of a sign language. Even if their parents are also deaf, this does not guarantee native-like sign language input, given that many deaf adults were raised and educated orally and only learned to sign at a later age. By far the majority of deaf children thus have to acquire a sign language from non-native input.

The context in which children with a CI acquire a sign language is different again. As we have seen in §1.4.2, children with severe-to-profound sensorineural hearing loss are often exposed to some form of signed input before implantation. In addition, in many countries these children are exposed to both speech and signs at home and school in the first year(s) following implantation. However, the extent and kind of their signed input is extremely variable both between children and within the same children over time. Unfortunately, whereas much information has been gathered about spoken language development in deaf children with a CI, fairly little is known about their sign language development. Because many studies have suggested that exposing children with a CI to signed input negatively affects their

proprioceptive monitoring during sign production and activation of an action observation-execution network (Knapp & Corina, 2010; MacSweeney et al., 2008).

¹⁴ These effects refer to specific negative (N) or positive (P) peaks in the EEG signal time-locked to the stimulus onset.

spoken language development (see §1.4.2), the topic seems to receive less attention. However, if we want to determine whether signed input to children with a CI hampers their spoken language development, it is necessary that both language modalities are assessed in the same children. This is in fact the second goal of this thesis. More specifically, we will examine the relationship between sign and speech perception abilities (§2.2.2), as well as the interaction between both language modalities during lexical processing (§2.2.3).

2.2.2 THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION

Only a handful of studies have looked at both spoken and signed language abilities in children with a CI. The majority of these studies were case studies, varying from one to three children (Cassandro et al., 2003; Coerts et al., 1994; Klatter-Folmer, Van Hout, Kolen, & Verhoeven, 2006; Nordqvist & Nelfelt, 2004; Yoshinaga-Itano, 2006). De Raeve et al. (2009) reported the results from a longitudinal study of two groups of children with a CI, one group educated in sign-supported speech plus a sign language, the other in sign-supported speech only. The children were followed from pre-implantation until three years post-implantation. Sign language development was assessed in all children educated in sign-supported speech plus a sign language and a subset of the children educated in sign-supported speech only. However, development in both language modalities was only directly compared in the former. Results showed that the number of words and utterances increased slightly faster in the spoken than in the signed modality. An advantage in mean length of utterance for the signed modality was found at the start of the study, but for the spoken modality at the end of the study.

In this thesis we hope to obtain further insight into the relationship between spoken and signed language abilities in children with a CI by examining their sign perception as well as their speech perception. In order to facilitate the comparison between the two modalities, we have tried to keep the sign perception tasks as similar as possible to the speech perception tasks. More specifically, we examined the use of visual cues in the categorization of hand configuration and locations of signs and the ability to learn novel minimal sign pairs after a limited amount of exposure to the novel signs and their referents. In addition, we assessed phonological short-term memory for signs.

As already mentioned at the beginning of this section, signs consist of phonemic elements similar to the consonants and vowels in words. These are hand configuration, location and movement. Similarly to listeners using acoustic cues to identify consonants and vowels, signers have to use specific visual cues to identify the sign, such as extension of the fingers and changes in location and spatial orientation of the hands. With respect to pre-lexical perception, Emmorey et al.

(2003) found that deaf signers perceived hand configurations in American Sign Language (ASL) categorically. That is, hand configurations that crossed a phoneme boundary in ASL were discriminated better than hand configurations that did not cross a phoneme boundary in ASL (cf. Baker et al., 2005b; Best et al., 2010; Morford et al., 2008). Location of signs was not perceived categorically. Location might be a more variable phonemic category in sign languages than hand configuration and thus have less stable category boundaries (Emmorey et al., 2003). Similarly, categorical perception effects in spoken languages are typically weaker for vowels than for consonants, presumably because of their more continuous articulation. Recently, McCullough and Emmorey (2009) also showed categorical perception of linguistic facial expressions in deaf signers.

A few studies have examined the nature and time course of sign recognition and shown that phonological parameters of signs contribute differentially to sign recognition. For instance, Emmorey and Corina (1990) reported that the location and hand configuration of the sign were recognized first by ASL signers, followed by the movement. Carreiras et al. (2008) examined effects of familiarity and phonological neighborhood density on lexical processing in Catalan Sign Language. Amongst other things, they found that recognition of low-familiarity signs was slowed down for locations with high neighborhood density, but facilitated for hand configurations with high neighborhood density. Finally, Orfanidou, Adam, McQueen and Morgan (2009), in a study of British Sign Language, found that signers misperceived hand configuration and movement more often than location in a sign spotting task (cf. Hildebrandt & Corina, 2002 for ASL).

Turning to phonological short-term memory, it is important to note that, despite similarities in the architecture of phonological short-term memory for both language modalities (Wilson & Emmorey, 1997, 1998, 2003), several studies have found a smaller phonological short-term memory capacity in deaf signers compared to hearing speakers (e.g. Boutla, Supalla, Newport, & Bavelier, 2004; Wilson, Bettger, Niculae, & Klima, 1997). The exact nature and underlying cause of the observed difference in phonological short-term memory capacity is debated, however (Bavelier, Newport, Hall, Supalla, & Boutla, 2006; Boutla et al., 2004; Emmorey & Wilson, 2005; Wilson & Emmorey, 2006). Recently, it has been suggested that speakers and signers only perform differently on tasks that require recall in a fixed order, as opposed to, for instance, free recall (Bavelier, Newport, Hall, Supalla, & Boutla, 2008).

With respect to sign language processing in children, Ormel et al. (2009) found inhibitory effects of phonological similarity and facilitative effects of iconicity on sign recognition by 8- to 12-year-old deaf signing children. Of special relevance to this thesis, Lederberg and colleagues (Lederberg & Spencer, 2009; Lederberg, Spencer, & Prezbindowski, 2000) examined rapid word and sign learning abilities in 2- to 6-year-old deaf and hard-of-hearing children (wearing an acoustic hearing aid

or a CI) and argued for similar developmental trajectories in both modalities (cf. Brackenbury, Ryan, & Messenheimer, 2006). However, they did not explicitly distinguish between both language modalities in their studies.

In the light of the relationships between the modalities, the third research question in this thesis is therefore: how do sign perception abilities relate to speech perception abilities in the same children with a CI?

2.2.3 THE INTERACTION BETWEEN SIGN AND SPEECH PERCEPTION

Examining speech and sign perception abilities independently (§2.2.2) allows us to compare performance in both language modalities and to relate this comparison to demographic variables such as age at implantation and length of CI use. However, many children with a CI are exposed to simultaneously produced combinations of speech and signs at home and school, i.e., sign-supported speech. In order to fully understand the effects of signed input on spoken language abilities it is therefore of crucial importance to also investigate the *interaction* between the two modalities during language processing. Therefore our fourth, final research question relates to the effects of bimodal (i.e., simultaneously spoken and signed) input on speech perception in children with a CI.

Perceiving sign-supported speech represents a specific case of processing more than one modality and language at the same time. Multimodal perception and its role in development and learning have been studied quite extensively in the nonverbal domain, often showing advantages of inter-sensory redundancy in sensory processing and learning (for reviews, see e.g. Bahrack, Lickliter, & Flom, 2004; De Gelder & Bertelson, 2003; Shams & Seitz, 2008). In the verbal domain, the majority of the available research on multimodal integration has focused on audiovisual integration in language processing (for reviews, see e.g. Rosenblum, 2005, 2008; Woodhouse, Hickson, & Dodd, 2009). More recently, however, the integration of gestures and speech has also received attention from researchers. In particular, it has been shown that gestures play an important role in language development and learning more generally (for recent reviews, see e.g. Gullberg, De Bot, & Volterra, 2008; Kelly, Manning, & Rodak, 2008). Importantly, part of this research concerns the role of gestures in facilitating communication with language-impaired children (Capone & McGregor, 2004).

Crucially, however, very little is known about multimodal processing and learning by children or adults with a CI and most of what we do know concerns audiovisual integration (Mitchell & Maslin, 2007; Strelnikov, Rouger, Barone, & Deguine, 2009). Two recent studies investigated the relationship between audiovisual integration and spoken language outcomes in children with a CI. Kirk et

al. (2007) found that auditory-only as well as audiovisual word and sentence recognition scores correlated with receptive vocabulary knowledge. Furthermore, Bergeson et al. (2005), in a longitudinal study, found that auditory-only and audiovisual sentence recognition scores correlated with a multitude of spoken language outcomes measures, including speech perception, speech production, receptive vocabulary and expressive and receptive language.

Bergeson et al. also found that in the early test intervals children in Oral Communication settings outperformed children in Total Communication settings in all conditions, even the speech reading condition. They suggested that the latter might have to distribute their attention over two visual sources of information (i.e., manual-visual and audiovisual). This could create competition for limited processing resources, which could negatively affect spoken language outcomes. However, this possibility has not yet been tested. Moreover, recent findings by Mollink, Hermans and Knoors (2008) suggest that sign-supported speech can in fact enhance spoken language processing. They showed that using signs in vocabulary training with hard-of-hearing children had a positive effect on their learning of new spoken vocabulary. However, these children had only mild-to-moderate hearing impairment and used acoustic hearing aids, not CIs.

The fourth, final research question in this thesis is therefore: does bimodal input hamper or facilitate speech perception in children with a CI?

3 METHODOLOGY

This chapter presents the methods used to answer the four research questions of this thesis that are restated below. More detailed information on the methodology is presented in the individual chapters.

- RQ 1. Do children with a CI use acoustic cues differently in consonant and vowel perception from children with normal hearing of the same age? More specifically, do they use the same cues and if so, do they use such cues as effectively? (Chapter 4)
- RQ 2. Are they able to learn novel minimal word pairs after a limited amount of exposure to the novel words and their referents? Furthermore, how do their sound perception and phonological short-term memory relate to their rapid word learning? (Chapter 5)
- RQ 3. How do their sign and speech perception abilities compare to one another? (Chapter 6)
- RQ 4. Does bimodal input hamper or facilitate their speech perception? (Chapter 7)

3.1 PARTICIPANTS

A group of 15 children with a CI, 20 age-matched children with normal hearing and 21 young adults with normal hearing participated in the series of experiments targeting (pre)lexical perception in speech and sign. By comparing the two groups of children it will be possible to establish whether children with a CI exhibit delays. The results from the adults will be used to determine how close children's performance is to the adult target.

3.1.1 CHILDREN WITH A CI

The children with a CI were 15 pre-lingually deaf 4- to 6-year old children (4 girls, 11 boys). Individual background information for the children is provided in Table 3.1. Their mean age was 5;9 (4;4 – 6;7, SD=10 mo). The majority (12) of these children were part of a group of children from the Netherlands and Flanders¹⁵ that had been followed longitudinally from shortly before implantation until three years post-implantation. The goal of this longitudinal project was to examine the effect of linguistic environment on spoken language development. The project was carried

¹⁵ Flanders refers to the Dutch-speaking part of Belgium; the adjectival form is 'Flemish'.

out by the Dutch Foundation for the Deaf and Hard of Hearing Child (Amsterdam, The Netherlands) and the Royal Institute for the Deaf (Hasselt, Belgium). De Raeve et al. (2009) present a summary of the most important results from this longitudinal project (see also Wiefferink, Spaai, Uilenburg, Vermeij, & De Raeve, 2008)¹⁶. Importantly, these children formed a relatively homogeneous group with respect to several variables known to affect spoken language outcomes in this population (see §1.3). None of the children in this group were known to have additional disabilities. For all children the surgery was uneventful and the implants were fully inserted. The children were fitted with the latest speech processing algorithm available at the time. For one child programming of the device had been problematic due to behavioral difficulties. For another child, initial problems in programming were solved within three months time. All children wore their implant for the greater part of the day. Parent involvement was overall average to high. All children had Dutch as their native language. Three Dutch children with a CI were added to the sample of 12 children to make the Dutch and Flemish group more comparable in number¹⁷. They were all pre-lingually deaf and further matched the other children.

All children had received their implant before their fourth birthday and the mean age at implantation in the sample was 1;8 (0;7 – 3;9, SD=11 mo). Six of the 15 children had received their implants before 12 months of age and ten of the 15 children had received their implants before 24 months of age. That is, the majority of the children with a CI included in the sample were implanted relatively early. Importantly, all except two of the children in the sample had received a CI before three years of age (the other two received a CI at 3;2 and 3;9). As a result, almost all children fell below the age cut-off reported in neurophysiological studies to be at risk for atypical (sub)cortical auditory processing (see §1.4.1). This allows us to look for behavioral effects of age at implantation within a narrow and early window. Given that there is substantial variation in age at implantation in the sample and all children were approximately between five and six years old when they were tested for the first time, they differed substantially in the length of time they had been using their implant. On average, they had been using their CI for four years (1 yr/7 mo – 5 yrs/11 mo; SD=14 mo). Thus, age at implantation and length of CI use are

¹⁶ The final report of this project can be downloaded from the website of ONICI (*Onafhankelijk Instituut voor Cochleaire Implantatie*, www.onici.be). The report is in Dutch, but includes a summary in English.

¹⁷ Initially, the parents of 15 children with a CI (7 Dutch, 8 Flemish) from the longitudinal study were asked by letter for their consent to include their child in the study. The parents of 12 children (5 Dutch, 7 Flemish) consented. Subsequently, the parents of six other Dutch children with a CI (from the same school as three of the five Dutch children in the sample) were asked by letter for their consent to include their child in the study; the parents of three children consented.

confounded in our sample. This will be taken into account when interpreting any effects of age at implantation on performance.

Despite the relative homogeneity of the sample, the Dutch and Flemish children differ in several respects. Firstly, in Flanders newborn hearing screening was introduced earlier than in the Netherlands. As a result, the age at diagnosis and first intervention for deaf and hard-of-hearing children in Flanders is on average earlier than in the Netherlands, and thus age at implantation is lower on average, that is, between 18 and 24 months in the Netherlands and between 11 and 17 in Flanders (De Raeve et al., 2009). Secondly, bilateral implantation as well as the use of CIs in combination with acoustic hearing aids is more common in Flanders than in the Netherlands. The mean age at implantation for the Dutch children in the sample was 2;2, whereas for the Flemish children it was 1;4. This difference was significant ($t(13)=2.36$, $p<.05$). In addition, at the time of study, three Flemish children had received a second CI and one had been fitted with an acoustic hearing aid for the non-implanted ear. One Dutch child had received a second CI, but wore it infrequently.

Table 3.1. Characteristics of the children with a CI ordered according to age at implantation.

ID	Gender	Country of origin	Stimulation	Implant type	Educational setting at time of study	Age at implantation	Age at time of study
N7	F	NL	CI	Clarion (Platinum)	bilingual	0;7	5;1
X5	M	B	CI+HA	Cochlear (Sprint)	SimCom	0;7	6;7
J8	M	B	CI	Cochlear (Sprint)	SimCom	0;8	4;10
A1	M	B	CI	Cochlear (Sprint)	mainstream	0;9	5;3
J3	M	B	CI	Cochlear (Sprint)	SimCom	0;10	4;4
V4	M	B	2CI	Cochlear (Freedom, 2x)	SimCom	0;11	6;7
S7	M	B	2CI	Cochlear (Sprint) / Digisonic (SP)	SimCom	1;2	5;2
S6	F	NL	CI	Cochlear (Sprint)	bilingual	1;8	4;10
T1	M	NL	CI	Cochlear (Sprint)	sign supported speech	1;11	4;10
L2	F	NL	CI	Clarion (Platinum)	bilingual	2;0	6;0
D8	M	NL	2CI	Cochlear (Sprint/Freedom)	mainstream	2;1	6;7
K3	M	NL	CI	Clarion (Platinum)	bilingual	2;1	6;4
L6	F	B	2CI	Digisonic SP (2x)	SimCom	2;9	6;7
L4	M	NL	CI	Cochlear (Sprint)	bilingual	3;2	6;7
S5	M	NL	CI	Cochlear (Freedom)	bilingual	3;9	5;4
						M=1;9, SD=11 mo	M=5;8, SD=10 mo

Note. Ages are in years;months, M=mean, SD=standard deviation, mo=months, SimCom=Simultaneous Communication

Crucially, the Dutch and Flemish children also differed in the type of educational setting, due to different perspectives on the role of sign language in education between the countries. The Dutch children were mainly educated in spoken Dutch (supported with signs) and Sign Language of the Netherlands, i.e., a bilingual approach. In contrast, the Flemish children were mainly educated in spoken Dutch, supported with signs (referred to as ‘Simultaneous Communication’ in Table 3.1)¹⁸. Furthermore, the parents of the Dutch children had followed courses in Sign Language of the Netherlands (NGT, *Nederlandse Gebarentaal*) and were encouraged to provide signed input to their child, whereas most Flemish parents had not followed courses and were encouraged to use only spoken language with their child. Importantly, this situation provides variation in the amount of signed input at home and school and thus in any effects of signing experience on their speech perception. It should be noted, however, that two children in this group already attended mainstream education at the time of this study. These children evidently no longer received signed input at school.

3.1.2 CHILDREN WITH NORMAL HEARING

The children with normal hearing were 20 Dutch children (14 girls, 6 boys) with no known history of speech, language or hearing difficulties (as reported by the school). Their mean age was 5;11 (5;2 – 6;6, SD=4 mo), which matched the chronological age of the children with a CI. Half of the children came from a middle class school in the central region of the Netherlands (The Hague) and half from a middle class school in the central region of Flanders (Hasselt). This was done in order to match the children with normal hearing and the children with a CI with respect to their native regional variety of Dutch (i.e., Northern Standard Dutch versus Southern Standard Dutch). A subset of the sample of children with normal hearing (10) also completed the sign perception tasks in this study, even though they had no signing experience, to compare their performance to that of the children with a CI.

3.1.3 ADULTS WITH NORMAL HEARING

In order to have an adult control for some of the tasks, 21 Dutch young adults (19 female, 2 male), 20 of who reported no history of speech, language or hearing

¹⁸ The signs in sign-supported communication are adopted from the surrounding sign languages, Sign Language of the Netherlands (NGT, *Nederlandse Gebarentaal*) in the Netherlands and Flemish Sign Language (VGT, *Vlaamse Gebarentaal*) in Flanders.

impairments, participated in this study¹⁹. Their mean age was 22;3 (19;0 – 26;3, SD=29 months). They were undergraduate students at the University of Amsterdam. They had Dutch as their native language. Even though they originally came from different parts in the Netherlands, all reported to use the regional variety of Dutch spoken in the central region of the Netherlands. A subset of the adults (11), second-year students in Sign Linguistics from the University of Amsterdam with 1-2 years of signing experience, completed also the sign perception tasks to compare their performance to that of the children with a CI. The others were mostly students in English Language and Culture from the University of Amsterdam.

3.2 TASKS

Several tasks were designed to answer the research questions posed in this thesis. Each task is briefly introduced in this section as related to the four research questions presented at the beginning of this chapter. Each task will be discussed in more detail in the chapter presenting its results.

3.2.1 THE PERCEPTION OF SPEECH SOUNDS: ACOUSTIC CUE WEIGHTING

In order to examine the perception of speech sounds, a speech sound categorization task was designed. This task was designed according to an XAB format, where participants have to decide whether stimulus X is more like A or B, where X is a randomly chosen stimulus from a stimulus series and A and B are the two endpoint stimuli of the series. The XAB categorization task has previously been used by Escudero, Benders and Lipski (2009) and Escudero and Wanrooij (2010), for instance, to examine acoustic cue weighting in adult native listeners and second language learners. In addition, an adapted version has been used by Brasileiro (2009) to examine acoustic cue weighting in young monolingual and bilingual 3- to 7-year-old children. The task allows to determine how effectively specific acoustic cues are used in phonetic categorization of speech sounds and whether specific cues are more important than others. Four speech sound contrasts were tested: two vowel contrasts and two consonant contrasts. The stimulus series for each contrast were created by modifying specific acoustic characteristics such as formant values and duration in naturally recorded speech sound tokens. E-Prime 2.0[®] (Psychology Software Tools, Pittsburgh PA) was used to present the stimuli and record

¹⁹ One adult reported a history of stuttering. Given that stuttering affects speech production but not speech perception, this participant completed only the tasks that did not require a spoken output (i.e. all tasks except the phonological short-term memory task).

responses. The speech sound categorization task will be explained in more detail in §4.2.3.

3.2.2 THE RELATIONSHIP BETWEEN SOUND PERCEPTION AND RAPID WORD LEARNING

Rapid word learning was assessed in two ways, namely with an on-line picture-matching task (§3.2.2.1) and with an off-line object-matching task (§3.2.2.2). An on-line as well as an off-line task were designed to consider the effects of task demands on the performance of children with a CI, given that previous research has shown that they have smaller verbal working memory capacity than their peers with normal hearing and may have problems with sustained visual attention (Burkholder & Pisoni, 2006; Horn et al., 2005). In addition, phonological short-term memory was independently assessed by means of a digit span task (§3.2.2.3).

The use of word learning tasks was preferred to the use of expressive or receptive vocabulary measures because the former are less dependent on language experience and directly assess word learning abilities, whereas vocabulary measures only assess how many words a child has already learned at a particular age (cf. Hwa-Froelich & Matsuo, 2005; Kan & Kohnert, 2008; Prezbindowski & Lederberg, 2003; Tomblin et al., 2007). Of course, both types of measures are related in the sense that the effectiveness of word learning abilities will partially determine how many words the child has learned at a particular age.

3.2.2.1 PICTURE-MATCHING

In order to assess on-line rapid word learning, a non-word picture-matching task was designed. Non-words are words that do not exist in a particular language (in this case Dutch), but do meet the phonotactic constraints of that language and therefore are possible words in that language (e.g., ‘blick’ /blik/ in Dutch). That is, they consist of native sounds and sound sequences.

The non-words used in this task formed minimal pairs, meaning that they only differed from each other in one phonemic segment. Crucially, in order to facilitate comparison between the speech sound categorization and word learning tasks, the phonetic contrasts that distinguished the minimal pairs were exactly the same as those used in the sound categorization task. The pictures used in this task were drawings of novel objects. The participants were familiarized with the word-object pairings preceding a set of two-alternative forced choice test trials in which participants had to match words with pictures. Some of the test trials were incongruent trials, in which the non-word that was presented did not match the novel

object shown on the screen. These trials were included as an additional measure of word learning based on reaction times, adapted from infant word learning studies.

E-Prime 2.0[®] (Psychology Software Tools, Pittsburgh PA) was used to present the stimuli and record responses. Both accuracy (number of trials correctly answered) and reaction times were recorded and analyzed. Reaction times were analyzed because, even if children with a CI are able to learn novel minimal pairs, they might encode, store and/or retrieve them less efficiently than children with normal hearing and thus show slower reaction times. The picture-matching task is explained in more detail in §5.2.2.1.

3.2.2.2 OBJECT-MATCHING

A non-word object-matching task was designed as a measure of off-line rapid word learning to control for performance differences related to some of the task demands of on-line picture matching. The object-matching task was an interactive rapid word learning task presented live to the child by the experimenter and consisted of three subtests: a novel word learning test, a generalization test and a rapid word learning test (Lederberg & Spencer, 2009; Lederberg et al., 2000). The novel word learning test examined whether the children could associate a novel word with an unfamiliar object without explicitly labeling the novel object. The generalization test examined whether the children could generalize a novel word to different exemplars of the same object. The rapid word learning test examined whether the children could learn novel words for novel objects with a limited amount of exposure to both the words and the objects.

Similar to the on-line picture-matching task, the novel words formed minimal pairs. The objects used in the task were mainly kitchen utensils for which it was unlikely that the young children knew the names. Given that adults would likely be able to name the majority of the objects, the object-matching task was only administered to the children. The children were familiarized with the word-object pairings and receptive knowledge of the novel words was tested immediately afterwards. Performance was scored on-site, but also recorded on video for off-site reviewing of the session and initial scoring. The object-matching task is explained in more detail in §5.2.2.2.

3.2.2.3 PHONOLOGICAL SHORT-TERM MEMORY

As mentioned in §2.1.2, phonological short-term memory capacity has been associated with vocabulary acquisition, as novel sound sequences need to be temporarily stored before they can be integrated in long-term memory. Because of this association and given reports of poorer phonological short-term memory in

children with a CI relative to children with normal hearing (Burkholder-Juhasz et al., 2007; Dawson et al., 2002; Pisoni et al., 1999; Willstedt-Svensson et al., 2004), we included a phonological short-term memory task in this study. Phonological short-term memory is usually tested by recalling sequences of digits, letters or (non-)words that increase in length as the test progresses (Gathercole, 1999). Digits were used in this thesis because these are less language experience-dependent than real words or non-words. In addition, it can be assumed that young children are familiar with the words for the digits. The sequences ranged from two to six digits, with three different sequences at each list length. Recall was in fixed, forward, order. That is, if the digit sequence was 5 3 2, the three digits had to be recalled in that order. The forward digit span task has been used extensively with young typically as well as atypically developing children, including children with a CI (e.g. Gathercole, 1999; Gray, 2003a; Pisoni et al., 1999). The digit span task is explained in more detail in §5.2.2.3.

3.2.3 THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION

In order to facilitate the comparison between perception in the signed and spoken modalities, we attempted to keep the tasks and the tested abilities as similar as possible. Thus, a sign categorization task, two rapid sign learning tasks and a signed phonological short-term memory task were designed that matched the designs of those described in §3.2.1 and §3.2.2.

Similar to the sound categorization task, the signed version was designed according to an XAB format. Two phonetic contrasts were included: a hand configuration and a location contrast. The stimulus series for both contrasts consisted of linearly interpolated still images of hand configurations and locations in signing space created in a 3-D animation program, which had been used before by Emmorey et al. (2003).

Two rapid sign learning tasks were designed to match the rapid word learning tasks. Non-signs were created that fulfilled the phonotactic constraints of NGT and VGT. In the picture matching task, video recordings were used to present the novel signs. In the object-matching task, the novel signs were presented by the experimenter. For the remainder, the design of the picture-matching and object-matching tasks were exactly the same as that of their auditory counterparts. It is important to note that in addition to a spoken and signed version, the object-matching task was administered in a bimodal condition to the children with a CI. In this condition, novel words and signs were presented simultaneously. It was added as a preliminary investigation of the effects of bimodal input compared to either spoken or signed input alone (see also §3.2.4).

Finally, a phonological short-term memory task for signs was designed in which participants had to repeat sequences of signed digits of increasing length. The children were free to recall the sequences in their preferred modality (speech or sign) to avoid an effect of production difficulties during recall. As mentioned in §2.2.2, ordered recall might be particularly difficult for deaf signers and a task with free recall might therefore be more suited to measure their phonological short-term memory (Bavelier et al., 2008). However, because the goal was to keep the tasks as similar as possible in both modalities, and because the auditory forward digit span task has been used before in studies of children with a CI, phonological short-term memory for signs was also measured with a forward digit span task.

3.2.4 THE EFFECTS OF BIMODAL INPUT ON SPEECH PERCEPTION

To address the question whether bimodal input facilitates or hampers speech perception, we designed a task in which participants were familiarized with and tested on phonologically similar or dissimilar names of familiar and novel objects. The task was administered in three conditions: speech, sign and bimodal. Crucially, in the bimodal condition, the word components of the bimodal stimuli were tested separately from the sign components. This was done to directly compare spoken word recognition and learning in the speech and bimodal condition, which only differed in whether or not the words were presented in combination with signs during familiarization. The design of the task further resembled the picture-matching task discussed in §3.2.2.1. E-Prime 2.0[®] (Psychology Software Tools, Pittsburgh PA) was used to present the stimuli and record responses. Both accuracy (number of trials correctly answered) and reaction times were recorded and analyzed.

The data for this task were collected after the initial set of data (the tasks presented in §3.2.1-3) had been collected. The task was administered to a subset of the children with a CI and the adults that had completed the earlier tasks. Further details on the task and the participants will be given in §7.2.2.

3.3 PROCEDURE

Administration of the first set of tasks (§3.2.1-3) took place individually in quiet testing rooms in the different schools and in a quiet testing room at the University of Amsterdam for the adults. The categorization, picture-matching and digit span tasks were administered on a Dell[®] Latitude D630 (Intel[®] Core[™] 2 Duo T7250, 14" display, 1280x800 resolution) laptop using two external speakers for the tasks that

involved presentation of auditory stimuli (Trust® SP-2310). The object-matching tasks were administered live by the experimenter.

The tasks were administered on two separate days for the children. On the first day, the speech categorization task, the sign categorization tasks (if applicable), the non-word picture-matching task and the non-sign picture-matching task were administered in that order; on the second day, the object-matching task and the digit span task were administered. The speech condition of the object-matching task was administered first, followed by the spoken digit span task, the signed condition of the object-matching task, the signed digit span task and the bimodal condition of the object-matching task. On both days, testing took approximately 45 minutes for the children that completed both the speech and sign perception tasks and 30 minutes for the children who only completed the speech perception tasks. At the end of each session, the children received a small gift. The adults completed all tasks in a single session of approximately one hour if they completed the speech and sign tasks, and approximately 45 minutes if they only completed the speech tasks. The adults received a small payment for their participation.

The picture-matching task investigating the effects of bimodal input on speech perception (§3.2.4) was administered separately after the initial set of data had been collected. It was administered on a Dell® Inspiron 1525 (Intel® Core™ 2 Duo T7250, 15.4 display, 1280x800 resolution) laptop using two external Trust® SP-2200 speakers. Administration took place individually in quiet testing rooms in the different schools and in a quiet testing room at the University of Amsterdam for the adults. Testing took approximately 25 minutes for the children and 20 minutes for the adults.

Given different testing environments, as well as probable inter-individual variation in post-implant hearing thresholds for the children with a CI, the sound volume level was not set at a fixed level, but at the participant's own range of comfort. The sound level was set during the practice sets for each task. Instructions for the children with normal hearing and the adults were in spoken Dutch and for all children with a CI in spoken Dutch supported with signs. Each task was preceded by a practice set, except for the object-matching task that was preceded by a novel word learning test and a generalization test. During practice sets, additional instructions were given when the experimenter felt that it was necessary.

After data collection and analysis, a written summary of the results and conclusions was sent to the schools, parents or caretakers of the child participants, and to the adult participants. Individual results were not provided in the summary, but were available on request.

3.4 STATISTICAL ANALYSES

The SPSS® 15, PASW® 17 and SPSS® 18 software packages were used for statistical analyses. Parametric statistical techniques were used to analyze the data from the picture-matching, object-matching 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 independent samples *t*-tests, the *t* statistic for unequal variances was adopted in case of a significant Levene's test for equality of variances.

The analysis of the results from the categorization tasks required the use of non-parametric statistics because the data were non-normally distributed. More specifically, the rank-based Kruskal-Wallis H test was used to examine main effects and the rank-based Mann-Whitney U test was used for post hoc comparisons. For the statistical interpretation of the Mann-Whitney U test, two-tailed exact significance was adopted to adjust for small and unbalanced samples. The Wilcoxon Signed Rank test was used for non-parametric paired samples comparisons.

In correlation analyses comparing performance in the spoken and signed modalities and investigating effects of age at implantation and length of CI use, Pearson product moment correlation coefficients are reported when the two correlated variables were both normally-distributed and Spearman rho rank-based coefficients when at least one variable was non-normally distributed.

In all analyses, significance is reported as $<.05$ or $<.01$. In all group post hoc comparisons, a correction was applied to adjust for multiple comparisons and the significance cut-off was $.02$ ($\alpha/n=.05/3=.02$). In all graphs reported in this thesis, the error bars represent one standard error from the mean.

4 THE USE OF ACOUSTIC CUES

In this chapter²⁰ we will investigate the use of acoustic cues by children with a CI. We compare their performance in a speech sound categorization task to that of children and adults with normal hearing. As briefly explained in §3.2.1, this task makes it possible to determine how effectively specific acoustic cues are used in phonetic categorization and whether some cues are more important than others. The chapter starts with a brief introduction to acoustic cue weighting and relevant earlier studies (§4.1), followed by a discussion of the research methodology (§4.2). The results are presented in §4.3 and discussed in §4.4.

4.1 BACKGROUND

As explained in §2.1.2, the speech signal provides acoustic cues that listeners can use to discriminate and identify speech sounds, i.e., they are the acoustic correlates of phonetic contrasts in a language (Nittrouer, 2002a). Because languages differ in which phonetic contrasts are relevant, these acoustic cues are language-specific. For instance, vowel length is a relevant acoustic cue to distinguish vowel contrasts such as /a/-/a/ in Dutch, but not in English. Children acquiring Dutch or English thus have to learn to attend to or ignore, respectively, vowel length when identifying vowels (e.g. Dietrich, Swingley, & Werker, 2007). Learning to perceive speech, therefore, consists of learning to identify, integrate and weigh the relevant acoustic cues in the speech signal according to language-specific patterns, whether in first language acquisition (Boersma et al., 2003; Jusczyk, 1993; Nittrouer, 2002a; Werker & Curtin, 2005) or second language acquisition (e.g. Escudero & Boersma, 2004; Flege, Bohn, & Jang, 1997; Iverson & Evans, 2007).

Adult-like cue weighting in a first language can take eight years or even longer to develop in typically developing children (e.g. Gerrits, 2001; Hazan & Barrett, 2000; Nittrouer, 2002a) and usually takes longer to develop for consonant than for vowel contrasts (Gerrits, 2001). One possible explanation for developmental changes in cue weighting are changes in auditory sensitivity, such as changes in the spectral distinctiveness needed to perceive phonetic contrasts (e.g. Mayo & Turk, 2005; but see also Nittrouer & Lowenstein, 2007). An alternative explanation is that children initially attend more to dynamic cues such as formant transitions than to static cues such as intensity of the noise spectrum in the perception of fricatives, but

²⁰ An adapted version of this chapter appears as Giezen, M.R., Escudero, P., & Baker, A.E. (2010). The use of acoustic cues by children with a CI. *Journal of Speech, Language and Hearing Research*, 53, 1440-1457.

that throughout development children shift their attention towards static cues (Hicks & Ohde, 2005; Nittrouer, 2002b, 2007; Nittrouer & Lowenstein, 2009; Nittrouer & Miller, 1997). The observed developmental shift from dynamic to static cues might be related to a shift from the syllable to the phoneme as the perceptual unit in speech perception (e.g. Hicks & Ohde, 2005; Nittrouer & Miller, 1997). This could be due either to the need for more fine-grained lexical and phonological representations in the growing mental lexicon (e.g. Jusczyk, 1993; Nittrouer, 1996; Walley & Flege, 1999) or to attunement of abstract phonological representations with the development of phonological awareness (e.g. Mayo, Scobbie, Hewlett, & Waters, 2003).

Regardless of which explanation for the observed developmental changes in acoustic cue weighting is correct, children with a CI seem to face an extra challenge because, as we have seen in §1.2.1, CIs differ from the human ear in the spectral, temporal and amplitude information provided (Moore, 2003; Shannon, 2002). Spectral information in particular is distorted. Reduced spectral resolution has clear adverse effects on speech recognition by children and adults with normal hearing (Eisenberg et al., 2000; Schwartz et al., 2008), and even more so on speech recognition by adults with sensorineural hearing loss (e.g. Baskent, 2006; Friesen et al., 2001; Henry, Turner, & Behrens, 2005).

Several studies have examined the role of acoustic cues in phoneme perception by post-lingually deaf adult CI users and by adults with normal hearing listening to CI simulations. For instance, Xu et al. (2005; see also Xu & Zheng, 2007) compared the contribution of spectral and temporal cues to phoneme recognition in adults listening to implant simulations. They showed that both spectral and temporal cues are important for accurate phoneme recognition. In consonant recognition, spectral cues were especially important for conveying information about place of articulation. A trade-off between spectral and temporal cues was observed for consonant recognition, but only minimally for vowel recognition (see Nie et al., 2006 for similar findings with adult implant users).

In an early study, Hedrick and Carney (1997) examined the perception and integration of relative amplitude and formant transition cues in consonant perception in four adult implant users compared to a group of adults with normal hearing. They found that the implant users attended more to relative amplitude than to formant transition and did not integrate the cues to the same extent as the adults with normal hearing. More recently, Rogers et al. (2006) showed that adult implant users were less sensitive to intensity and fundamental frequency increments than adults with normal hearing, but that both groups integrated the cues to the same extent. Iverson (2003) found shifted sensitivity peaks towards longer voice onset times in English /t/-/d/ discrimination and speculated on increased inter-individual variability in the use of spectral and temporal cues among adult implant users. Iverson et al. (2006)

showed similarities between adult implant users and adults listening to implant simulations in the use of formant movement and durational cues in vowel recognition. Munson and Nelson (2005) compared phonetic identification in quiet and in noise by adult implant users and adults with normal hearing listening to unfiltered speech and to implant simulations. They found that sound contrasts distinguished by rapidly changing spectral patterns were most likely to be misperceived by the implant users. Finally, Lane et al. (2007) compared phoneme identification and discrimination of one vowel and one sibilant contrast in seven adult implant users one-month and one-year post-implant. Phoneme identification improved significantly over one year, but discrimination remained relatively poor.

In one of the few studies available on the use of acoustic cues by children with a CI, Summerfield et al. (2002) analysed the use of unambiguous vocalic information in the identification of preceding ambiguous fricative sounds by children and adults with a CI compared to children and adults with normal hearing. They showed that all groups were able to use the vocalic information to disambiguate the fricatives, but the implant users did so to a lesser extent than the listeners with normal hearing. Furthermore, in an unpublished doctoral dissertation, Bahng (2008) examined acoustic cue weighting in consonant perception in eight 5- to 8-year-old children with a CI. Similarly to a control group of age-matched children with normal hearing and a group of adults with normal hearing, the children with a CI gave more weight to the spectral cue than the formant transition cue in a voiceless fricative contrast and more weight to the formant transition cue than the release burst in a voiceless stop contrast. However, differently from both control groups, the children with a CI did not appear to integrate the two cues for either contrast.

These earlier studies examined the perception of a single contrast (Summerfield et al., 2002) or only consonant contrasts (Bahng, 2008). It is important to include both consonant and vowel contrasts since studies of phoneme recognition in children with a CI have shown an advantage for vowels over consonants, with place of articulation contrasts being more difficult than manner of articulation contrasts, as well as long-lasting difficulties with perceiving voicing distinctions (Kishon-Rabin et al., 2002; Mildner, Sindija, & Zrinski, 2006; Pisoni et al., 1999). Two vowel contrasts, the low vowel contrast /a/-/a/ and the high vowel contrast /i/-/i/, as well as two consonant contrasts, the voicing contrast /b/-/p/ and the place of articulation contrast /t/-/s/, were selected for inclusion in this study.

In the two vowel contrasts /a/-/a/ and /i/-/i/, formant frequency and vowel duration were manipulated. It is known that Dutch-speaking children of four years of age and older use both spectral and durational cues to categorize the low vowel contrast /a/-/a/, with the spectral cues typically weighted as relatively stronger than the durational cues (Gerrits, 2001). However, given that only limited spectral information is transmitted by the implant, children with a CI might rely more on

durational cues as a compensatory strategy. The smaller spectral and temporal difference between the two vowels in the /i/-/i/ contrast relative to the /a/-/a/ contrast should make the /i/-/i/ contrast more difficult to discriminate for these children and may lead to an even stronger reliance on the durational cues.

In the voicing contrast /b/-/p/, voice onset time (VOT) was manipulated. The presence or absence of prevoicing (a negative VOT) has been found to be a strong cue in the perception of the voicing distinction for word-initial labial and alveolar plosives in Dutch (Van Alphen & Smits, 2004). In children wearing acoustic hearing aids, perception of VOT cues has been found to be normal in English-speaking children with mild to moderate hearing impairment, but not in children with severe hearing impairment (Jerger, 2007).

In the place of articulation contrast /t/-/s/, noise frequency and intensity were manipulated. Accurate perception of high frequency noise spectra has been found to be difficult for young Dutch-speaking children up to the age of nine years (Gerrits, 2001). A study by Pittman, Stelmachowicz, Lewis and Hoover (2002) showed that English-speaking children (5-10 years old) and adults with mild-to-moderate hearing impairment wearing acoustic hearing aids attributed similar perceptual weight to fricative-vowel formant transitions in the perception of consonant-vowel-consonant words as adults and children with normal hearing.

4.2 METHODOLOGY

4.2.1 PARTICIPANTS

Participants in the experiment reported in this chapter were 15 children with a CI (mean age: 5;8), 20 children with normal hearing (mean age: 5;11) and, as a control for the task, 21 young adults with normal hearing (mean age: 22;3). Background characteristics of the participants were provided in §3.1.

4.2.2 STIMULI

Natural speech of a male adult native speaker of Dutch was recorded with a Sennheiser® MKH105T microphone on a digital TASCAM® CD-RW900 recorder in a sound-attenuated room. The speaker came from the central region of the Netherlands and spoke Northern Standard Dutch, as spoken in the provinces North-Holland, South-Holland and Utrecht in the Netherlands (Adank, Van Hout, & Van de Velde, 2007). The adult listeners also spoke Northern Standard Dutch. The

children, however, spoke either Northern Standard Dutch or Southern Standard Dutch, as spoken in the provinces Antwerp and Flemish-Brabant in Belgium (Adank et al., 2007). Regional phonetic variation in production of the four phonetic contrasts included here has been reported in the literature (Adank et al., 2007; Van Alphen & Smits, 2004; Ziliak & Van de Velde, 2007), but this is not very relevant for our study, however, because the focus is on similarities and differences between the children with a CI and the children with normal hearing. Given that both groups of children included children that spoke Northern Standard Dutch and Southern Standard Dutch, any specific property of the stimuli that affects the perception by children that speak one or the other variety differentially can be expected to affect both groups of children to the same extent.

In total, four stimuli series were constructed from recordings of monosyllabic words: a low vowel contrast (/a/-/a/), a high vowel contrast (/i/-/i/), a voicing contrast (/bu/-/pu/) and a place of articulation contrast (/fu/-/su/). Words, instead of single segments, were recorded to ensure that the vowels and consonants had natural speech-like characteristics. The sampling rate for the recordings was 44100 Hz. Recorded sound files were converted to the Wave sound format and later modified in Praat[®] v5.0.23 (Boersma & Weenink, 2008). The range for each acoustic cue in the stimuli series was largely representative of that observed in naturally produced Dutch tokens (Adank, Van Hout, & Smits, 2004; Kissine, Van de Velde, & Van Hout, 2003; Kuijpers, 1996; Pols, Tromp, & Plomp, 1973).

4.2.2.1 VOWEL CONTRASTS

For the vowel contrasts /a/-/a/ and /i/-/i/, VCV words (/a:pa:/, /a:pa/, /i:pi/, /i:pi/) were recorded. A VCV context was chosen to reduce the influence of consonant context on subsequent vowel formant values. A voiceless plosive was chosen for the intervocalic consonant in order to ensure that the vowel segment was clearly demarcated in the waveform and spectrogram. The production of each initial vowel was lengthened to ensure reliable steady-state parts in the vowels. Steady-state parts of the initial vowels were extracted at the end of a pitch pulse at a zero crossing. The duration of the extracted vowel segments was 210 milliseconds for the /a/-/a/ contrast and 100 milliseconds for the /i/-/i/ contrast, which were the maximum durations included in the /a/-/a/ and /i/-/i/ stimuli series, respectively. Both vowel stimuli series consisted of 12 isolated tokens covering the four edges of a 4x4 matrix. The stimulus set for the low vowel contrast /a/-/a/ is given as an example in Figure 4.1. Given that the participants included young children and that several contrasts were tested, a stimulus set covering only the edges of the matrix (i.e., 12

stimuli) was preferred to a stimulus set covering the entire matrix (i.e., 16 stimuli) in order to limit task duration²¹.

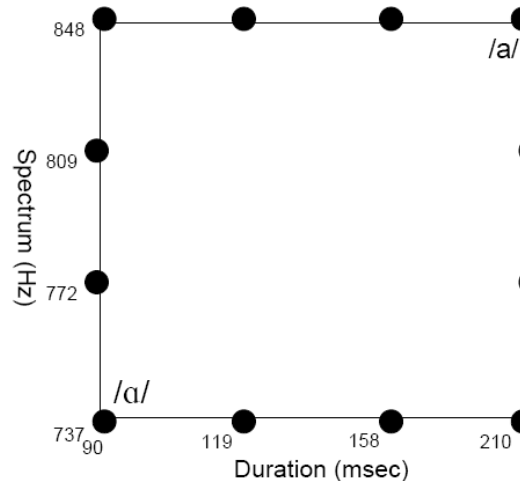


Figure 4.1. Example stimulus set for the low vowel /a/-/a/ contrast. The two cue dimensions spectrum (Hz) and duration (msec) are represented on the y-axis and x-axis, respectively.

The naturally produced tokens of the vowels /a/ and /a/ were used to create a two-dimensional series varying in duration and an F1-F2 combination. Duration was modified in three equal fractional step sizes between the two endpoints by removing increasingly larger segments of the original vowel segments (selected at the end of a pitch pulse at a zero crossing). Formant values for F1 and F2 in the extracted vowel segments were obtained using the implemented LPC formant analysis in Praat[®] (maximum frequency set at 5500 Hz, effective window length set at 0.025 seconds, pre-emphasis for an inverted low-pass filter (+6dB/octave) set at 50 Hz). In the resulting formant filter, F1 and F2 were modified in three equal fractional step sizes between the two endpoints. The required step sizes were determined using the auditorily-based mel scale²². The resulting formant filters were synthesized with the shorter and longer /a/ and /a/ stimuli to create the intermediate stimuli between the four corner stimuli in the matrix (see Appendix A).

²¹ Boersma & Escudero (2005) compared simulated listeners' perception of stimuli along the edges and stimuli covering the entire 4x4 matrix and found no effect of number of stimuli.

²² The formula given by Fant (1973) was used to convert values in Hertz to values in Mel: $M = (1000 / \log_{10} 2) \times \log(1 + f/1000)$.

The naturally produced tokens of the vowels /u/ and /i/ were used to create a two-dimensional stimulus series varying in duration and an F1-F2 combination. Using the same procedure as for the /a/-/a/ stimulus series, duration was modified in three equal fractional step sizes between the two endpoints. Again using the same procedure as for the /a/-/a/ stimulus series, F1 and F2 extracted from the original sound were modified in three equal fractional step sizes between the two endpoints and the resulting formant filters were synthesized with the shorter and longer /u/ and /i/ stimuli to create the intermediate stimuli between the four corner stimuli in the stimulus matrix (see Appendix A).

4.2.2.2 CONSONANT CONTRASTS

For the consonant contrasts /bu/-/pu/ and /fu/-/su/ monosyllabic CVC words (/bub/, /pup/, /fuf/, /sus/) were recorded from which the initial consonant and the first 100 milliseconds of the vowel were extracted and modified for presentation. A CVC context was chosen to avoid unnatural production of CV syllables given that monosyllabic CV words are highly infrequent in Dutch. The vowel context /u/ was chosen because the vowels /a/, /a/, /i/ and /i/ were already included as stimuli in the vowel stimuli series and the vowels /o/ and /e/ are slightly diphthongized in the central region of the Netherlands.

The naturally produced syllables /bu/ and /pu/ were used to create a stimulus series varying in VOT between a negative VOT (-83 msec) and a positive VOT (20 msec) in five intermediate steps. Intermediate stimuli were obtained by deleting increasingly longer segments of periodic energy from the endpoint /b/ for stimuli with negative VOT values and deleting segments of aperiodic energy from the endpoint /p/ for positive VOT values (see Appendix A). All segments were deleted at the end of a pitch pulse at a zero crossing. The final stimulus set was obtained by cross-splicing the consonant and vowel segments resulting in two exemplars for each point in the stimulus series with different formant transitions: one exemplar spliced with the vowel extracted from the syllable /bu/ and one exemplar spliced with the vowel extracted from the syllable /pu/. Both exemplars were included in the categorization task.

The naturally produced tokens of the vowels /fu/ and /su/ were used to create a two-dimensional stimulus series varying in intensity and noise spectrum. Intensity was modified in three equal fractional step sizes on the decibel scale by scaling the average intensity of the /t/ and /s/ segments at different levels. Using the same procedure as for the vowel stimuli series, the first four formants extracted from the /t/ and /s/ segments were modified in three equal fractional step sizes between the two endpoints and the resulting filters were synthesized with the softer and louder /t/

and /s/ stimuli to create the intermediate stimuli between the four corner stimuli in the stimulus matrix (see Appendix A). The resulting stimuli were all 150 milliseconds in duration. Similar to the VOT stimulus set, the final stimulus set was obtained by cross-splicing the consonant and vowel segments resulting in two exemplars for each point in the stimulus series with different formant transitions: one exemplar spliced with the vowel extracted from the syllable /tu/ and one exemplar spliced with the vowel extracted from the syllable /su/. Both exemplars were included in the categorization task.

4.2.3 TASK

An XAB categorization task was designed using E-Prime[®] v2.0 software (Psychology Software Tools, Pittsburgh PA). In this task, participants have to decide whether sound X is more like sound A or sound B, where X is a randomly chosen stimulus from a stimulus series and A and B are the two endpoint stimuli of the series (see also §3.2.1). The XAB format is considered to be less abstract, and therefore more appropriate for children, than the ABX format, which had previously been used with children (e.g. Gerrits, 2001). The task was further made as child-friendly as possible by associating X, A and B with cartoon bird pictures (see Figure 4.2). The inter-stimulus interval between presentation of X and A was 2000 milliseconds and between A and B 1000 milliseconds. Inter-stimulus intervals were chosen thus to target listener's phonetic perception instead of purely auditory discrimination (Pisoni, 1973; Van Hoesen & Schouten, 1992; Werker & Logan, 1985) and also to create a clear distinction between the stimulus to be categorized (X) and the response categories (A and B). The inter-trial interval was set at 1000 milliseconds. There was no limit on the response time. Both the order of the stimuli assigned to the first bird (X) and the order of the two phoneme endpoints assigned to the other two birds (A and B) were randomized. Listeners responded by pressing one of two keys on the laptop (labelled with stickers).

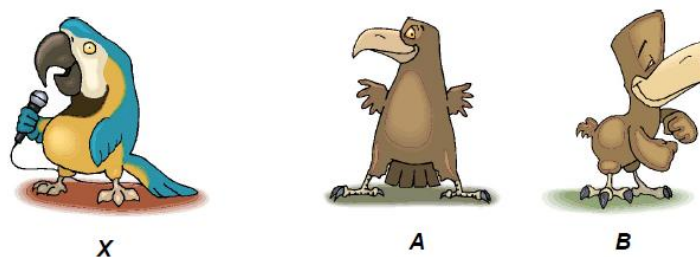


Figure 4.2. Animation bird pictures associated with presentation of the target stimuli (X) and response categories (A and B) in the sound categorization task.

For the two vowel contrasts /a/-/a/ and /i/-/i/, participants had to categorize each stimulus twice, resulting in a total of 24 trials. For the place of articulation contrast /fu/-/su/, participants had to categorize each stimulus twice, once with the formant transition appropriate for /fu/ and once with the formant transition appropriate for /su/, resulting in a total of 24 trials. Finally, for the voicing contrast /bu/-/pu/, participants had to categorize each stimulus twice, once with the formant transition appropriate for /bu/ and once with the formant transition appropriate for /pu/, resulting in a total of 12 trials.

Each child completed the task for two contrasts, one vowel and one consonant contrast, in order to reduce the length of testing. The adults completed the task for all four contrasts. Presentation of contrasts was counterbalanced across listeners. Participants were told that two birds would try to imitate the sounds of a third bird and that they had to decide which of the two succeeded best. Prior to the test session, participants completed a practice session consisting of six trials from one of the two vowel contrasts. For the children, this was the vowel contrast they were not tested on. Because the adults were tested on both vowel contrasts, their practice session consisted by necessity of trials from a contrast they were also tested on. Categorization for different contrasts was separated by a brief pause. The task took children between 10 and 15 minutes and adults between 15 and 20 minutes.

4.2.4 DEPENDENT VARIABLES

Four dependent variables were analysed in the sound categorization task: phoneme endpoint identification, individual cue reliance, cue weighting and classification slope.

4.2.4.1 PHONEME ENDPOINT IDENTIFICATION

As part of the task, information was obtained as to whether listeners were able to correctly identify the two phoneme endpoints in the experiment, i.e., the two stimuli in the bottom-left corner and the top-right corner in Figure 4.1. If listeners are unable to identify the phoneme endpoints correctly, they are either unable to discriminate between the two phonemes or they do not pay sufficient attention to the task. As a result, identification scores in combination with cut-off values (e.g., 80% correct) are often used in cue weighting studies to exclude listeners from a subsequent cue-weighting analysis (e.g. Nittrouer & Miller, 1997). Because in our study listeners were exposed to each stimulus only twice, the maximum identification score that could be obtained for each contrast was 4, complicating the

use of any cut-off score. More importantly, given the nature of the population in our study, namely hard-of-hearing children, removing children from the analysis that do not seem to hear the difference (solely based on their identification scores) would leave an unrepresentative sample of only high-performing children with a CI for comparison with the other two groups of listeners. For these reasons, phoneme endpoint identification was not used as an exclusion criterion, but included as a dependent variable.

4.2.4.2 INDIVIDUAL CUE RELIANCE, CUE WEIGHTING AND CLASSIFICATION SLOPE

As proposed by Morrison (2005, 2007), logistic regression analysis can be used to derive several measures of acoustic cue use for one-dimensional and two-dimensional contrasts. In logistic regression analyses, sigmoidal curves are fitted to categorical response data. Logistic regression resembles linear regression (in terms of an intercept and regression coefficients), but differs in that it expresses the dependent variable in logarithmic values. The regression coefficients are measures of *individual cue reliance*. In order to make the regression coefficients for each cue comparable to each other for purposes of measuring cue weighting (see below), each stimulus was assigned a number on a scale from 1 to 4 for both cue dimensions and this value was entered into the logistic regression analysis (cf. Escudero et al., 2009)²³.

In addition, for those contrasts in which two acoustic cues were manipulated a measure of *cue weighting* was obtained to compare the relative use of acoustic cues within or between groups of listeners regardless of overall differences in absolute reliance on each cue, as was previously done in Escudero et al. (2009). A cue ratio was derived by dividing the regression coefficient of one of the cues by the sum of the regression coefficients of both cues. More specifically, the spectral cue coefficient was divided by the sum of the spectral cue and the durational or intensity coefficients. In the division any negative coefficients were recoded as positive coefficients. A cue ratio higher than 0.5 indicated that the spectral cue was weighted as relatively stronger, whereas a cue ratio lower than 0.5 indicated that the durational or intensity cue was weighted as relatively stronger. A cue ratio of 0.5 exactly indicated that both cues were weighted as equally strong.

Finally, the rate of change from one response category, i.e., each of the two phonemes in each of the sound contrasts, to the other was used as a discrimination function which is referred to here as *classification slope*. For two-dimensional contrasts, this discrimination function is found by taking the square root of the sum of the squares of both contrast coefficients obtained in the logistic regression

²³ Logistic regression analysis was performed in Praat[®] v5.0.23 (Boersma & Weenink, 2008).

analysis; for one-dimensional binomial contrasts, the discrimination function is equal to one fourth of the value of the contrast coefficient (Morrison, 2007).

4.2.5 STATISTICAL ANALYSIS

Because the sample sizes for this experiment were relatively small and unequal (see §4.2.3 and also §4.3), non-parametric statistical tests were performed in the majority of the analyses. Specifically, the rank-based Kruskal-Wallis H test for more than two independent samples was used to examine main effects and the rank-based Mann-Whitney U test was used for post hoc comparisons. In all group wise post hoc comparisons, a correction was applied to adjust for multiple comparisons where the significance cut-off was $p=.02$ ($\alpha/n=.05/3=.02$). For the statistical interpretation of the Mann-Whitney U test, two-tailed exact significance was adopted to adjust for small and unbalanced samples.

4.3 RESULTS

Three out of the 15 children with a CI who participated in this experiment did not complete the task for any of the contrasts due to concentration difficulties during the task²⁴. One of these children (L4, see Table 3.1) was implanted relatively late (3;2) and as a result had less “hearing experience” than many of the other children. For another child (S6, see Table 3.1), fitting and programming of the device had been problematic due to behavioral difficulties. In general, she was considered a low performer with the implant and relied to a large extent on sign language in daily communication. The third child (J8, see Table 3.1) was implanted early (0;8) and fitting and programming of the implant had been unproblematic; however, this child was very inattentive on both testing days. Three children with a CI and two children with normal hearing completed the task for only one contrast due to concentration difficulties. Of the 21 adults who participated in the experiment, 20 completed the task for all contrasts and one completed the task for only two contrasts due to an experimenter error. In this section phoneme endpoint identification is analyzed first (§4.3.1), followed by individual cue reliance (§4.3.2), cue weighting (§4.3.3) and classification slope (§4.3.4). Depending on the contrast tested, sample sizes in the

²⁴ Relative high drop-out rates are not uncommon in studies of children with a CI. Of particular interest is the study by Summerfield et al. (2002) referred to in §4.1, who studied the use of vocalic cues in the identification of fricatives. They recruited 39 4-10-year-old children with a CI, of which only ten completed all 48 trials; twelve children were unwilling or unable to perform the task.

analyses were $n=5-6$ for the children with a CI, $n=8-11$ for the children with normal hearing and $n=20-21$ for the adults. Means and medians of the dependent variables for all three groups of listeners are provided in Appendix B. Individual results for the children with a CI are provided in Appendix C.

4.3.1 PHONEME ENDPOINT IDENTIFICATION

As expected, the adults performed close to ceiling-level (100% correct) on phoneme endpoint identification for all four contrasts (see Figure 4.3). The children with normal hearing scored around 80% correct, with the place of articulation contrast /fʊ/-/su/ being even higher. The children with a CI scored between 50% (place of articulation contrast /fʊ/-/su/) and 75% (low vowel contrast /a/-/a/) correct.

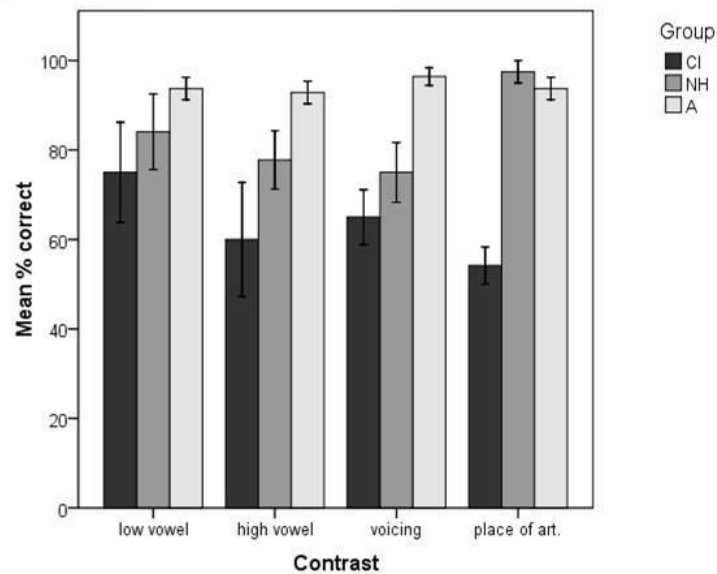


Figure 4.3. Mean phoneme endpoint identification (% correct) for the children with a CI (CI), the children with normal hearing (NH) and the adults (A) for each contrast (place of art.=place of articulation).

Statistical comparison of the phoneme endpoint identification scores revealed no effect of Group for the *low vowel contrast* /a/-/a/ ($\chi^2=3.03$, $p=.22$) and as a result, post hoc comparisons are not reported. Statistical analysis of the other three contrasts did reveal a main effect of Group (/ɪ/-/i/: $\chi^2=9.61$, $p<.01$; /bʊ/-/pu/: $\chi^2=17.90$, $p<.01$; /fʊ/-/su/: $\chi^2=20.11$, $p<.01$). For the *high vowel contrast* /ɪ/-/i/, the

children with a CI did not differ significantly from the children with normal hearing ($Z=-1.26$, $p=.24$). They did appear to score lower than the adults, but this effect was only marginally significant ($Z=-2.71$, $p=.02$). The children with normal hearing did not differ significantly from the adults ($Z=-2.20$, $p=.06$). For the *voicing contrast* /bu/-/pu/, the children with a CI did not differ significantly from the children with normal hearing ($Z=-.97$, $p=.44$). Both child groups scored significantly lower than the adults (children with a CI: $Z=-3.85$, $p<.01$; children with normal hearing: $Z=-3.25$, $p<.01$). Finally, for the *place of articulation contrast* /fu/-/su/, the children with a CI scored significantly lower than the children with normal hearing ($Z=-3.60$, $p<.01$) and the adults ($Z=-3.94$, $p<.01$). The children with normal hearing did not differ significantly from the adults ($Z=-.95$, $p=.53$). These results show that the children with a CI had clear difficulty consistently distinguishing the phoneme endpoints in the stimulus series for the place of articulation contrast /fu/-/su/. This finding corresponds with studies in other languages that found that children with a CI perceived place of articulation contrasts less accurately than, for instance, manner of articulation contrasts (Kishon-Rabin et al., 2002; Mildner et al., 2006; Pisoni et al., 1999). Furthermore, in comparison with the adults, the children with normal hearing showed some difficulty in consistently identifying the phoneme endpoints in the stimuli series for the voicing contrast /bu/-/pu/. Kishon-Rabin et al. (2002) similarly found showed that the perception of voicing contrasts was difficult for Hebrew-speaking children with normal hearing as well as children with a CI. We will now turn to the analysis of the use of individual acoustic cues in the categorization of the vowel and consonant contrasts.

4.3.2 INDIVIDUAL CUE RELIANCE

To examine the similarities and differences in the reliance on individual acoustic cues among the three groups of listeners, statistical group comparisons of the logistic regression coefficients for each individual acoustic cue were performed within each contrast. For the *low vowel contrast* /a/-/a/, a significant effect of Group was observed for both the spectral cue ($\chi^2=6.95$, $p<.05$) and the durational cue ($\chi^2=18.28$, $p<.01$). The children with a CI did not differ significantly from the children with normal hearing in their use of the spectral cue ($Z=-.54$, $p=.22$), but they used it significantly less than the adults ($Z=-2.53$, $p<.02$). The children with normal hearing did not differ significantly from the adults in their use of the spectral cue ($Z=-1.41$, $p=.17$). The children with a CI seemed to use the durational cue less than the children with normal hearing, but this effect was only marginally significant ($Z=-2.10$, $p=.04$). Both child groups used the durational cue significantly less than

the adults (children with a CI: $Z=-3.21$, $p<.01$; children with normal hearing: $Z=-3.34$, $p<.01$).

For the *high vowel contrast* /i/-/i/, a significant effect of Group was observed for both the spectral cue ($\chi^2=19.99$, $p<.01$) and the durational cue ($\chi^2=22.64$, $p<.01$). The children with a CI seemed to use the spectral cue less than the children with normal hearing, but this effect was only marginally significant ($Z=-1.26$, $p=.03$). They did use the spectral cue significantly less than the adults ($Z=-3.43$, $p<.01$). Surprisingly, the children with normal hearing used the spectral cue significantly *more* than the adults ($Z=-3.38$, $p<.01$). The children with a CI did not differ significantly from the children with normal hearing in their use of the durational cue ($Z=-1.74$, $p=.08$). Both child groups used the durational cue significantly less than the adults (children with a CI: $Z=-3.10$, $p<.01$; children with normal hearing: $Z=-4.15$, $p<.01$).

For the *voicing contrast* /bu/-/pu/, a significant effect of Group was observed for the VOT cue ($\chi^2=17.05$, $p<.01$). The children with a CI seemed to use this cue significantly less than the children with normal hearing, but this effect was only marginally significant ($Z=-1.98$, $p=.05$). Both child groups used the VOT cue significantly less than the adults (children with a CI: $Z=-3.47$, $p<.01$; children with normal hearing: $Z=-2.79$, $p<.01$).

Finally, for the *place of articulation contrast* /fu/-/su/, a significant effect of Group was observed for the spectral cue ($\chi^2=19.20$, $p<.01$) and the intensity cue ($\chi^2=7.50$, $p<.05$). The children with a CI used the spectral cue significantly less than the children with normal hearing ($Z=-3.15$, $p<.01$). Both child groups used the spectral cue significantly less than the adults (children with a CI: $Z=-3.66$, $p<.01$; children with normal hearing: $Z=-3.38$, $p<.01$). The children with a CI did not differ significantly from the children with normal hearing in their use of the intensity cue ($Z=-1.30$, $p=.22$), but they did use it significantly less than the adults ($Z=-2.56$, $p<.01$). The children with normal hearing did not differ significantly from the adults in their use of the intensity cue ($Z=-1.52$, $p=.13$).

In sum, the children with a CI clearly used the spectral cue in the place of articulation contrast /fu/-/su/ less effectively than the children with normal hearing. They also appeared to use the durational cue in the low vowel contrast /a/-/a/ and the VOT cue in the voicing contrast /bu/-/pu/ less effectively, but these effects were only marginally significant. Both child groups consistently used acoustic cues less effectively than the adults. It appears then, that the children with a CI are able to use many acoustic cues in the same way as their peers with normal hearing. It is still possible, however, that the children differ in the relative use of acoustic cues in sound categorization. We will consider this possibility in the next section.

4.3.3 CUE WEIGHTING

To examine the relative use of acoustic cues by the three groups of listeners, a cue ratio of the spectral cue in relation to the other cues was obtained by dividing the contrast coefficient of the spectral cue by the sum of the contrast coefficients of both relevant cues, i.e., the spectral cue and the durational or intensity cue (see Figure 4.4). A measure of cue weighting was not available for the voicing contrast /bʌ/-/pʌ/ because only one cue was manipulated in this contrast (see §4.2.2.2).

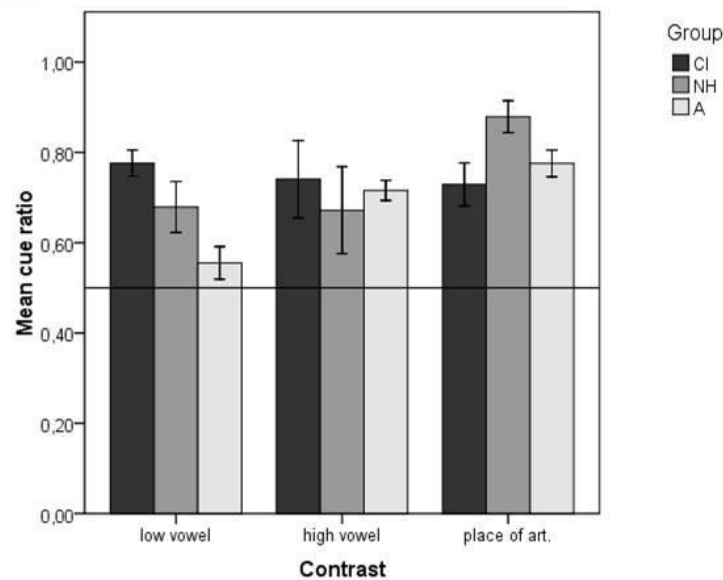


Figure 4.4. Mean spectral cue ratios for the children with a CI (CI), the children with normal hearing (NH) and the adults (A) for both vowel contrasts and the place of articulation (place of art.) contrast. A horizontal reference line is indicated at a cue ratio level of 0.5, the value when both acoustic cues are weighted as equally strong.

Statistical comparison of the cue ratios revealed a significant effect of Group for the low vowel contrast /a/-/a/ ($\chi^2=10.03$, $p<.01$). The children with a CI did not differ significantly in their cue weighting from the children with normal hearing ($Z=-1.19$, $p=.27$). However, they did have a significantly lower cue ratio than the adults ($Z=-3.14$, $p<.01$). The children with normal hearing also seemed to have a lower cue ratio than the adults, but this effect was only marginally significant ($Z=-1.99$, $p=.05$). The mean cue ratios show that the children with a CI (.78), the children with normal hearing (.68) and the adults (.56) as a group each attributed more weight to the spectral cue than to the durational cue for this contrast. This relative preference for

the spectral cue was most pronounced in the children with a CI, due to the fact that they hardly used the durational cue in the categorization of this contrast, unlike the adults, and to a slightly lesser extent, the children with normal hearing, who did use this cue. For the high vowel contrast /i/-/i/, no effect of Group was observed ($\chi^2=.07$, $p=.96$). The mean cue ratios show that the children with a CI (.74), the children with normal hearing (.67) and the adults (.72) as a group each attributed more weight to the spectral cue than to the durational cue for this contrast. Finally, for the place of articulation contrast /fʊ/-/su/, no effect of Group was observed ($\chi^2=5.55$, $p=.06$). The mean cue ratios show that the children with a CI (.73), the children with normal hearing (.88) and the adults (.78) as a group each attributed more weight to the spectral cue than to the intensity cue for this contrast.

The results from the cue weighting analysis show that all listener groups shared a preference for using the spectral cues in sound categorization as opposed to other available cues. That is, despite differences in individual cue reliance between the children and the adults (§4.3.2), cue weighting patterns were similar. This is a particularly unexpected finding for the children with a CI, who have to perceive speech by means of a spectrally reduced signal. Possible explanations for this finding will be discussed in §4.4.2.

4.3.4 CLASSIFICATION SLOPE

To examine overall discrimination of the contrasts by the three groups of listeners, classification slopes were compared for the four contrasts (Figures 4.5-4.8). A significant effect of Group was observed for all contrasts: /a/-/a/ ($\chi^2=15.46$, $p<.01$), /i/-/i/ ($\chi^2=18.41$, $p<.01$), /bu/-/pu/ ($\chi^2=16.74$, $p<.01$) and /fʊ/-/su/ ($\chi^2=19.61$, $p<.01$). In line with the findings in the analysis of endpoint phoneme identification (§4.3.1) and individual cue reliance (§4.3.2), the children with a CI showed significantly shallower classification slopes than the children with normal hearing only for the place of articulation contrast /fʊ/-/su/ ($Z=-3.04$, $p<.01$). The effects for the other three contrasts were only marginally significant but all in the same direction, namely shallower slopes for the children with a CI (/a/-/a/: $Z=-1.98$, $p=.05$; /i/-/i/: $Z=-2.20$, $p=.03$; /bu/-/pu/: $Z=-1.98$, $p=.05$). Finally, as expected, given less effective use of many acoustic cues (§4.3.2), both child groups showed significantly shallower classification slopes than the adults for each of the four contrasts: /a/-/a/ (children with a CI: $Z=-2.30$, $p<.01$; children with normal hearing: $Z=-3.00$, $p<.01$), /i/-/i/ (children with a CI: $Z=-3.23$, $p<.01$; children with normal hearing: $Z=-3.29$, $p<.01$), /bu/-/pu/ (children with a CI: $Z=-3.47$, children with normal hearing: $Z=-2.79$, $p<.01$) and /fʊ/-/su/ (children with a CI: $Z=-3.66$, $p<.01$, children with normal hearing: $Z=-2.78$, $p<.01$). Clearly, children's sound categorization was not yet adult-like.

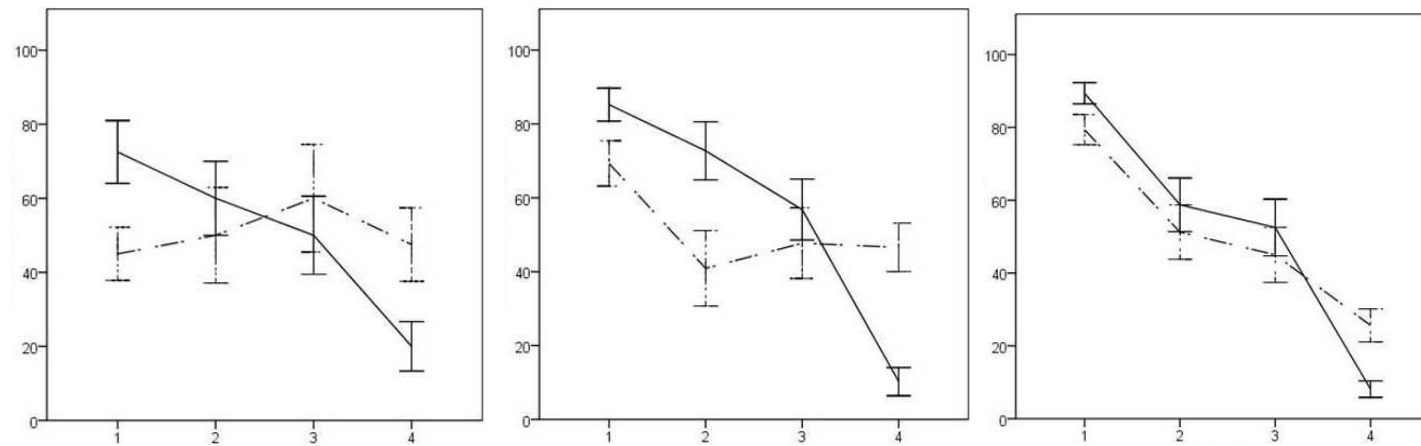


Figure 4.5. Classification slopes for the high vowel contrast /a/-/a/ for the children with a CI (left panel), the children with normal hearing (middle panel) and the adults (right panel). Stimulus number is presented on the horizontal axis; the specific acoustic values for the stimulus numbers can be found in Appendix A. % /a/ responses are presented on the vertical axis. The solid line represents the spectral cue and the dashed line the durational cue.

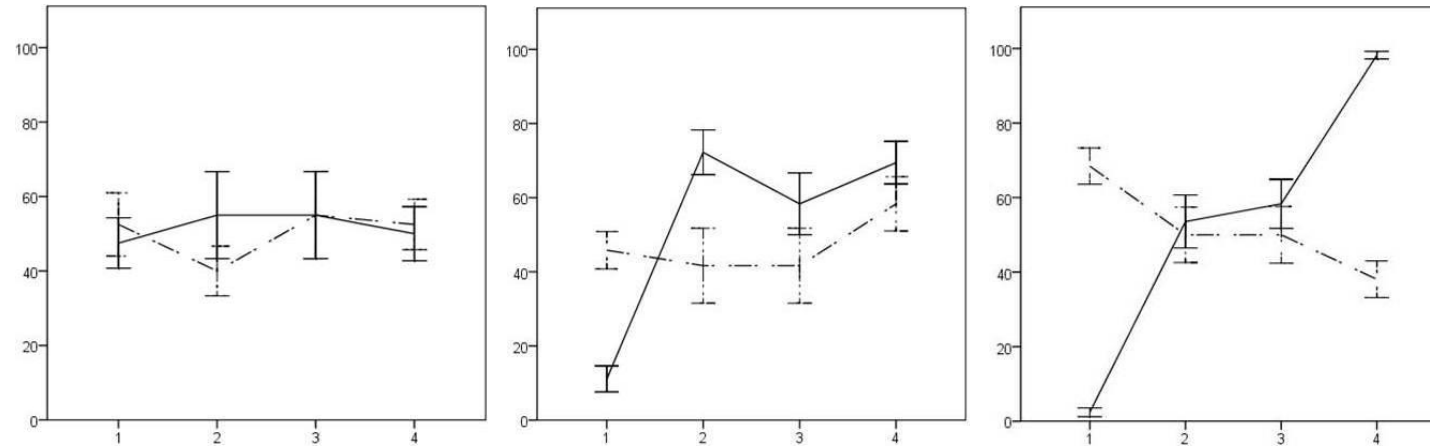


Figure 4.6. Classification slopes for the high vowel contrast /i/-/i/ for the children with a CI (left panel), the children with normal hearing (middle panel) and the adults (right panel). Stimulus number is presented on the horizontal axis; the specific acoustic values for the stimulus numbers can be found in Appendix A. % /i/ responses are presented on the vertical axis. The solid line represents the spectral cue and the dashed line the durational cue.

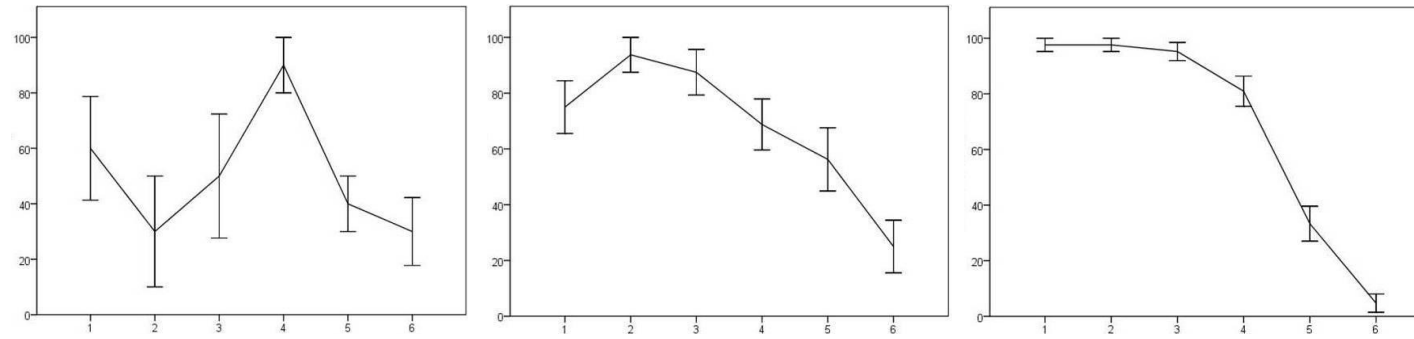


Figure 4.7. Classification slopes for the voicing contrast /bu/-/pu/ for the children with a CI (left panel), the children with normal hearing (middle panel) and the adults (right panel). % /b/ responses are presented on the vertical axis. Stimulus number is presented on the horizontal axis; the specific acoustic values for the stimulus numbers can be found in Appendix A.

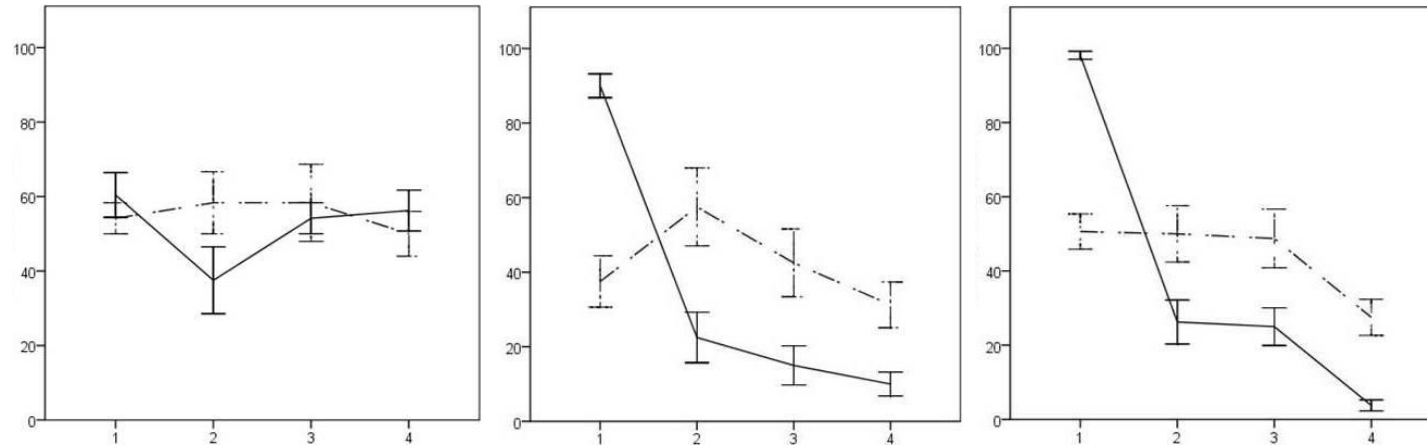


Figure 4.8. Classification slopes for the place of articulation contrast /fu-/su/ for the children with a CI (top left panel), the children with normal hearing (top right panel) and the adults (bottom left panel). Stimulus number is presented on the horizontal axis; the specific acoustic values for the stimulus numbers can be found in Appendix A. % /f/ responses are presented on the vertical axis. The solid line represents the noise spectrum cue and the dashed line the intensity cue.

4.4 DISCUSSION

The discussion of the results from the acoustic cue weighting experiment will first address differences between the children with normal hearing and the adults, i.e., age effects (§4.4.1). The effects of perceptually degraded auditory input are discussed in §4.4.2.

4.4.1 AGE EFFECTS IN ACOUSTIC CUE WEIGHTING

The performance of the children with normal hearing differed in several respects from that of the adults. They showed poorer phoneme endpoint identification only for the voicing contrast /bʊ/-/pʊ/, suggesting that they were able to accurately identify the phoneme endpoints in most stimulus series. They consistently used individual acoustic cues less effectively than the adults, except for the spectral cue in the low vowel contrast /a/-/a/ and the intensity cue in the place of articulation contrast /tʰ/-/sʊ/. In addition, their classification slopes were significantly shallower than those of the adults for all four contrasts. These findings are not unexpected, given the relatively young age of the children in our study (between five and six years old) and the observation in the literature that the development of adult-like cue weighting takes several years to complete. For instance, Gerrits (2001) examined 4-, 6- and 9-year old Dutch-speaking children and observed developmental differences in cue weighting strategies at all three ages, especially for the perception of consonant contrasts. Hazan and Barrett (2000) found that even 12-year old children categorized consonant contrasts less consistently than adults.

Developmental shifts in cue weighting strategies are not the only possible explanation for the observed age effects, however. First of all, the inter-stimulus interval (ISI) implemented in the speech sound categorization task was relatively long (on average 1500 msec). This ISI was chosen to distinguish between auditory perception and phonetic perception (Pisoni, 1973; Van Hesson & Schouten, 1992; Werker & Logan, 1985). Because our interest was in phonetic sound categorization, a long ISI was used. However, using a long ISI could have introduced auditory short-term memory-related performance difficulties for the children and perhaps even more so for the children with a CI, who have been shown to have a smaller phonological short-term memory capacity than age-matched children with normal hearing (Pisoni et al., 1999). Phonological short-memory capacity did in fact correlate with classification slopes for the children with a CI, but not for the children with normal hearing. This relationship will be explored in more detail in §5.3.4 together with rapid word learning.

Secondly, completing a speech discrimination or categorization task typically involves listening for a relatively long time to many more or less natural sounding speech stimuli, raising the possibility that attention demands might have affected the results (cf. Green, 1995). This is of particular concern when children are performing the task and when a relatively small number of trials were presented, as was the case in our study. Unfortunately, we were not able to explicitly control for attention demands. However, listeners' accuracy in identifying phoneme endpoints is often used as an indirect measure of attention in the task (e.g. Nittrouer & Miller, 1997). A significant difference between the children with normal hearing and the adults was only found for the voicing contrast /bu-/pu/, suggesting that attention demands cannot account for the observed performance differences.

Thirdly, the observed age effects might in fact be effects of the regional phonetic variation among the listeners. Recall that the children spoke either Northern Standard Dutch or Southern Standard Dutch; the adults, on the other hand, all spoke Northern Standard Dutch (see §4.2.2). The stimuli in the speech sound categorization task were also recorded using a speaker of Northern Standard Dutch. The children who spoke Southern Standard Dutch therefore might have had difficulty with the task simply because they were unfamiliar with the other variety. To determine any effect of regional phonetic variation, phoneme identification scores and classification slopes were averaged across all four contrasts and a 2 x 2 MANOVA was performed with Group (CI vs. normal hearing) and Regional phonetic variety (Northern Standard Dutch vs. Southern Standard Dutch) as two-level independent variables and phoneme endpoint identification and classification slope as dependent variables. Use of a parametric statistical test in this particular analysis was deemed justified because of the increase in sample size obtained by averaging the data and because the ANOVA statistic has been shown to be quite robust for violations of normality assumptions. As expected, there was a significant main effect of Group ($F(1,28)=14.70$, $p<.01$) on phoneme endpoint identification as well as on classification slope ($F(1,28)=5.32$, $p<.05$). More importantly, however, there was no effect of Regional variety ($F(1,28)=.92$, $p=.35$ and $F(1,28)=.46$, $p=.50$) and no interaction ($F(1,28)=.35$, $p=.56$ and $F(1,28)=.61$, $p=.44$). In effect, it is unlikely that the observed age effects in phoneme endpoint identification and classification slope are the result of regional phonetic variation between the children and the adults²⁵.

²⁵ In addition to this overall ANOVA, separate non-parametric Mann-Whitney U tests comparing Dutch and Flemish children were performed on each of the four contrasts for all available measures (i.e., phoneme endpoint identification, individual cue reliance, cue weighting and classification slope). The Flemish children obtained significantly higher phoneme endpoint identification scores than the Dutch children on the voicing contrast /bu-/pu/ ($Z=-2.27$, $p<.05$). Furthermore, the Dutch children appeared to have used the intensity cue

Finally, the children might have tried to use other acoustic cues to categorize the sound contrasts than those systematically manipulated here. For the vowel contrasts, the spectral and the durational cue would seem to be the two most salient acoustic cues for children and adults alike (Gerrits, 2001). For the consonant contrasts, however, one additional cue was present, namely formant transition. In fact, this cue has been found to be considerably used by typically developing children in categorization of fricative contrasts (e.g. Gerrits, 2001; Nittrouer, 2002b). Even though the use of formant transitions was to some extent controlled for by creating stimuli with both correct and incorrect formant transitions for the place of articulation contrast /fu/-/su/ and the voicing contrast /bu/-/pu/ (see §4.2.2), it is still possible that the children used formant transitions instead of the other cues present in the stimuli to categorize one or both contrasts. To account for this possibility, performance on both consonant contrasts was reanalyzed substituting formant transition as acoustic cue for noise spectrum and intensity or VOT in the logistic regression analysis. This reanalysis showed that only one child with a CI and none of the adults had used the formant transition consistently for categorization of the place of articulation contrast /fu/-/su/. However, three children with normal hearing (and two children with a CI), as opposed to none of the adults, had used the formant transition consistently for categorization of the voicing contrast /bu/-/pu/. Possibly, for these children the VOT cue was not sufficiently salient to use in categorization of the contrast and they instead relied on formant transitions. As mentioned in §4.1, it has been suggested that throughout development children shift their attention from dynamic acoustic cues towards static acoustic cues in sound perception (e.g. Hicks & Ohde, 2005; Nittrouer, 2002b, 2007; Nittrouer & Lowenstein, 2009; Nittrouer & Miller, 1997). The finding that a few children heavily relied on formant transitions in the categorization of the voicing contrast /bu/-/pu/ could therefore indicate that their perception was in an earlier developmental stage for this sound contrast.

4.4.2 USE OF ACOUSTIC CUES BY CHILDREN WITH A CI

The results show that of the four contrasts, the place of articulation contrast /fu/-/su/ caused most problems for the children with a CI. For this contrast, they had clear

in the place of articulation contrast /fu/-/su/ more effectively than the Flemish children, although this effect did not reach significance ($Z=-1.95$, $p=.05$). None of the other comparisons approached significance. The difficulty of the Dutch children with the voicing contrast may be related to a more general shift in the Netherlands towards the devoicing of voiced obstruents (e.g. Van de Velde, Van Hout, & Gerritsen, 1997). However, it should be noted that Ziliak and Van de Velde (2007) have recently shown that voiced labials are actually more devoiced in Flanders than in the Netherlands.

difficulty consistently distinguishing the phoneme endpoints in the stimulus series. In addition, they used available spectral cues in this contrast less effectively than the children with normal hearing. In line with the phoneme endpoint identification and individual cue reliance findings, their classification slopes for this contrast were significantly shallower than those of their peers with normal hearing. Accurate perception of high-frequency noise spectra has also been found to be difficult for young typically developing children (Gerrits, 2001; Nittrouer, 2002b), which might explain the particular difficulties for the children with a CI with this contrast. Furthermore, children with a CI have more generally been shown to perceive place of articulation contrasts, such as /t/-/s/, less accurately than, for instance, manner of articulation contrasts, such as /t/-/s/ (Kishon-Rabin et al., 2002; Mildner et al., 2006; Pisoni et al., 1999).

Results for the other three contrasts were less clear. Effects for the use of the durational cue in the low vowel contrast /a/-/a/, the spectral cue in the high vowel contrast /i/-/i/ and the VOT cue in the voicing contrast /bu/-/pu/ were only marginally significant after adjusting for multiple comparisons, but all in the same direction, namely less effective use by the children with a CI. Similarly, classification slopes of the children with a CI for these contrasts appeared to be shallower than those of their peers with normal hearing, but the effects were again only marginally significant after adjusting for multiple comparisons. Most importantly, no differences in cue weighting patterns between children with a CI and children with normal hearing were observed. For each of the three contrasts that allowed an analysis of cue weighting, the cue ratios indicated that both child groups weighted the spectral cues as relatively stronger than the other available acoustic cues (i.e., duration or intensity).

Overall then, the performance of the children with a CI was quite similar to that of the children with normal hearing, suggesting that they are able to use many acoustic cues effectively in speech perception. This is a remarkable finding given their different auditory input and given that they have had less auditory experience than the children with normal hearing. The fact that they were implanted relatively early might have contributed to this finding. However, we did not find a significant correlation between either age at implantation or length of CI use and performance in the task. Overall, it should be emphasized that sample sizes in our study were small, limiting the statistical power of the analyses.

We specifically expected that spectral cues might be more difficult for children with a CI than temporal or intensity cues, given the relatively poor spectral resolution of sound processing with a CI. Thus, one might expect that they would weigh temporal and intensity cues as more strongly to compensate for this poor spectral resolution. However, such reversals in cue weighting were not observed. In fact, although the children with a CI used the spectral cue significantly less

effectively than their peers with normal hearing in their categorization of the place of articulation contrast /tʰu/-/su/, only a marginally significant effect in the same direction was observed for the high vowel contrast /i/-/i/. Moreover, they did not seem to have difficulty with using the spectral cue in categorization of the low vowel contrast /a/-/a/.

Importantly, the difference in formant values between /a/ and /a/ was larger than the difference in formant values between /i/ and /i/, which might have made the spectral cue in /a/-/a/ more accessible to the children with a CI. Some support for this explanation can be found in the data of the children with normal hearing. These children did not differ significantly from the adults in their use of the spectral cue in categorization of /a/-/a/, whereas they did for /i/-/i/. In addition, the children with a CI and the children with normal hearing did not use the durational cue in categorization of the /i/-/i/ contrast to the same extent as the adults. One of the purposes of including duration as an acoustic cue in the stimulus series for the /i/-/i/ contrast was to allow listeners, especially children with a CI, to use this cue, given that the spectral cue was not highly informative for this contrast. However, the distinction in duration (30 ms) might not have been large enough for them to consistently use it.

The finding that the children with a CI did not show a reversal in cue weighting for either vowel contrast or the place of articulation contrast despite the reduced spectral resolution of sounds transmitted by the implant is nevertheless surprising. However, Iverson et al. (2006) found that adult implant users did not use formant movement and duration cues in vowel recognition differently from adults listening to CI simulations. In their discussion, they propose one possible explanation pertinent to the pediatric population, namely that shifts in perceptual cue-weighting for a particular contrast would also affect the production of that contrast and thus its intelligibility to listeners. This may prevent large shifts in perceptual cue-weighting.

Another possible explanation relates to the language-specific reliability of acoustic cues in adult speech production and perception. The range for each acoustic cue in the stimuli series used in our study was representative of the range observed in Dutch tokens that were naturally produced. In other words, for the sound contrasts tested, cues other than spectral cues might simply be relatively unreliable cues in Dutch. As a result, if a child with a CI would rely too much on durational cues in categorizing sound contrasts that are more reliably differentiated by spectral cues, word recognition might suffer considerably (cf. Iverson, 2003). One way to examine this possibility would be to look at sound contrasts for which both cues are equally reliable or to use non-speech stimuli. In addition, step sizes on both cue dimensions would ideally represent equal psychophysical differences, something that we did not control for. It is possible that when categorizing such stimuli, children with a CI do

show different cue weighting than children with normal hearing and, for instance, rely more on temporal cues than spectral cues.

In sum, compared to age-matched children with normal hearing, the children with a CI appeared to use some acoustic cues less effectively in categorizing vowel and consonant contrasts. Overall, however, performance in the two groups was quite similar. Most importantly, cue weighting patterns did not differ significantly either. Despite relatively poor spectral resolution of sound processing with a CI, children with a CI are able to use spectral cues in speech perception, sometimes as effectively as their peers with normal hearing.

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 chapter²⁶, 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

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, Holowecky 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

tests, standardized vocabulary measures are of limited use in obtaining insight into lexical development by children with a CI because they mainly reflect their previous spoken language experience and do not directly assess their ability to learn novel words (Prezbindowski & Lederberg, 2003; Tomblin et al., 2007).

Houston, Ying, Pisoni and Kirk (2004) presented infants with two different speech sounds presented simultaneously with two different visual events. 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-Juhász 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).

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 (/a/-/a/ and /i/-/i/) or initial consonant (/t/-/s/ and /b/-/p/). 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 (Schaerlaekens, 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.

non-word pairs		familiar words		
orthographic forms	phonetic forms	orthographic forms	phonetic forms	English translation
kig - kieg	/kɪχ/ - /kiχ/	deur	/døʀ/	door
gik - giek	/χɪk/ - /χik/	hoed	/hut/	hat
tig - tieg	/tɪχ/ - /tiχ/	muur	/myʀ/	wall
kag - kaag	/kaχ/ - /kaχ/	weg	/wɛχ/	road
tag - taag	/taχ/ - /taχ/	vork	/vɔrk/	fork
tat - taat	/tat/ - /tat/	jurk	/jʏrk/	dress
buuk - puuk	/byk/ - /pyk/	touw	/tauw/	rope
beet - peet	/bet/ - /pet/	trui	/trœʏ/	sweater
beeg - peeg	/beχ/ - /peχ/			
suuk - fuuk	/syk/ - /fyk/			
soot - foot	/sot/ - /fot/			
seet - feet	/set/ - /fet/			

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.

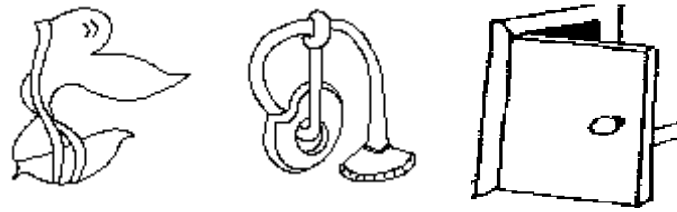


Figure 5.1. Example pictures from the picture-matching task of two novel objects labeled /tat/ and /tat/ (left and middle) and one familiar object /døR/ ‘door’ (right).

The experiment was divided into four blocks, corresponding to four stimulus sets of two novel words/objects (e.g., the novel minimal pair /tat/-/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 /tat/!*). 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 /tat/?*) 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 /tat/ 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 /tat/?* followed by pictures of /tat/ 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 /tat/?* followed by pictures of /tat/ 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 (/wɪʃ/ and /wɒt/) and a familiar word (/rɒk/, ‘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 the /lɪk/. The word /lɪk/ 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., /fɪk/ 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 /fɪk/, 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 /fɪk/. 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 (/zevən/) and 9 (/neχən/) 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 §5.3.4²⁷. 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) $\times$ 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 $\times$ 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).

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

Note. M=mean, SD=standard deviation

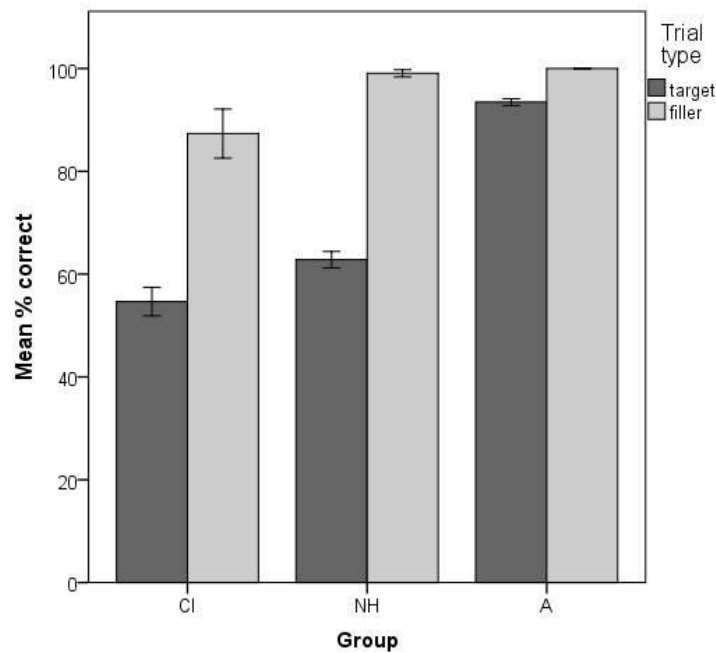


Figure 5.2. Mean percentage correct scores on the target and filler trials in the picture-matching task for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

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.

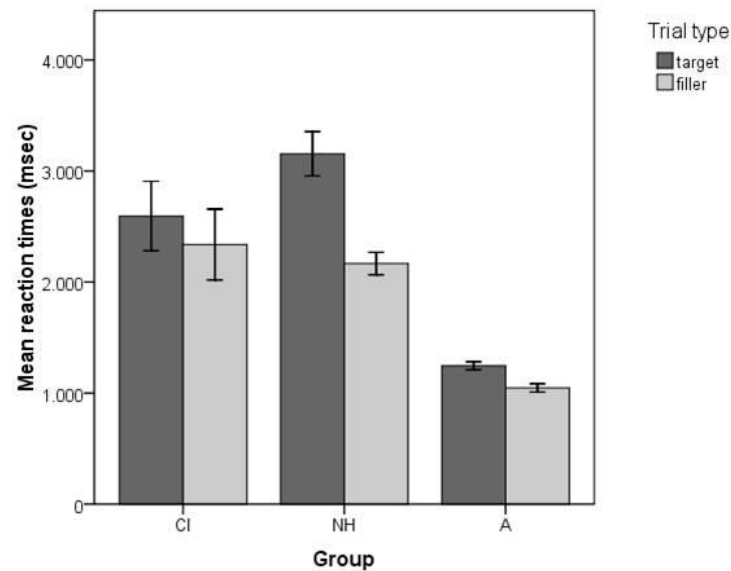


Figure 5.3. Mean reaction times on the target and filler trials in the picture-matching task for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

In 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) $\times$ 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 $\times$ 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.

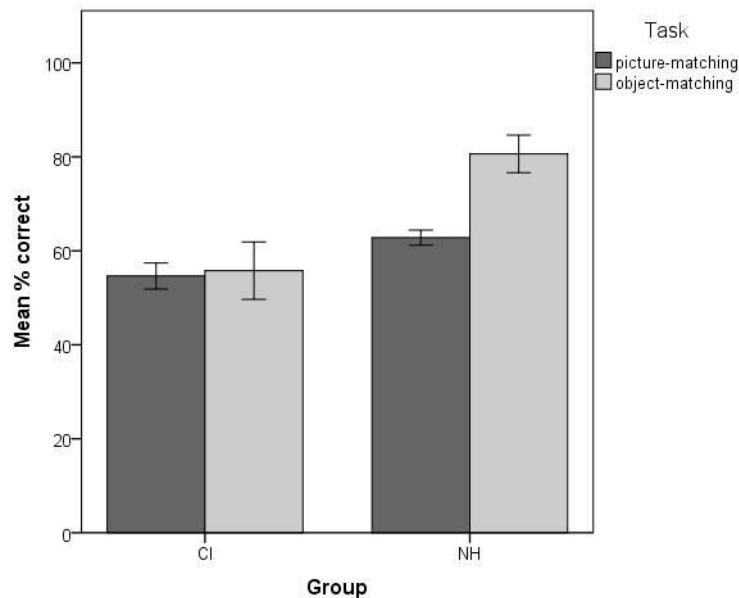


Figure 5.4. Mean percentage correct scores in the picture-matching task and the object-matching task for the children with a CI (CI) and the children with normal hearing (NH).

5.3.3 DIGIT SPAN

Data from the digit span task were available for 10 children with a CI²⁸, 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

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.

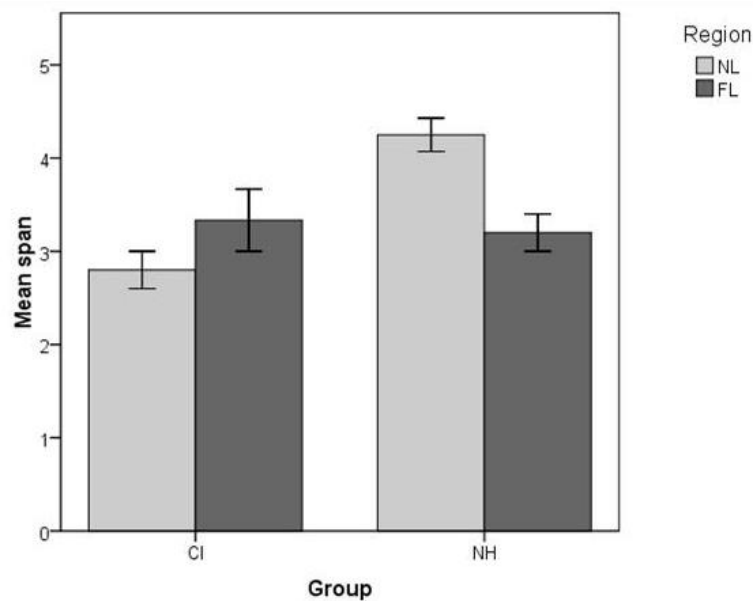


Figure 5.5. Mean digit spans for the children with a CI (CI) and the children with normal hearing (NH) split according to region (NL=Netherlands, FL=Flanders).

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 ($r=-.49$, $p<.05$).

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

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

* $p < .05$ ** $p < .01$

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.

	C-age	I-age	H-age	XAB		PICT		OBJ	
	mo	mo	mo	%	slope	%	msec	ratio	%
I-age	.34								
H-age	.45	-.69**							
% (XAB)	.62*	.17	.29						
slope (XAB)	.45	-.15	.40	.25					
% (PICT)	.41	-.10	.37	.14	-.02				
msec (PICT)	-.33	-.38	.14	-.11	.08	-.33			
ratio (PICT)	-.23	.01	-.25	.10	-.23	.12	-.05		
% (OBJ)	.12	.45	-.33	.01	.25	-.32	-.49	-.34	
span	.56	-.32	.79**	.11	.70*	.02	.14	-.05	.18

* $p < .05$ ** $p < .01$

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 Rispen 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 information²⁹.

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 ($t(17)=-2.73$, $p<.05$).

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)³⁰. 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

³⁰ 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.

6 THE RELATIONSHIP BETWEEN SIGN AND SPEECH PERCEPTION

Until now we have only considered the spoken modality in relation to language processing by children with a CI. The experiments and findings discussed in Chapters 4 and 5 provided answers to the first two research questions posed in this thesis (§2.1). In Chapter 4 we saw that children with a CI used acoustic cues in the categorization of sound contrasts largely in the same way as their peers with normal hearing, although they showed a tendency towards poorer overall discrimination of most contrasts. In Chapter 5 we saw that they had substantial difficulties learning novel minimal pairs in rapid word learning tasks. Whereas reduced task demands and better sound categorization were associated with rapid word scores for the children with normal hearing, we were unable to establish such relationships for the children with a CI.

Chapters 6 and 7 will address the two remaining research questions, namely those that concern language processing in the signed modality in relation to language processing in the spoken modality (§2.2). More specifically, in this chapter we will examine how sign perception abilities relate to speech perception abilities in the same children with a CI (§2.2.2). To that end, the two modalities were independently assessed and related to one another. In Chapter 7 the focus will be on the interaction between the two modalities in a sign-supported speech context (§2.2.3). More specifically, we will investigate whether bimodal (i.e., simultaneously spoken and signed) input hampers or facilitates speech perception in children with a CI.

In order to relate sign perception abilities to speech perception abilities, the perception tasks in both modalities needed to be as similar as possible. Thus, we designed sign perception tasks that maximally resembled the speech perception tasks discussed in Chapters 4 and 5. Following an introduction to previous research on the relationship between spoken and signed language development in children with a CI (§6.1), the research methodology in the sign perception study is discussed in §6.2. In §6.3 the results from the sign perception tasks are compared to those of the speech perception tasks presented in the two previous chapters. Correlations between the two language modalities are presented in §6.4. In §6.5 performance in both language modalities is examined in relation to the children's signing experience. The chapter ends with conclusions presented in §6.6.

6.1 BACKGROUND

As mentioned in §1.4.2, many children with a CI receive some form of signed input before and, at least for some time, after implantation. This signed input can take several forms such as an artificial sign system, a sign language, cued speech (i.e., manual cues that complement lip gestures) or combinations thereof such as in many Total Communication programs (Spencer & Tomblin, 2006). The role of signing in the education of deaf children has been and is still a question of debate and controversy with the debate impacting on educational programs available in different countries (Lynas, 2005; Marschark et al., 2005; Marschark & Spencer, 2006). Newborn hearing screening programs and cochlear implantation have had a profound impact on the deaf population, but the debate and controversy remain, perhaps even more strongly than before (Leigh, 2008). Although these developments have ensured early access to spoken language input for many deaf children, the diversity in reported outcomes makes it imperative that alternative educational approaches are available for deaf children and that these approaches match the needs of individual deaf children (Knoors, 2007; Leigh, 2008).

The crucial question in this debate is how signing affects spoken language development in deaf children, more specifically those with a CI. As discussed in §1.4.2, a large number of studies have addressed the question as to whether the communication modality used with the children affects spoken language outcomes, including speech production (e.g. Tobey, Geers, Brenner, Altuna, & Gabbert, 2003; Tobey, Rekart, Buckley, & Geers, 2004; Tobey et al., 2007), speech perception (e.g. Archbold et al., 2000; Bergeson et al., 2005; Geers et al., 2003a), vocabulary knowledge (e.g. Connor et al., 2000; El-Hakim et al., 2001; Kirk et al., 2003) and more general spoken language abilities (e.g. Geers et al., 2003b; Kirk et al., 2003; Svirsky et al., 2000). However, the findings in these studies have been contradictory and both advantages and disadvantages have been reported for children in Total Communication programs compared to children in Oral Communication settings (Geers, 2006). Recall that in the latter only spoken language is used, whereas in the former spoken language as well as some form of signed communication is used (§1.4.2). Furthermore, even if spoken language development might proceed somewhat more slowly in children with a CI that receive signed input as well, no strong evidence is available that signing prevents spoken language development in any way (Leigh, 2008)³¹. As rightly pointed out by Leigh, although the time and

³¹ The situation of children with a CI learning a spoken language and a sign language might resemble bilingual spoken language development in children with normal hearing, who also show delays in some linguistic domains (e.g. Bialystok, 2001, 2009; Genesee, Paradis, & Crago, 2004). However, this comparison should be applied with caution. In contrast to children with normal hearing, deaf children have limited access to both languages because of

effort invested in stimulating spoken language development is justified, it remains unknown how much exposure to spoken language is necessary for children with a CI to gain optimal benefit from their implant.

In contrast to spoken language outcomes, very few studies have examined sign language development in children with a CI (Knoors, 2006; Thoutenhoofd et al., 2005). Moreover, the few available studies are mainly limited to case descriptions of a few children (Cassandro et al., 2003; Coerts et al., 1994; Nordqvist & Nelfelt, 2004; Yoshinaga-Itano, 2006). The only exception is De Raeve et al. (2009; see also Wiefferink et al., 2008), who reported data from a longitudinal study on the influence of linguistic environment on language outcomes in a group of 22 children with a CI educated in either a spoken language (supported with signs) plus a sign language ($n=7$) or sign-supported speech only ($n=15$). In addition to the spoken modality, the children educated in sign-supported speech plus a sign language and a subset of the children educated in sign-supported speech only were also assessed in the signed modality. The authors concluded that speech perception, speech production and spoken language abilities developed more rapidly in the children without a sign language in their input. However, they noted that the children without a sign language had been diagnosed and implanted at an earlier age than the children with a sign language, and that this could also explain their findings. Spoken and signed language abilities were only directly compared in the children educated in sign-supported speech plus a sign language. The obtained measures included mean length of utterance, number of spoken and signed utterances, and number of words and signs used in spontaneous language samples. The number of words and spoken utterances as well as the number of signs and signed utterances increased in the course of the study, but slightly faster for the spoken modality. Initially mean length of utterance was longer in signed utterances than in spoken utterances, but by the end of the study it was the opposite.

Klatter-Folmer et al. (2006) followed six deaf children of deaf and hearing parents longitudinally over a period of three years from 3;5. They analyzed lexical richness, syntactic complexity, language dominance and interactional participation in semi-structured conversations. Three children received a CI in the course of the study. The authors concluded that the development in both language modalities was intertwined in these children and that signing did not have a negative effect on their spoken language development (cf. Coerts et al., 1994). In fact, syntactic complexity was highest for mixed utterances, i.e., utterances with both speech and signs.

This latter finding raises an interesting question, namely whether using speech and signs simultaneously might have an additive advantage to using either of them separately. Being bilingual in a spoken language and a sign language, i.e., bimodal

their hearing difficulties and because most of them have hearing parents and receive non-native signed input (see §2.2.1).

bilingualism, offers a unique opportunity to produce two languages at the same time, which is physically impossible for bilinguals in two spoken languages, i.e., unimodal bilinguals. Simultaneous production of words and signs is called code-blending and occurs quite frequently in conversations among bimodal bilinguals (Bishop, 2006a; Emmorey, Borinstein, Thompson, & Gollan, 2008), sometimes even in conversations between bimodal bilinguals and non-signers (Casey & Emmorey, 2009). Hearing children from deaf parents have also been found to frequently produce code-blended utterances, more so than deaf children from deaf parents (Baker & Van den Bogaerde, 2008; Van den Bogaerde & Baker, 2005, 2008). The study of bimodal bilingualism and possible implications for children with a CI will be further considered in Chapter 7, which will examine bimodal perception in children with a CI.

Here, we will focus on how sign and speech perception interrelate in children with a CI. Speech perception in this population has been discussed in detail in §2.1, but practically nothing is known about their sign perception. In fact, very few studies have examined sign perception in deaf children (e.g. Ormel et al., 2009). In addition, two studies investigated sign perception by hearing non-signing infants (Baker, Golinkoff, & Petitto, 2006; Krentz & Corina, 2008). Lederberg and colleagues have investigated rapid word and sign learning in deaf children with acoustic hearing aids or CIs, but did not explicitly distinguish between both language modalities (Lederberg & Spencer, 2009; Lederberg et al., 2000).

The rationale behind the comparison between sign and speech perception abilities in the present chapter is as follows. If signing experience had a direct negative impact on spoken language outcomes in children with a CI, relatively high sign perception abilities would result in relatively low speech perception abilities and vice versa. For such a direct comparison, it is imperative that the tasks in both modalities measure the same underlying constructs and are as similar as possible. As already described in §2.2, studies with deaf signing adults have shown that many processes involved in speech and sign perception are comparable, including pre-lexical perception, lexical processing and phonological storage (for a review, see Emmorey, 2007). To further facilitate the comparison between the two modalities, we designed a sign categorization task, two rapid sign learning tasks and a phonological short-term memory task for signs that maximally resembled the auditory counterparts described in Chapters 4 and 5. Similar to the speech perception tasks, the same phonetic contrasts, namely a hand configuration and a location contrast, were tested in the sign categorization and the rapid sign learning tasks.

Performance on the speech and sign perception tasks will be compared for children with a CI, age-matched children with normal hearing with no signing experience and young adult second language learners of Sign Language of the Netherlands (NGT, *Nederlandse Gebarentaal*). This first analysis will show the

relative performance levels in both modalities across groups. In addition, correlation analyses between both modalities will be performed for the children with a CI. Finally, a comparison of two subgroups of the children with a CI, divided according to their signing experience, will be presented.

6.2 METHODOLOGY

6.2.1 PARTICIPANTS

Participants were 15 children with a CI (mean age: 5;8), 10 children with normal hearing with no signing experience (mean age: 6;0) and 11 young adult second language learners of NGT with 1-2 years of signing experience (mean age: 21;7). The children with normal hearing and the adults were subsets of those reported for the speech perception experiments in Chapters 4 and 5 (see also §3.1).

6.2.2 MATERIALS

6.2.2.1 SIGN CATEGORIZATION

To measure pre-lexical sign perception, a sign categorization task was designed using E-Prime® v2.0 software (Psychology Software Tools, Pittsburgh PA). Similar to the sound categorization task discussed in §4.2.3, the task was designed according to an XAB format. Two phonetic contrasts were included in the task: a hand configuration and a location contrast. The stimuli were still images that represented a continuum between two endpoint hand configurations or locations in signing space. These stimuli had previously been used by Emmorey et al. (2003) and permission was obtained from the first author to use their stimuli. The stimuli series had been created with 3-D animation software (Poser from MetaCreations) by linear interpolation from the two endpoints in ten steps, resulting in 11 stimuli for each contrast (for details, see Emmorey et al., 2003). The stimuli series for the hand configuration and location contrasts are shown in Figure 6.1 and 6.2, respectively and will further be referred to as */open/-/closed/* (hand configuration) and */eye/-/chin/* (location). The stimuli were projected directly above animation monkey pictures, associated with X, A and B. An example of what a categorization trial looked like is provided in Figure 6.3. We chose to use the animation monkey pictures to increase similarity to the sound categorization task. If we had directly asked the participants to choose between the two endpoint stimuli images (the

stimuli associated with A and B in Figure 6.3), the endpoint stimuli would have been perceptually available to participants when they had to indicate their choice for A or B, which was not the case in the sound categorization task.



Figure 6.1. Stimuli series for the hand configuration contrast representing a gradual change from an open flat hand (referred to in the text as *open*) to a closed fist (referred to in the text as *closed*).



Figure 6.2. Stimuli series of for the location contrast representing a gradual change from a location near the eye (referred to in the text as *eye*) to a location near the chin (referred to in the text as *chin*).

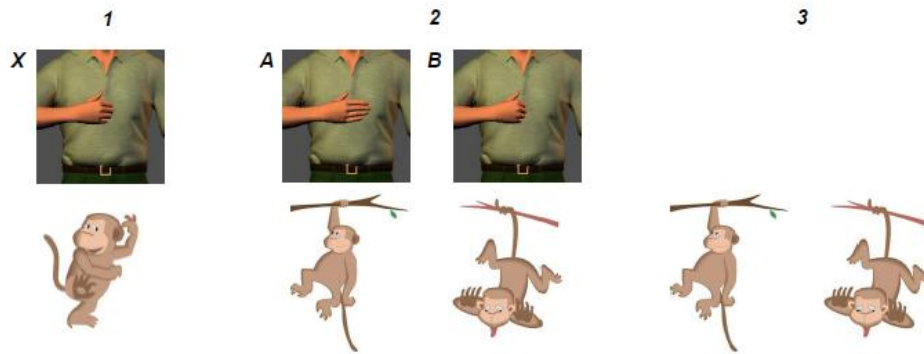


Figure 6.3. Example of a trial in the sign categorization task. Presentation of stimulus X (1) was followed by presentation of stimuli A and B (2). X, A, and B were presented together with animation monkey pictures. In their response, participants had to choose between the two animation monkey pictures associated with the A and B stimulus (3).

Inter-stimulus and inter-trial intervals were the same as in the sound categorization task, as was randomization of stimuli presentation. Children performed on one contrast only in order to reduce the length of testing (cf. §4.2.3), while adults performed on both contrasts and had a brief pause between contrasts. Presentation of contrasts was counterbalanced across viewers. Prior to the test session, children completed a practice session consisting of four trials using the contrast they were not tested on. For adults, the practice session consisted by necessity of trials from a contrast they were also tested on. The task took between 5 and 10 minutes for children and 10 and 15 minutes for adults. Participants were told that two monkeys would try to imitate the signs of a third monkey and that they had to decide which of the two succeeded best. Data analysis proceeded in the same way as for the sound categorization task reported in §4.2.4. However, given that a single visual cue was manipulated in both phonetic contrasts, the dependent variables were only phoneme endpoint identification (§4.2.4.1) and classification slope (§4.2.4.2).

6.2.2.2 PICTURE-MATCHING

E-Prime[®] v2.0 software (Psychology Software Tools, Pittsburgh PA) was used to create a non/-sign picture-matching task similar in design to the non-word picture matching task discussed in §5.2.2.1. Instead of auditory stimuli, video stimuli were presented, consisting of a target sign (either a non-sign or a familiar sign) embedded in a carrier phrase: ‘KUK, X!’ (*LOOK, X!*) during familiarization, and ‘WAAR X?’

(*WHERE X?*) during testing³². The video stimuli were recorded against a blue-grey background to optimize visibility of the signs. Because the experimenter, a second language learner of NGT, administered the signed object-matching task (§6.2.2.3), he also signed the stimuli for the picture-matching task. The recorded stimuli were captured, digitized and compressed to WMV format (440 kbps, 25 fps, 360x280 pixels) using Pinnacle® Studio 11. They averaged about 3000 milliseconds in duration.

Minimal non-sign pairs were created by the experimenter and non-sign status was checked by native signers of NGT and Flemish Sign Language (VGT, *Vlaamse Gebarentaal*). The non-signs included both one-handed and two-handed signs. The minimal non-sign pairs were distinguished by hand configuration (*/open/-closed/*) or location (*/eye/-chin/*), as in the sign categorization task. In total, six non-sign pairs were formed; three pairs for each phonological contrast (illustrated in Appendix D). One pair for each contrast was presented in the picture-matching task, the other two in the object-matching task (see §6.2.2.3). In addition, two familiar signs that were the same for NGT and VGT were selected as filler stimuli from NGT teaching material for young deaf children because ratings of signs for age of acquisition are not available for NGT or VGT (RIEM, ‘belt’ and SCHAAR, ‘scissors’). Finally, drawings of novel and familiar objects were selected from the same databases as for the non-word picture-matching task (§5.2.2.1).

The experiment was divided into two blocks, corresponding to two stimulus sets of one minimal non-sign pair and one familiar sign. Familiarization and testing phase were as in the non-word picture-matching task, i.e., nine familiarization trials followed by ten two-alternative forced choice identification trials including two incongruent trials. In the familiarization trials and the testing trials, the novel objects were presented 25% upwards from the center of the screen and the video stimuli 25% downwards.

The task took children approximately ten minutes and adults five minutes. They were told that they would be presented with novel and familiar signs together with pictures of novel and familiar objects, and that they had to remember which sign was associated to which object. Presentation of the two 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 motivate the children. The task was preceded by a practice block with two phonologically dissimilar non-signs (see Appendix D) and a familiar sign.

Accuracy and reaction times were automatically recorded within the program. Accuracy was defined as the number of trials correctly answered (maximum score was 2 blocks x 8 trials = 16). Reaction times were measured from the offset of the

³² The common practice of representing glosses of signs in small capitals is followed here (Baker, Van den Bogaerde, & Woll, 2005a).

video stimulus to the overt response, i.e., the key press. As in the non-word picture matching task, reaction times were analyzed separately for the trials with two novel objects, the congruent filler trials and the incongruent filler trials. Furthermore, only trials correctly answered were analyzed and 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 4.0% of the trials for the children with a CI, 1.4% for the children with normal hearing and 2.9% for the adults. The difference in reaction times for the congruent and incongruent filler trials was used as an index of sensitivity to a switch in sign-object mappings.

6.2.2.3 OBJECT-MATCHING

The object-matching task discussed in §5.2.2.2 was also administered in a sign condition (see §3.1). Similar to the speech condition, it consisted of three subtests: a novel sign learning test, a generalization test and a rapid sign learning test. The only difference with the speech condition was that minimal non-sign pairs and familiar signs were presented together with novel and familiar objects.

In the rapid sign learning test, the objects were placed in random order on the table in front of the child and were labeled once from left to right with the phrase 'KIJK, X!' (*LOOK, X!*), accompanied by pointing to the objects. The three objects were then labeled again from left to right, accompanied by pointing. As in the speech condition, familiarization was followed by three test trials in which the children were asked to point to one of the three objects in response to the question 'WAAR X?' (*WHERE X?*). The same procedure as for the speech condition was adopted here, i.e., the experimenter asked for both novel objects or for a single novel object twice. The non-signs originated from the set of non-signs mentioned above (§6.2.2.2). In addition, two familiar signs that were the same for NGT and VGT were selected as filler stimuli from NGT teaching material for young deaf children (PET 'cap' and BRIL 'glasses'). Similar to the speech condition, uncommonly and frequently used objects such as different types of kitchen utensils were used as novel objects and familiar objects, respectively.

Two blocks, corresponding to two stimulus sets, were administered in a fixed order (hand configuration contrast followed by location contrast). The task took approximately five minutes. The children were told that they would be presented with novel and familiar signs together with novel and familiar objects, and that they had to remember which sign belonged to which object. The number of trials in which a child correctly associated the non-sign with the correct novel object was used as the dependent variable in the analysis. Presentation of the non-sign pairs for each contrast in the two rapid sign learning tasks was counterbalanced across participants such that subsets of participants were presented with different non-sign

pairs in the same task, but they were never presented with the same non-sign pair twice across tasks.

Importantly, this task was also administered to the children with a CI in a speech plus sign (i.e., bimodal) condition. The bimodal condition was included as a preliminary investigation of the effects of bimodal input as compared to spoken or signed input alone, a topic that will be addressed in more detail in Chapter 7. Familiarization and testing phases were presented simultaneously in speech and sign to the child. Four stimulus sets were created by arbitrarily pairing a non-word pair with a non-sign pair³³. These had not yet been presented to the child in the speech or sign condition. The four stimulus sets, corresponding to four blocks, were administered in the following order for all participants: /a/-/a/ + /open/-/closed/ → /b/-/p/ + /eye/-/chin/ → /t/-/i/ + /open/-/closed/ → /t/-/s/ + /eye/-/chin/. The task took approximately ten minutes to complete. Children were told that, this time, they would be presented with novel and familiar words and signs at the same time and that they had to remember which words and signs belonged to which object. Scoring proceeded in the same way as for the other conditions.

6.2.2.4 DIGIT SPAN

A signed digit span was created in the same way as the auditory digit span task discussed in §5.2.2.3. It consisted of 15 sequences of five different lengths (i.e., three sequences for each length), ranging from two to six digits. As in the auditory digit span task, inter-stimulus interval was set at 2000 milliseconds. To allow comparison with the spoken version the digits 7 and 9 were also excluded. The video stimuli for the digit span task were signed by the experimenter using the same recording equipment and background as for the non-sign picture matching task (§6.2.2.2). The digits were produced in neutral signing space and only the torso of the signer was visible in the recordings. The signer's hands returned to rest position (off screen) between subsequent digits. Presentation and scoring was equal to the spoken version, including the presentation of a two-digit practice sequence at the beginning. The task took approximately five minutes for children and adults. They were told that they would see sequences of signed digits that they had to memorize and then recall in the same order as they were presented.

³³ Most stimuli presented in the bimodal condition originated from the larger set of (non-)words and (non-)signs referred to in §5.2.2.1 and §6.2.2.2, respectively. However, because only two phonetic contrasts were included in the rapid sign learning tasks, as opposed to four in the rapid word learning tasks, two additional non-sign pairs were created and presented in this condition. These non-sign pairs contrasted minimally in the same hand configuration or location as the larger set of non-sign pairs and are also included in Appendix D). Non-sign status was checked by native NGT and VGT signers.

Importantly, it has been observed that digit spans differ across languages due to cross-linguistic differences in the number of syllables in words for digits (e.g. Olazaran, Jacobs, & Stern, 1996). Such cross-linguistic differences are not relevant here, however, because the digits included were monosyllabic in both language modalities (but see Bavelier et al., 2006; Boutla et al., 2004; Emmorey & Wilson, 2005; Wilson & Emmorey, 2006 and also §2.2.2 for discussion on possible cross-modality differences in digit spans).

6.2.3 STATISTICAL ANALYSIS

The non-parametric Wilcoxon Signed Rank test was used to compare performance on the sound and sign categorization tasks. The parametric repeated measures ANOVA was used to compare performance in the two modalities on the other tasks. Independent and paired samples *t*-tests were used for post hoc comparisons, where 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 ($\alpha/n=.05/3=.02$). Only participants that completed a task in both modalities were included in the analyses. As in Chapter 5, 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.

The results are discussed in three sections. First, we compare relative performance in both language modalities across groups (§6.3.1). Next, we present the correlation analyses (§6.3.2). Finally, we compare results from two subgroups of children with a CI formed on the basis of their signing experience (§6.3.3). Individual results for the children with a CI are provided in Appendix C.

6.3 RELATIVE PERFORMANCE IN BOTH LANGUAGE MODALITIES

The analyses were based on different numbers of participants for each task due to missing data. These numbers are mentioned when discussing the results for a particular task. One child with a CI (J8 in Table 3.1) was excluded from all analyses because he failed to complete any of the four tasks. He had also been excluded from the analyses presented in Chapters 4 and 5 because of inattentiveness during testing. In this section, results for sign and sound categorization are presented first (§6.3.1), followed by rapid sign and word learning (§6.3.2 and §6.3.3) and phonological short-term memory (§6.3.4).

6.3.1 SIGN AND SOUND CATEGORIZATION

Data from both the sound and sign categorization tasks were available from 9 children with a CI, 10 children with normal hearing and 11 adults. Figure 6.4 illustrates the mean phoneme endpoint identification scores in both language modalities for all three groups. Because of small sample sizes, phoneme identification scores were averaged across phonetic contrasts in the statistical analysis. Separate Wilcoxon Signed Rank Tests revealed no significant difference between the two language modalities for the children with a CI ($Z=-.850$, $p=.40$), significantly higher scores in the spoken modality for the children with normal hearing ($Z=-2.38$, $p<.05$), and significantly higher scores in the signed modality for the adults ($Z=-3.04$, $p<.01$). Higher endpoint identification scores in the signed modality for the adults, who had only limited signing experience, were unexpected. However, it should be noted that they performed near-ceiling on this measure in both language modalities. We will therefore not further interpret this modality effect.

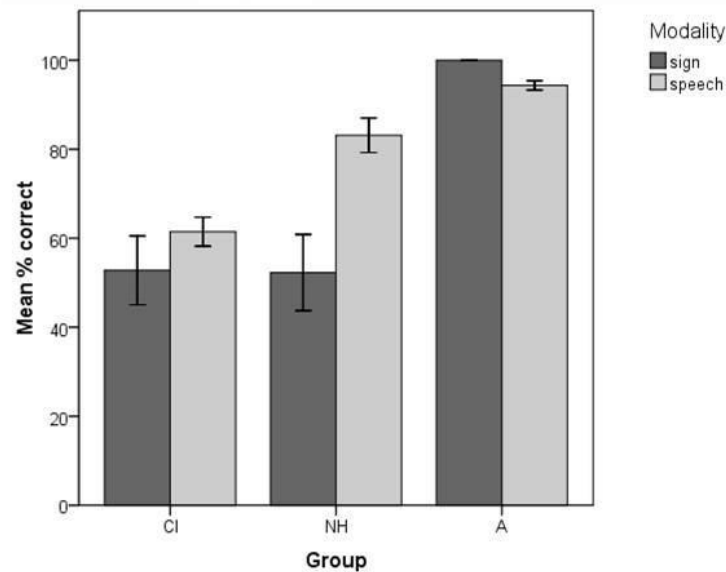


Figure 6.4. Mean phoneme endpoint identification scores in both language modalities for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

Separate Wilcoxon Signed Rank Tests were also performed on the classification slopes for both language modalities across contrasts. Significantly steeper classification slopes were observed in the spoken modality for all three groups

(children with a CI: $Z=-2.67$, $p<.01$; children with normal hearing: $Z=-2.67$, $p<.01$; adults: $Z=-2.85$, $p<.01$). Classification slopes for the hand configuration contrast and the location contrast for the three groups of participants are illustrated in Figures 6.5 and 6.6.

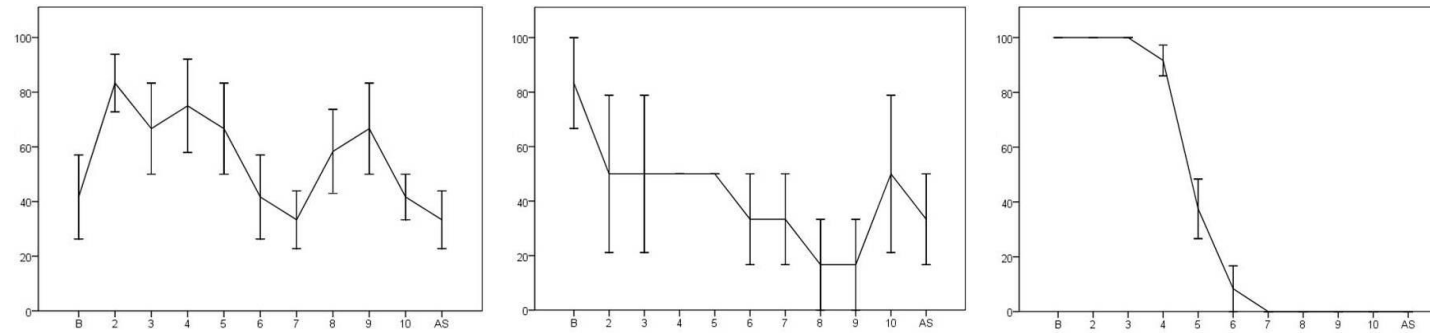


Figure 6.5. Classification slopes for the hand configuration contrast for the children with a CI (left panel), the children with normal hearing (middle panel) and the adults (right panel). Stimulus number is presented on the horizontal axis. % /open/ responses are presented on the vertical axis.

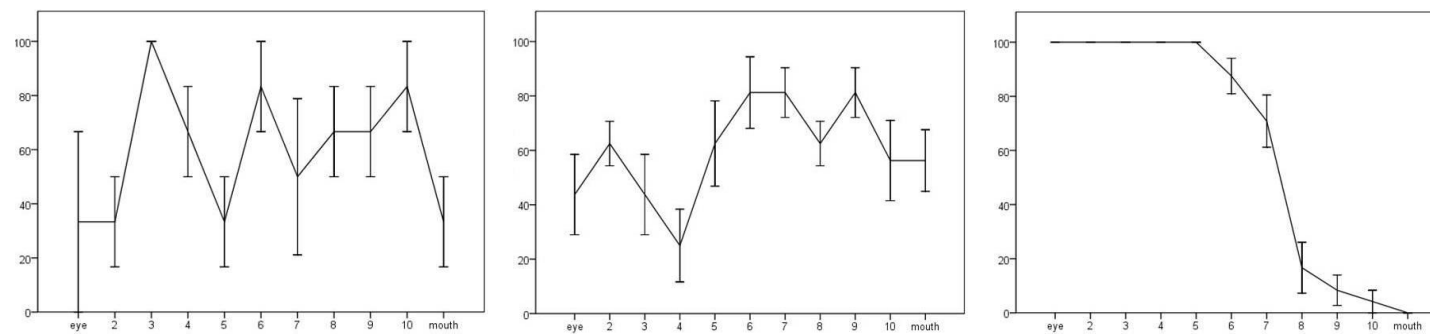


Figure 6.6. Classification slopes for the location contrast for the children with a CI (left panel), the children with normal hearing (middle panel) and the adults (right panel). Stimulus number is presented on the horizontal axis. % /eye/ responses are presented on the vertical axis.

The results from the sign categorization task show that the adult second language learners of NGT had no difficulty identifying the phoneme endpoints and had relatively steep classification slopes. By contrast, mean phoneme endpoint identification scores for both child groups generally did not exceed chance-level (50%). Furthermore, as Figure 6.5 and 6.6 illustrate, there is no evidence that the children discriminated the phonetic contrasts. The sigmoidal function (S-curve) that is typically observed in categorization tasks and is clearly visible in the figures for the adults, is absent in the figures for the children. One possible explanation for the difficulties experienced by the children is that they had insufficient signing experience to do the task. Recall that the children with normal hearing had no signing experience at all. The children with a CI did have signing experience, but the extent and nature of signing experience varied substantially between them (see §3.1.1). Perhaps their signing experience was insufficient to consistently discriminate these phonetic contrasts. This explanation is somewhat unlikely, however, because the adult second language learners of NGT also had limited signing experience, but clearly did discriminate the contrasts. In addition, as we will see below, many of the children with a CI were able to learn novel minimal pairs that differed in these contrasts. Moreover, previous studies have shown that adults with no signing experience could discriminate similar contrasts (Baker et al., 2005b; Best et al., 2010; Emmorey et al., 2003).

Alternatively, the task might have been too complex for the children. As explained in §6.2.1, we had tried to make the sign categorization task as similar to the sound categorization task as possible. However, our efforts to make the two tasks comparable might have increased cognitive demands. Particularly, the combined use of stills of signs and animation monkey pictures might have confused the children because they had to make a categorization decision on one type of visual stimuli (i.e., the stills), while they had to give a response using the other type of visual stimuli (i.e., the monkey pictures).

In order to disentangle these two alternative explanations, we administered the sign categorization task to four deaf children without a CI (5-6 years of age) who were acquiring NGT from birth, and four hearing adults with no signing experience. If the reason for the difficulties that the children in our study experienced were insufficient signing experience, then children acquiring NGT from birth should not have as much difficulty with the task, whereas adults with no signing experience should have great difficulty. If task complexity were the reason, the deaf children without a CI should also perform poorly, whereas the hearing adults might show less difficulty with the task. A third alternative is that both explanations are correct, in which case both deaf children and hearing adults would show difficulty.

The outcomes clearly supported the second explanation. Similar to the children with a CI, phoneme endpoint identification scores of the deaf children without a CI

did not exceed chance-level and they had shallow classification slopes. By contrast, identification scores of the adult non-signers were at ceiling-level and they had classification slopes in between those of the children and the adult second language learners. The poor performance by the children with a CI therefore appears to be due to the complexity of the task and not to insufficient signing experience. Moreover, the results from the adult non-signers confirm findings from previous studies that, in addition to a linguistic basis, at least some phonological contrasts in sign languages have also a perceptual basis that is common to signers and non-signers (Baker et al., 2005b; Best et al., 2010; Emmorey et al., 2003).

6.3.2 PICTURE-MATCHING

Data from the picture-matching tasks in both language modalities were available from 13 children with a CI, 9 children with normal hearing and 10 adults. Figure 6.7 shows the mean overall percentage correct scores in both language modalities across contrasts for the three groups of participants. A 3 (Group) x 2 (Modality) x 2 (Trial type) repeated measures ANOVA with Group as a between-subjects variable and Modality and Trial type as within-subjects variable revealed a main effect of Group ($F(2,29)=14.34$, $p<.01$), Modality ($F(1,29)=5.20$, $p<.05$) and Trial type ($F(1,29)=86.74$, $p<.01$). Importantly, these main effects were qualified by a Group x Modality interaction ($F(2,29)=7.82$, $p<.01$) and a Group x Trial type interaction ($F(2,29)=4.67$, $p<.05$).

Paired samples *t*-tests were performed to further interpret the two significant interactions. Scores were significantly higher in the spoken modality than the signed modality for the children with normal hearing ($t(8)=-4.32$, $p<.01$) and the adults ($t(9)=-2.76$, $p<.05$), but not for the children with a CI ($t(12)=1.27$, $p=.23$). Furthermore, the adults obtained significantly higher scores on target trials than the children (children with a CI: $t(18)=-10.34$, $p<.01$; children with normal hearing: $t(17)=-7.91$, $p<.01$), who did not differ significantly from one another ($t(20)=.38$, $p=.71$). No significant differences between the three groups of participants were observed for scores on filler trials.

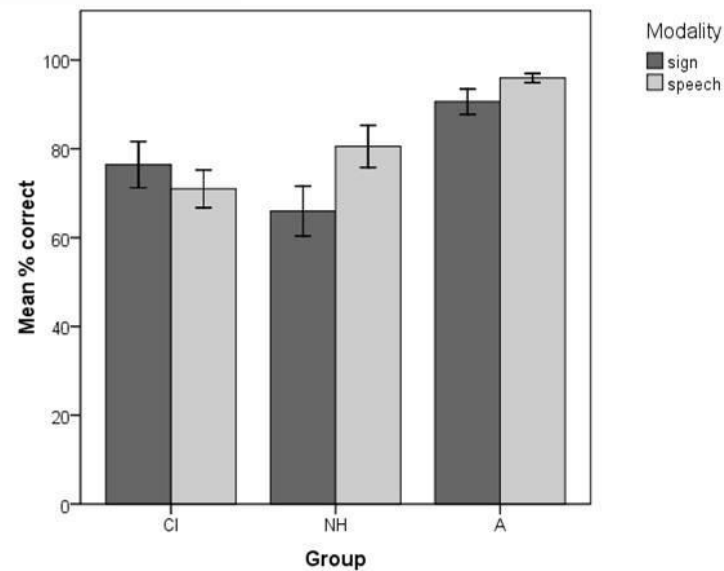


Figure 6.7. Mean percentage correct scores in the picture matching tasks in both language modalities for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

In the analysis of overall reaction times the incongruent trials were excluded and will be discussed separately below. Figure 6.8 shows the mean reaction times across contrasts for the three groups of participants. A 3 (Group) x 2 (Modality) x 2 (Trial type) repeated measures ANOVA with Group as a between-subjects variable and Modality and Trial type as within-subjects variable revealed a main effect of Group ($F(2,29)=10.17, p<.01$) and Trial type ($F(2,29)=17.75, p<.01$). Independent samples t -tests showed that the adults responded significantly faster than the children (children with a CI: $t(12)=3.87, p<.01$; children with normal hearing: $t(24)=12.86, p<.01$). The reaction times for the two child groups did not differ significantly ($t(33)=.90, p=.37$). Furthermore, across groups responses were faster on filler than target trials ($t(31)=4.21, p<.01$).

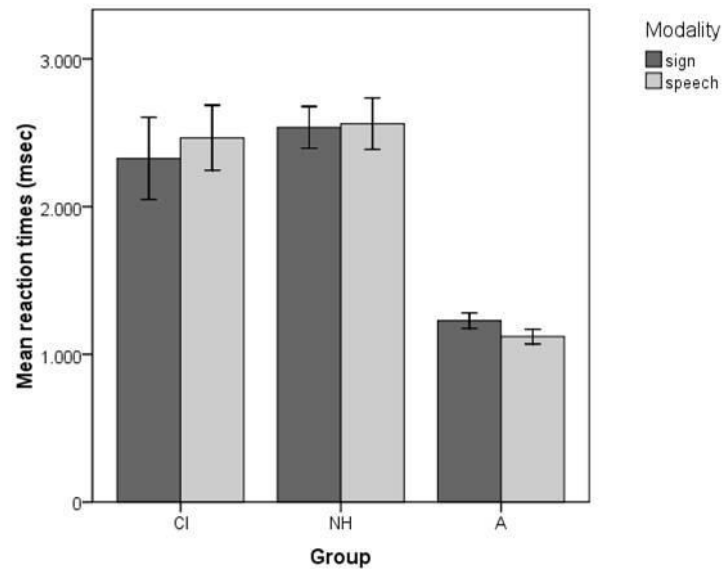


Figure 6.8. Mean reaction times in the picture matching tasks in both language modalities for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

Finally, sensitivity to a switch in word- or sign-object mappings was compared between the two language modalities for each group of participants. Recall that 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. A 3 (Group) $\times$ 2 (Modality) repeated measures ANOVA with Group as between-subjects variable and Modality as within-subjects variable only revealed a main effect of Group ($F(2,29)=5.90$, $p<.01$). Independent samples t -tests indicated that the adults learners were more sensitive in their reaction times to a switch in word- or sign-object mappings than the children (children with a CI: $t(21)=-2.79$, $p<.05$; children with normal hearing: $t(17)=-4.36$, $p<.01$), who did not differ significantly from each other ($t(20)=-1.57$, $p=.13$). Separate one-sample t -tests on the difference ratios in the signed modality for each group of participants showed that the difference ratio was significantly higher than 0.5 for the adults (.59, $t(9)=6.29$, $p<.01$), but not for the children with a CI (.56, $t(9)=1.33$, $p=.22$) and the children with normal hearing (.50, $t(6)=.53$, $p=.61$). In other words, only the adults showed clear sensitivity to a switch in sign-object mappings.

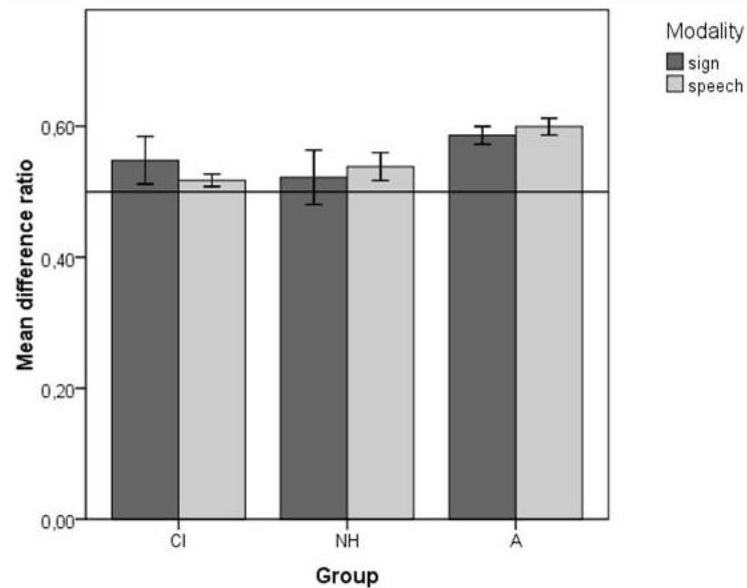


Figure 6.9. Mean difference ratios in the picture-matching tasks in both language modalities for the children with a CI (CI), the children with normal hearing (NH) and the adults (A). The horizontal reference line indicates the 0.5 cut-off point for sensitivity to the switch in sign-object mappings (< 0.5 = insensitive; > 0.5 = sensitive).

6.3.3 OBJECT-MATCHING

Data from the object-matching task in the speech and sign conditions were available from 11 children with a CI and 10 children with normal hearing. Figure 6.10 shows the mean percentage correct scores in both language modalities across phonetic contrasts for the children with a CI and the children with normal hearing. A 2 (Group) $\times$ 2 (Modality) repeated measures ANOVA with Group as a between-subjects variable and Modality as a within-subjects variable only revealed a significant Group $\times$ Modality interaction ($F(1,19)=7.35$, $p<.05$). Paired samples t -tests showed that scores in the speech condition were significantly higher than scores in the sign condition for the children with normal hearing ($t(8)=3.02$, $p<.05$), but not for the children with a CI ($t(10)=-.75$, $p=.47$).

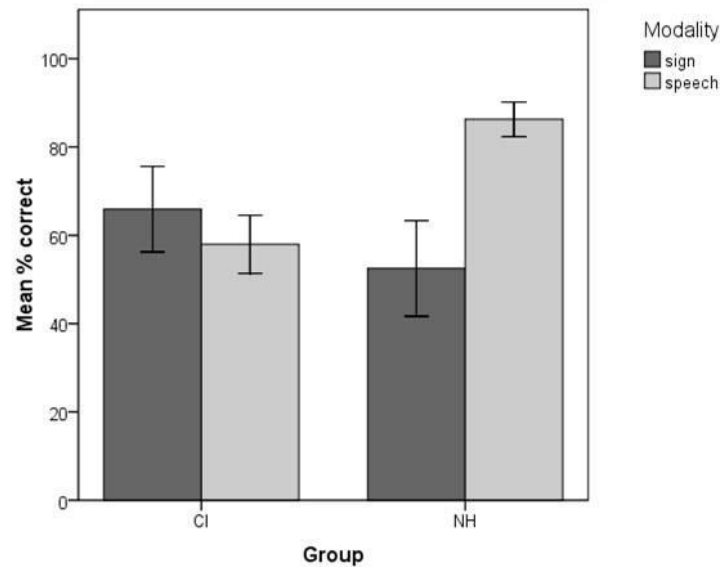


Figure 6.10. Mean percentage correct scores in the speech and sign conditions of the object-matching task for the children with a CI (CI) and the children with normal hearing (NH).

Figure 6.11 illustrates the mean percentage correct scores in the three conditions (i.e., speech, sign and bimodal) in the object-matching task for the children with a CI. A one-way repeated measures ANOVA revealed no significant differences between the three conditions ($F(2,20)=.30$, $p=.75$). That is, in this preliminary investigation we were unable to find either positive or negative effects of bimodal input on lexical learning. However, it should be noted that both familiarization and testing were in speech and sign in the bimodal condition (§6.2.2.3) and the children therefore could have used either modality to learn the labels for the novel objects in this condition. The children may have predominantly attended to the words during familiarization, to the signs or to both. Therefore, the results tell us little about the effects of bimodal input on language processing in the spoken modality specifically. We will address this limitation in Chapter 7 that investigates in more detail the effects of bimodal input on speech perception.

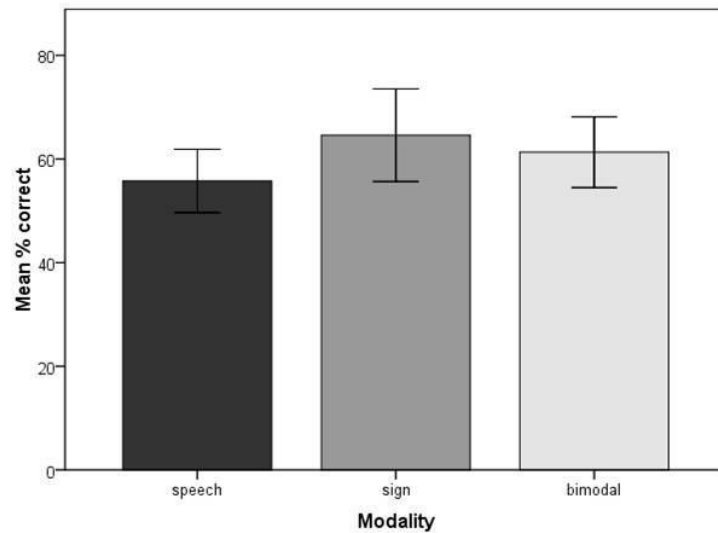


Figure 6.11. Mean percentage correct scores in the speech, sign and bimodal conditions of the object-matching task for the children with a CI.

6.3.4 DIGIT SPAN

Data from the digit span tasks in both language modalities were available for 9 children with a CI, 10 children with normal hearing and 9 adults. Figure 6.12 shows the mean digit span in both modalities for the three groups. A 2 (Group) x 2 (Modality) repeated measures ANOVA revealed a main effect of Group ($F(2,28)=127.64$, $p<.01$) and Modality ($F(1,25)=30.44$, $p<.01$), as well as a significant Group x Modality interaction ($F(1,25)=17.93$, $p<.01$). paired samples t -tests showed that digit spans were significantly greater in the spoken than in the signed modality for the children with normal hearing ($t(9)=8.14$, $p<.01$), but not for the children with a CI ($t(8)=1.64$, $p=.14$) or the adults ($t(8)=-1.00$, $p=.35$).

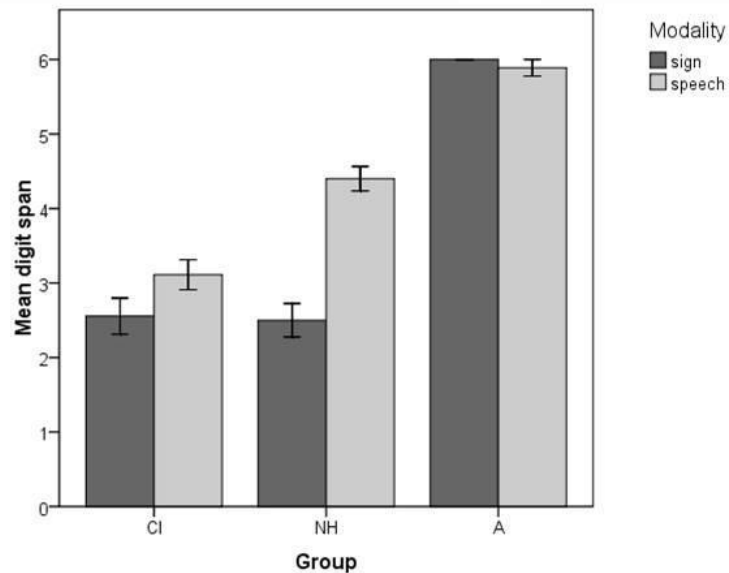


Figure 6.12. Mean digit spans in both language modalities for the children with a CI (CI), the children with normal hearing (NH) and the adults (A).

6.3.5 SUMMARY

The analyses in this section show that performance in the signed modality did not differ from performance in the spoken modality for the children with a CI on the picture-matching, object-matching and digit span tasks, whereas as expected the children with normal hearing and the adults mostly performed better in the spoken modality. The children with a CI performed more poorly in the signed than the spoken modality on the categorization task as measured by classification slopes (no modality effect was found for phoneme endpoint identification). However, as already discussed in §6.3.1, this could very well have been due to the higher cognitive demands of the sign categorization task compared to the sound categorization task.

This first analysis of the relationship between the two language modalities in children with a CI thus shows that speech and sign perception abilities of children with a CI tend to be at the same level. However, as judged from the greater error bars for the signed compared to the spoken modality in Figures 6.4-6.12, inter-individual variation in performance on the tasks in the signed modality was relatively large (see also Appendix C). In the next section, we will examine whether this observed inter-individual variation in sign perception abilities is associated with variation in performance in the spoken modality.

6.4 CORRELATIONS BETWEEN LANGUAGE MODALITIES

To further examine the relationship between speech perception abilities and sign perception abilities among the children with a CI, a correlation analysis was performed between outcome measures in the two modalities: between sound and sign categorization, between rapid word and sign learning, and between phonological short-term memory for spoken and signed digits. The outcome measures included in the correlation analyses were phoneme endpoint identification and classification slope for sign categorization; scores, reaction times and difference ratio for picture-matching; scores for object-matching; and digit span for phonological short-term memory. In addition, chronological age, length of CI use, and age at implantation were included as variables in the correlation analysis to determine their effects on performance in the signed modality³⁴.

This analysis revealed significant correlations between phoneme endpoint identification scores in the sound categorization task and classification slopes in the sign categorization task ($r=.71$, $p<.05$), reaction times in the non-word and picture-matching tasks ($r=.82$, $p<.01$), and scores in the non-word and non-sign picture-matching tasks ($r=.67$, $p<.05$). In addition, chronological age and length of CI use both correlated significantly with scores in the non-sign picture matching task (chronological age: $r=.70$, $p<.01$; length of CI use: $r=.67$, $p<.05$). These age effects might have resulted from an increase in signing experience through the years after implantation for the children who continue to receive signed input.

This correlation analysis shows that in contrast to what would be expected if signing experience had a direct negative effect on speech perception abilities, both language modalities correlated positively with each other. That is, children that had higher phoneme endpoint identification scores in the sound categorization task, showed relatively better discrimination of the signed phonetic contrasts. In addition, the children who obtained higher scores and responded faster in the non-word picture matching task were the same children who obtained higher scores and responded faster in the non-sign picture-matching task. It is important to note that these positive correlations between the two language modalities do not imply a causal relationship between the abilities involved. That is, it is not the case that good sign perception abilities cause good speech perception abilities or vice versa. Rather, the relevant message here is that relatively good sign perception abilities do not exclude relatively good speech perception abilities.

³⁴ Correlations of these factors with performance in the spoken modality were discussed in §5.3.4 (see Table 5.4).

6.5 THE ROLE OF SIGNING EXPERIENCE

As a final step in the investigation of the relationship between sign and speech perception abilities, the sample of children with a CI was divided into two groups according to signing experience. As explained in §3.1, half of the children with a CI in the sample, namely the Dutch children, had received a considerable amount of signed input over the years, whereas the other half, namely the Flemish children, had received only limited signed input. Figures 6.13-6.16 show the performance of the Dutch and Flemish children with a CI on the different outcome measures in both modalities: sound and sign categorization (Figure 6.13), rapid word and sign learning (Figures 6.14 and 6.15) and phonological short-term memory (Figure 6.16).

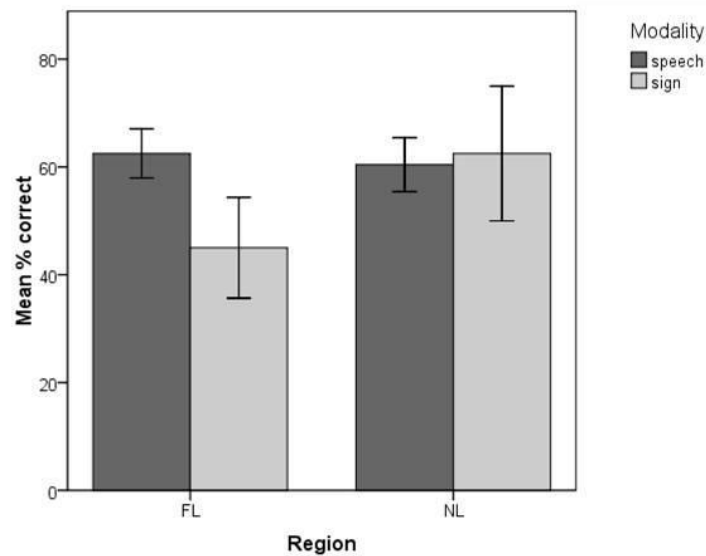


Figure 6.13. Mean phoneme endpoint identification scores in the sound (speech) and sign (sign) categorization tasks for the Flemish (FL) and Dutch (NL) children with a CI.

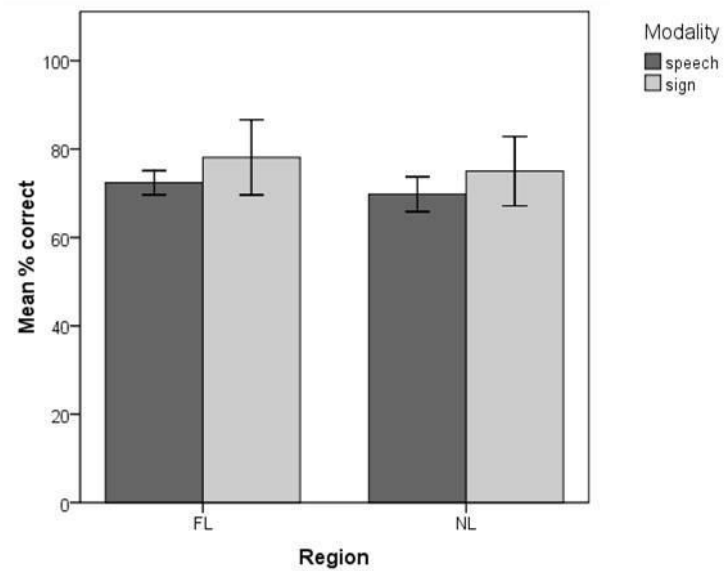


Figure 6.14. Mean percentage correct scores in the non-word picture matching task (speech) and the non-sign picture matching task (sign) for the Flemish (FL) and Dutch (NL) children with a CI.

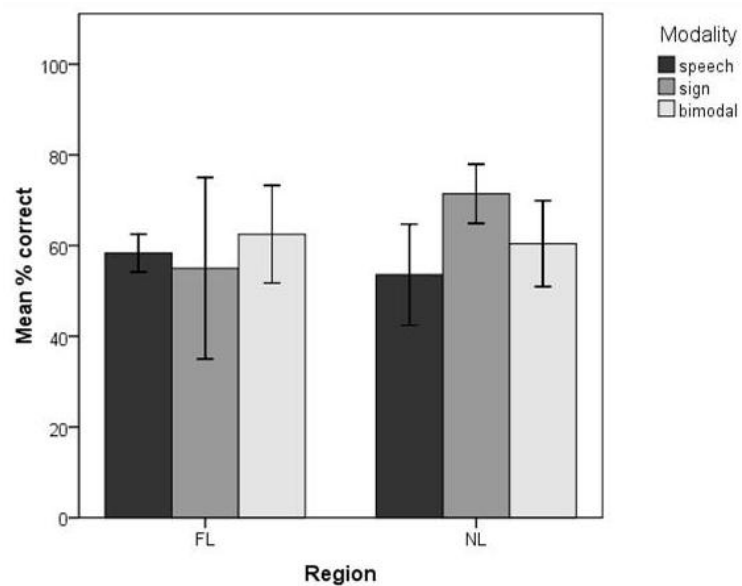


Figure 6.15. Mean percentage correct scores in the speech, sign and bimodal condition of the object-matching task for the Flemish (FL) and Dutch (NL) children with a CI.

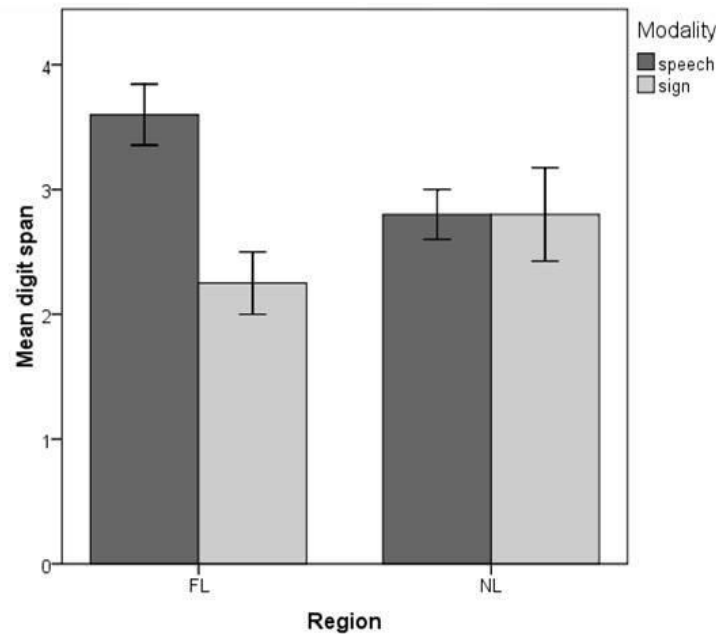


Figure 6.16. Mean digit spans in the spoken and signed modality for the Flemish (FL) and Dutch (NL) children with a CI.

Although the respective sample sizes in both groups are too small for statistical comparison, the figures show by inspection that the Dutch children with a CI, as expected, generally obtain higher scores on the sign perception tasks than the Flemish children with a CI (most notably on the categorization and object-matching tasks). Importantly, however, except for phonological short-term memory, their higher sign perception scores are not associated with lower speech perception scores. The considerable difference in spoken digit spans between the Dutch and Flemish children is remarkable and might indeed be the result of their respective linguistic environments. Consistent with this idea, Pisoni et al. (1999) found smaller digit spans for children in Total Communication settings compared to children in Oral communication settings. They suggested that reduced amounts of exposure to speech following implantation might lead to less efficient processing of auditory information in verbal short-term memory. The different linguistic environment is not the only possible explanation for the observed difference in spoken digit spans, however. Recall that a significant positive correlation was observed between length of CI use and spoken digit span scores (see §5.3.4). On average, the Flemish children were implanted earlier than the Dutch children; as a result, they were using

their CI for a longer time when tested (§3.1). The difference in spoken digit spans could therefore also be an effect of “hearing” experience with the CI.

6.6 CONCLUSION

In this chapter we have shown that, in general, the sign perception abilities of the children with a CI are on the same level as their speech perception abilities. However, the range in observed sign perception abilities is large due to substantial inter-individual variation in the amount of signed input received by the child and thus their signing experience. Crucially, we found no evidence that better sign perception abilities led to poorer speech perception abilities in the same children. In contrast, on three outcome measures we observed positive correlations between the two language modalities. Our results thus suggest that relatively good signing and speech perception abilities are not mutually exclusive for children with a CI (cf. De Raeve et al., 2009; Klatter-Folmer et al., 2006; Preisler et al., 2001). Evidence from correlations should be interpreted with caution, however, because they do not imply causality. In addition, the results from the bimodal condition of the object-matching task warrant further research into the interaction between both modalities during language processing. In Chapter 7, therefore, an experiment will be reported that more directly examined the effects of signed input on speech perception.

7 EFFECTS OF BIMODAL INPUT ON SPEECH PERCEPTION

The comparison of perception abilities in the spoken and signed modality in Chapter 6 showed that the children with a CI, in general, performed at similar levels in both language modalities. In addition, contrary to what would be expected if signing experience had a direct negative impact on spoken language outcomes, performance in both language modalities correlated positively. In other words, relatively good performance in one modality does not generally imply relatively poor performance in the other modality. In this chapter, we will address more direct effects of signed input on speech perception. More specifically, we will report the results from an experiment that examined whether bimodal (i.e., simultaneously spoken and signed) input helps or hinders children with a CI to recognize and learn spoken words.

The data for this experiment were collected separately from the data presented in Chapters 4 to 6 and are available from a subset of the children with a CI that completed the other experiments. In §7.1 background information is provided on the role of the visual modality in language processing in general and in children with a CI in particular. In §7.2, the research methodology will be described and the results and discussion are presented in §7.3 and §7.4, respectively.

7.1 BACKGROUND

7.1.1 THE ROLE OF THE VISUAL MODALITY IN LANGUAGE PROCESSING

Although the primary sensory channel in spoken language processing is auditory, information is often reinforced and enriched by visual input, for instance, from the face and for sounds specifically visible, movements of the articulators. A famous example of such audiovisual integration is the ‘McGurk’ effect (McGurk & MacDonald, 1976). When people hear the syllable /ba/, but see a speaker producing the syllable /ga/, they often perceive the syllable /da/, where the consonant has a place of articulation between that of /b/ and /g/ and visually looks like /g/. Conversely, when they hear /ga/, but see /ba/, they often perceive /bagba/ or /gaba/ because they related the observed bilabial closure to a bilabial sound. Following this seminal work, a multitude of studies have shown that infants, children and adults are sensitive to visual speech information during spoken language processing, especially in unfavorable conditions such as in the presence of background noise or because of hearing impairment (for recent reviews, see e.g. Rosenblum, 2005, 2008; Woodhouse et al., 2009).

In addition to the face, however, auditory information is also enriched by visual input from the hands. Behavioral and neuro-imaging studies have shown that co-speech gestures, i.e., facial and hand movements that accompany speech, are tightly integrated with auditory input in language comprehension (Kelly et al., 2008; Skipper, Goldin-Meadow, Nusbaum, & Small, 2009). This is particularly striking when the information expressed in speech and gesture is incongruent. For instance, Kelly, Ozyurek and Maris (2010) recently showed that adults related short movies of someone performing a specific action (e.g., someone chopping vegetables) more quickly and accurately to bimodal speech-gesture targets when both speech and gesture matched the action (i.e., speech: “chop”, gesture: chop) than when one of them did not (e.g., speech: “chop”, gesture: twist). Importantly, participants were unable to ignore the gestures, even when explicitly instructed to do so, suggesting that the interaction between speech and gesture in language comprehension is mutual and automatic. Moreover, it is already present in early language development. For instance, the occurrence of word-gesture combinations predicts the onset of two-word combinations (e.g. Iverson & Goldin-Meadow, 2005). Conversely, delays in the early productive use of gestures are associated with delays in language development at a later age (e.g. Thal, Tobias, & Morrison, 1991). Most importantly for the present study, co-speech gestures have been found to support word learning in a foreign language in both children and adults (e.g. Kelly, McDevitt, & Esch, 2009; Tellier, 2008) and are used to support communication in children with language learning difficulties (Capone & McGregor, 2004).

Interaction between the oral-auditory and manual-visual modality in language processing is further illustrated by bimodal bilinguals, hearing people with one or two deaf parents who grew up learning both a spoken and a signed language. Although the spoken language is dominant in such bilinguals, they often also produce signs in their utterances. Interestingly, Emmorey et al. (2008) have shown that they prefer simultaneous productions of speech and sign (code-blending) over sequential switches between speech and sign (code-switching). The latter is a typical phenomenon in conversations between bilinguals who speak two spoken languages, i.e., unimodal bilinguals (see also Bishop, 2006b; Bishop & Hicks, 2005). Moreover, Emmorey, Petrich and Gollan (2010) found faster semantic decision times in bimodal bilinguals when they were presented with code-blends in comparison to words or signs alone. These results suggest that bimodality in language comprehension produces a processing advantage for hearing adults who are native speakers of a signed and a spoken language. The authors explain this result in terms of the Redundant Signals Effect (e.g. Miller & Ulrich, 2003): a combination of two redundant stimuli co-activates a response and results in a processing advantage. Although this effect has mainly been applied to the processing of nonverbal sensory signals, it might also apply to the combined activation of redundant lexical representations.

Importantly, the blending of spoken and signed utterances is also frequently observed in hearing and deaf children of deaf parents (Baker & Van den Bogaerde, 2008; Van den Bogaerde & Baker, 2005, 2008) and deaf children of hearing parents, including children with a CI (Klatter-Folmer et al., 2006). Emmorey et al.'s finding of processing advantages for bimodality in adult bimodal bilinguals might therefore also apply to children with a CI.

7.1.2 CHILDREN WITH A CI AND THE VISUAL MODALITY IN LANGUAGE PROCESSING

The role of the visual modality in language processing by children with a CI has only recently received attention from researchers and most studies have been on the integration of auditory and visual speech information (for a review, see Mitchell & Maslin, 2007). Bergeson et al. (2005), for instance, studied the development of audiovisual comprehension abilities in 80 children with a CI that were followed for five years from pre-implantation. In addition to a sentence recognition test administered in auditory-alone, visual-alone and audiovisual format, they included a battery of standardized spoken language tests. In general, they found that over time the children's sentence recognition mostly improved in the auditory-alone and audiovisual format. However, complex interactions were observed between length of CI use, age at implantation, communication modality and improvement over time. Children in Oral Communication settings outperformed children in Total Communication settings in all three conditions before implantation, even the speech reading condition, but no longer so after five years of CI use. Furthermore, pre-implant scores in the visual-alone condition correlated strongly with speech perception, vocabulary knowledge and speech intelligibility three years after implantation. In other words, children that were better speech readers before implantation perceived and produced speech more accurately after implantation. According to the authors, children's success in combining auditory and visual cues in speech perception after implantation seems already to be reflected in their efficiency in using visual speech information before implantation.

Other studies have looked in more detail at the development of audiovisual integration abilities in young children with a CI. For instance, Bergeson, Houston and Miyamoto (2010) showed that infants and young children with a CI between 16 and 39 months of age were not able to match silent video clips of a woman speaking the words 'judge' and 'back' to the respective sound tracks after three months of CI use, but succeeded after six months. Schorr, Fox, Van Wassenhove and Knudsen (2005) compared occurrence of the McGurk effect in a group of 5- to 14 year-old children with a CI and a group of age-matched children with normal hearing. The authors found that none of the children with a CI implanted after 2.5 years of age showed the McGurk effect (see §7.1.1), compared to 38% of the children implanted

before that age and 57% of the children with normal hearing. When hearing the syllable /pa/ and seeing the syllable /ka/, they mostly reported having perceived /ka/ and not the syllable /ta/ where the consonant has a place of articulation between that of /p/ and /k/.

In contrast to the integration of auditory and visual *speech* information, the integration of auditory and visual input from the hands such as signs or co-speech gestures has to our knowledge not yet been studied in children with a CI. Bergeson et al. (2005) discuss possible negative consequences of simultaneously exposing children with a CI to speech and signs. They hypothesized that one of the possible explanations for poorer speech reading and spoken language outcomes in children with a CI from Total Communication settings is that they have to divide their visual attention between the hands (i.e., signs) and the face (i.e., speech reading). Such division of attention could create competition between limited processing resources in working memory and result in less efficient speech processing (see also Burkholder & Pisoni, 2006).

There is, however, evidence suggesting that exposing deaf or hard-of-hearing children and adults to speech and signs simultaneously may actually *enhance* spoken language processing. For instance, Hamilton and Holzman (1989) investigated modality effects on linguistic encoding in short-term memory in deaf and hearing adults varying in spoken and signed language experience. They found that subjects with both sign and speech experience recalled bimodal stimuli better than stimuli that were only spoken or signed³⁵. More recently, Mollink et al. (2008) examined the effects of using signs in spoken vocabulary training for children with a mild-to-moderate hearing loss and found that signs had a positive effect on the learning and retention of new spoken vocabulary. In their study 14 children were exposed to a set of 64 pictures in four different naming conditions: with words, words and signs, words and colors, and no naming (only pictures). They were presented with the words three times in a period of three weeks: in each session the pictures were named twice by the experimenter and the child repeated the word on each occasion. Naming was tested one week and five weeks after the last session. At both test moments, the pictures that had been trained with words and signs combined received the highest percentage correct scores.

To summarize, although audiovisual integration is being considered in the pediatric CI literature, attention has only been paid to visual input from the face and not from the hands. On the one hand, simultaneous exposure to speech and signs might present a processing advantage for children with a CI compared to speech or sign alone, possibly because of the co-activation of redundant lexical representations as discussed above (cf. Hamilton & Holzman, 1989; Mollink et al., 2008). On the

³⁵ They had to remember lists of five items (words, signs or word-sign combinations); immediate recall was in written words.

other hand, such bimodal input might present a challenge because it can generate competition in working memory (Bergeson et al., 2005). To determine which of these alternative hypotheses is correct, we designed an experiment that tested the effects of bimodal input on spoken word recognition and learning. Here, we present preliminary results from a small sample of children with a CI. The children were a subset of those that participated in the experiments reported in Chapters 4 to 6.

7.2 METHODOLOGY

7.2.1 PARTICIPANTS

The participants were eight children with a CI (mean age at testing: 6;11, mean age at implantation: 1;10). Background information on the children is provided in Table 7.1 below (see also §3.1.1). They were a subset of the children that participated in the experiments reported in Chapters 4-6. At the time of testing, three of the children attended mainstream education and five children attended schools for the deaf. To ensure that the stimuli were clear and that the task was not too difficult for the children, data were also collected from ten adults (mean age 22;7), whose signing experience varied from null to two years in second language learning classes³⁶. They were expected to perform at ceiling-level.

³⁶ Similar to the children, they were a subset of the adults that participated in the experiments reported in Chapters 4-6.

Table 7.1. Characteristics of the children with a CI ordered according to age at implantation.

ID	Gender	Country of origin	Stimulation	Implant type	Educational setting at time of study	Age at implantation	Age at time of study
N7	F	NL	CI	Clarion (Platinum)	mainstream	0;7	6;6
A1	M	B	CI	Cochlear (Sprint)	mainstream	0;9	6;8
J3	M	B	CI	Cochlear (Sprint)	SimCom	0;10	5;9
S7	M	B	2CI	Cochlear (Sprint) / Digisonic (SP)	SimCom	1;2	6;7
L2	F	NL	CI	Clarion (Platinum)	bilingual	2;0	7;4
D8	M	NL	2CI	Cochlear (Sprint/Freedom)	mainstream	2;1	8;1
L4	M	NL	CI	Cochlear (Sprint)	bilingual	3;2	7;11
S5	M	NL	CI	Cochlear (Freedom)	bilingual	3;9	6;9
						M=1;10, sd=14 mo	M=6;11, sd=9 mo

Note. Ages are in years;months, M=mean, SD=standard deviation, mo=months

7.2.2 MATERIALS

7.2.2.1 TASK

Based on the picture-matching tasks discussed earlier in this thesis (§5.2.2.1 and §6.2.2.2), a new task was designed to measure word and sign recognition and learning. Recognition was tested with familiar items and learning with novel items. In addition, the role of phonological (dis)similarity was addressed by including both minimal and non-minimal pairs.

The experiment consisted of three conditions: speech, sign and bimodal. The experiment consisted of six blocks, two for each modality condition. In the first block the relatively easy non-minimal novel and familiar pairs were presented, followed by a block with the more difficult minimal novel and familiar pairs. Each block consisted of a familiarization and a testing phase. During familiarization, depending on the condition, participants were familiarized with one novel and one familiar pair of objects either in speech, sign or both, i.e., bimodal (see Figure 7.1 for instances of movie stills). The testing phase consisted of a set of two-alternative forced-choice identification trials. Crucially, after familiarization in the bimodal condition, participants were first tested on the words in the bimodal pairs and on the signs only after all word trials had been completed. In this way, the effects of *bimodal* input on *spoken* word recognition and learning could be examined. If the testing phase had also been bimodal, it would have been difficult, if not impossible, to establish whether the participants primarily responded to the words or the signs in the bimodal pairs. They could simply rely on their best modality during familiarization and testing, as was the case in the bimodal condition of the object-matching task discussed earlier (§6.2.2.3). The disadvantage of testing word before sign recognition and learning is that the familiarization-testing interval is longer for signs than for words. As a result, performance on the signs in the bimodal condition might be poorer than performance in the sign condition simply because more time had elapsed between familiarization and testing. However, the advantage of this design is that the word testing phase in the bimodal condition was identical to that in the speech condition. That is, the single difference between the conditions was the modality used during familiarization.



Figure 7.1. Example movie stills for the stimulus /tauw/ ‘rope’ from the familiarization phase in the speech (left), sign (middle) and bimodal (right) conditions. The stills represent the end of the stimulus.

During familiarization, a picture and a movie were presented next to each other in the center of the screen. The picture was always presented on the left side in this phase. Each stimulus was presented three times with inter-trial intervals of 500 milliseconds. Following familiarization, a black-and-white blocked flag was displayed in the center of the screen for 2000 milliseconds in order to fixate attention to the center. Next, 12 testing trials were presented in random order. In each trial a movie stimulus was played in the center of the screen, immediately followed by two pictures, one at the left and one at the right side of the screen. Left and right response keys on the laptop were indicated by stickers. The next movie stimulus was presented immediately following the participant’s response. Participants responded to four *novel* (e.g., /tuk/ and /tik/), four *familiar* (e.g., /mauw/ ‘sleeve’ and /dos/ ‘box’), and four *filler* (e.g., /tuk/ and /dos/) trials. Side of presentation of the pictures on the screen in the testing phase was counterbalanced.

E-Prime 2.0[®] (Psychology Software Tools, Pittsburgh PA) was used to present the stimuli and record accuracy and reaction times. Accuracy was defined as the number of trials correctly answered. For each block, the minimum score that could be obtained was 0 and the maximum 12. Thus, the maximum score for the entire task was 6 blocks x 12 trials = 72. Reaction times were measured from the offset of the auditory stimulus to the overt response, i.e., the key press. Reaction times were analyzed separately for the three trial types. Only trials that were correctly answered were included and trials with reaction times more than 2.5 standard deviations above and below the mean reaction time for each participant were excluded from the analysis, resulting in the exclusion of 4.6% of the trials for the adults and 2.7% for the children with a CI.

7.2.2.2 STIMULI

The stimuli in the experiment consisted of video recordings of words and signs embedded in carrier phrases. For the words, the carrier phrases were ‘Kijk, een X!’ (*Look, a X!*) during familiarization, and ‘Waar is de X?’ (*Where is the X?*) during testing. For the signs, the carrier phrases were ‘*pointing to picture*³⁷ X!’ during familiarization, and ‘WAAR X?’ (*WHERE X ?*) during testing. The stimuli were spoken and signed by the same person who produced the stimuli reported in §4.2.2, §5.2.2 and §6.2.2. The stimuli were recorded against a blue background to optimize sign visibility using an external microphone attached to the video camera. The recorded stimuli were captured and digitalized using iMovie® and compressed to WMV format (440 kbps, 25 fps, 360x280 pixels) using Pinnacle® Studio 11³⁸. They averaged about 3000 milliseconds in duration. The pictures that were presented together with the movie stimuli were black-and-white drawings of novel and familiar objects from the same picture databases as used for the picture-matching tasks (see §5.2.2.1).

In total, four non-word pairs and four familiar word pairs were used in this experiment, half were minimal pairs and half were non-minimal pairs. The two non-minimal non-word pairs were selected from the set of non-words that was used in the picture-matching and object-matching tasks (see §5.2.2.1). Two new monosyllabic consonant-vowel-consonant minimal non-word pairs selected were distinguished by the vowels /u/ and /i/, a sound contrast with a strong visual correlate (lip rounding). Similar to the other non-words, they conformed to a monosyllabic consonant-vowel-consonant structure. Furthermore, we presented two familiar minimal and two familiar non-minimal word pairs that were judged to be known to typically developing six-year old children (Schaerlaekens et al., 1999), and for which pictures were available in the database (see §5.2.2.1). The selected novel and familiar word pairs are listed in Table 7.2.

Presentation of these word pairs in the speech and bimodal conditions was counterbalanced across participants. For instance, some participants were presented with the /tuk/-/tik/ and /kɔp/-/pɔp/ pairs in the speech condition and with the /fup/-/fip/

³⁷ Pointing was preferred over the lexical sign KUK (*LOOK*) that was used in the non-sign picture-matching task (see §6.2.2.2), because pointing establishes a more explicit relation between the following sign and the picture.

³⁸ This experiment was designed in the Laboratory for Language and Cognitive Neuroscience in San Diego during a 4-month visit in the Fulbright Visiting Scholar Program. Recorded stimuli were digitalized and compressed to QuickTime® format using iMovie®. Psyscope X (Cohen, MacWhinney, Flatt, & Provost, 1993) was used to present the stimuli. A pilot study with adults was completed with stimuli in English and American Sign Language. The experiment was later converted to E-Prime® 2.0 and the original video recordings compressed to WMV format.

and /tak/-/zak/ pairs as the auditory parts of the stimuli in the bimodal condition, whereas this was reversed for other participants.

Table 7.2. Minimal and non-minimal non-word pairs included in the experiment.

Novel word pairs		Familiar word pairs		
Orthographic form	Phonological form	Orthographic form	Phonological form	English translation
Minimal		Minimal		
toek - tiek	/tuk/ - /tik/	kop - pop	/kɔp/ - /pɔp/	<i>mug - doll</i>
foep - fiep	/fup/ - /fip/	tak - zak	/tak/ - /zak/	<i>branch - sack</i>
Non-minimal		Non-minimal		
fuuk - soot	/fyk/ - /sot/	mouw - doos	/mauw/ - /dos/	<i>sleeve - box</i>
taat - peeg	/tat/ - /peχ/	touw - roos	/tauw/ - /ros/	<i>rope - rose</i>

The non-sign pairs included in the experiment came from the set of non-signs that was used in the picture-matching and object-matching tasks (see §6.2.2.2); illustrations are provided in Appendix D. These included both minimal and non-minimal non-sign pairs. Minimal *familiar* sign pairs were not included in the experiment because we were unable to find a stimulus pair for the bimodal condition that was a minimal pair in Dutch as well as in NGT and VGT. Presentation of the non-sign pairs in the sign and bimodal conditions was counterbalanced across participants. Given that the familiar word pairs in the speech and bimodal conditions were already counterbalanced, counterbalancing the familiar sign pairs in the sign and bimodal conditions would have resulted in the same pictures being presented twice to participants. Therefore, in addition to the familiar signs in the bimodal condition that matched the meaning of the familiar words in Table 7.2, two new familiar sign pairs that were the same in NGT and VGT were selected from NGT teaching material for young deaf children, and were only presented in the sign condition (BEER ‘bear’, BOEK ‘book’, BRIL ‘glasses’, PET ‘cap’).

7.2.3 PROCEDURE

Participants completed the experiment in one of two different orders: half completed the speech before the sign condition, and half completed the sign before the speech condition. All participants completed the bimodal condition last. This was done to

make sure that participants were familiarized with both language modalities before completing the bimodal condition. The order of the speech and sign condition was counterbalanced to account for potential priming effects in the bimodal condition from the preceding modality. That is, participants who had just completed the speech condition might show a bias in relative attention towards that modality when processing the stimuli in the bimodal condition, and similarly for participants who had just completed the sign condition. These processing biases could affect the interaction between the two modalities in the bimodal condition and thus the results of the study, hence the counterbalancing of the speech and sign conditions.

Participants were told beforehand that they would see pictures of novel and familiar objects together with movies in which the objects were named. They were also told that they would see the task in speech, sign or both. Their task was to remember which word and/or sign was associated to which picture. In between blocks, they were reminded of the type of block that would follow (speech, sign or bimodal). Before the bimodal condition, they were told that the names of the objects would be both spoken and signed and that they would have to remember both, but that they would be tested on the words and signs separately. There was a pause between blocks, which was also used to provide non-specific feedback to stimulate the children. The experiment was preceded by a practice block in speech with two phonologically dissimilar non-words (/kax/ and /fet/) and two phonologically dissimilar familiar words (/dɔr/, 'door' and /bal/, 'ball'). Familiarization was identical to the experimental blocks, but testing was limited to six trials, two for each type of testing trials, presented in random order. The task took children approximately 25 minutes and adults 15 minutes.

7.2.4 STATISTICAL ANALYSIS

Parametric statistical tests were used to analyze raw scores, expressed as percentage correct scores in the text, and reaction times. To compare performance in the speech, sign and bimodal conditions, we first performed a repeated measures ANOVA on overall scores and reaction times. In this analysis the bimodal condition was further divided in two “sub-conditions” according to the modality in which the participants were tested, namely speech or sign. These will be referred to here as bimodal_{speech} and bimodal_{sign}, respectively (see Table 7.4). Paired samples *t*-tests were used for post hoc comparisons. Furthermore, to specifically compare the bimodal to the unimodal conditions, we ran a series of planned paired samples *t*-tests on scores and reaction times in the two bimodal conditions (i.e., bimodal_{speech} and bimodal_{sign}) paired with those in the respective unimodal conditions (i.e., speech and sign) for the different types of stimulus pairs: novel or familiar, and minimally different or not

minimally different. Bivariate Pearson product moment coefficients are reported in correlation analyses.

Table 7.4. Description of the four testing conditions and the labels used for reference in the text and figures.

Label	Description
Speech	Familiarized with words and tested on these words
Sign	Familiarized with signs and tested on these signs
Bimodal_{speech}	Familiarized with word-sign combinations and tested on the words
Bimodal_{sign}	Familiarized with word-sign combinations and tested on the signs

7.3 RESULTS

Data were available from all participants. In this section, we will first report the results from the adults (§7.3.1), followed by the results from the children (§7.3.2). In §7.3.3 correlations with age at implantation, length of CI use and chronological age are presented (§7.3.3). Individual results for the children with a CI are presented in Appendix E.

7.3.1 ADULTS

Table 7.5 provides the descriptive statistics of the percentage correct scores and reaction times in the four conditions for the adults. As predicted, their scores were high overall and approached ceiling³⁹. More specifically, they scored $\geq 90\%$ correct on all stimulus pairs except for the novel word pairs in the bimodal_{speech} condition ($M=80.0\%$ correct, highlighted in Table 7.5). A repeated measures ANOVA on overall scores in the four conditions revealed no significant effect of condition ($F(1,9)=1.11$, $p=.36$). Furthermore, none of the planned paired samples comparisons between scores in the two bimodal and respective unimodal testing conditions approached significance.

³⁹ Percentage correct scores approached ceiling for both the adults with signing experience and those without. Reaction times for the adults without signing experience were slower overall, but showed the same patterns across conditions as for the adults with signing experience. As a result, they are included as one group in the analyses presented below.

A repeated measures ANOVA on overall reaction times in the four conditions revealed a significant main effect of condition ($F(1,9)=7.37, p<.05$). Post hoc paired samples comparisons showed that the adults responded significantly faster in the bimodal_{sign} condition compared to the bimodal_{speech} condition (bimodal_{sign}: $M=537$ msec, bimodal_{speech}: $M=591$ msec; $t(9)=2.78, p<.05$). Furthermore, planned paired samples t -tests between the two bimodal and respective unimodal testing conditions showed that they responded significantly slower in the bimodal_{sign} condition compared to the sign condition for novel minimal sign pairs (bimodal_{sign}: $M=654$ msec, sign: $M=490$ msec, $t(9)=-3.15, p<.05$). None of the other planned paired samples comparisons approached significance.

Table 7.5. Descriptive statistics of percentage correct scores (%) and reaction times (RT, msec) for the adults ($n=10$).

Stimulus type	Trial type		Speech	Sign	Bimodal _{speech}	Bimodal _{sign}
Minimal pairs	Familiar	%	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	97.5 (7.9)
		RT	472 (101)	489 (78)	489 (76)	505 (68)
	Novel	%	90.0 (17.5)	97.5 (7.9)	80.0 (22.9)	95 (10.5)
		RT	590 (148)	490 (111)	786 (337)	654 (210)
	Filler	%	100.0 (0.0)	100.0 (0.0)	97.5 (7.9)	97.5 (7.9)
		RT	541 (155)	511 (116)	579 (133)	507 (79)
Non-minimal pairs	Familiar	%	100.0 (0.0)	100.0 (0.0)	100.0 (0.0)	95.0 (10.5)
		RT	498 (74)	489 (61)	520 (122)	483 (83)
	Novel	%	92.5 (16.9)	90.0 (17.5)	92.5 (12.1)	95.0 (10.5)
		RT	596 (153)	620 (91)	632 (107)	579 (128)
	Filler	%	100.0 (0.0)	100.0 (0.0)	97.5 (7.9)	100.0 (0.0)
		RT	548 (117)	512 (60)	542 (104)	491 (72)

Note. Numbers represent means and standard deviations (between parentheses).

7.3.2 CHILDREN WITH A CI

Table 7.6 provides the descriptive statistics of the percentage correct scores and reaction times in the four conditions for the children with a CI. Figure 7.2 illustrates their mean percentage correct scores in the four conditions according to stimulus type (familiar or novel, and phonologically similar or different). A repeated measures ANOVA on overall scores in the four conditions revealed no significant effect of modality ($F(1,7)=.44, p=.66$). Furthermore, none of the planned paired samples comparisons between scores in the two bimodal and respective unimodal testing conditions approached significance.

Table 7.6. Descriptive statistics of percentage correct scores (%) and reaction times (RT, msec) for the children with a CI ($n=8$).

Stimulus type	Trial type		Speech	Sign-alone	Bimodal _{speech}	Bimodal _{sign}
Minimal pairs	Familiar	%	90.6 (18.6)	96.9 (8.8)	96.9 (8.8)	96.9 (8.8)
		RT	1409 (571)	1173 (365)	1142 (377)	1726 (516)
	Novel	%	84.4 (12.9)	78.1 (20.9)	93.8 (11.6)	71.9 (20.9)
		RT	1585 (501)	2235 (910)	1566 (475)	2079 (553)
	Filler	%	96.9 (8.8)	96.9 (8.8)	93.8 (11.6)	96.9 (8.8)
		RT	1524 (502)	1289 (663)	1305 (403)	1663 (370)
Non-minimal pairs	Familiar	%	100.0 (0.0)	93.8 (11.6)	100.0 (0.0)	100.0 (0.0)
		RT	1551 (935)	1165 (236)	1018 (333)	1268 (530)
	Novel	%	78.1 (24.8)	93.8 (11.6)	62.5 (37.8)	84.4 (18.6)
		RT	2101 (1126)	1453 (501)	2086 (1196)	2006 (595)
	Filler	%	93.8 (17.7)	100.0 (0.0)	96.9 (8.8)	96.9 (8.8)
		RT	1356 (563)	1335 (394)	1425 (352)	1608 (448)

Note. Numbers represent means and standard deviations (between parentheses).

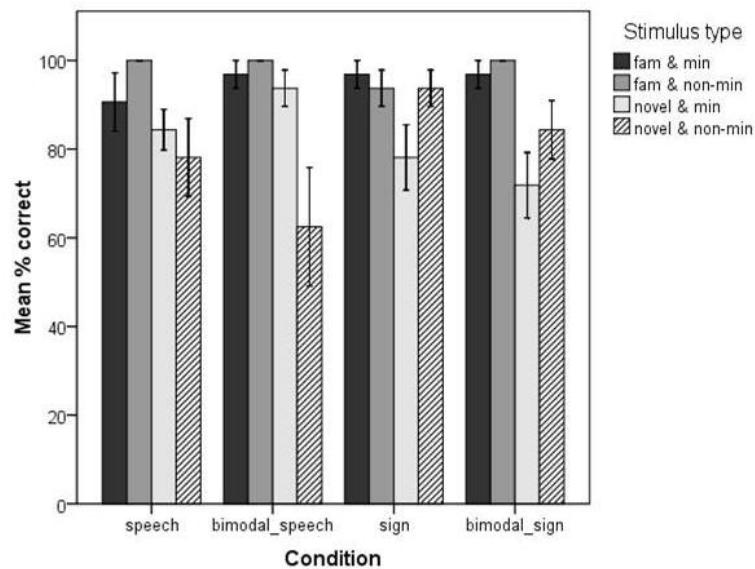
**Figure 7.2.** Mean % correct scores for the children with a CI in the four conditions according to stimulus type: familiar (fam) or novel, and minimal pairs similar (min) or non-minimal pairs (non-min).

Figure 7.3 illustrates the children's mean reaction times in the four conditions according to stimulus type (familiar or novel, and phonologically similar or different). A repeated measures ANOVA on overall reaction times in the four conditions revealed no significant effect of condition ($F(1,7)=4.56$, $p=.07$). However, planned paired samples comparisons between reaction times in the two bimodal and respective unimodal testing conditions showed that the children responded marginally significantly faster in the bimodal_{speech} condition compared to the speech condition for familiar minimal word pairs (bimodal_{audiovisual}: $M=1142$ msec, speech: $M=1409$ msec, $t(7)=2.24$, $p=.06$). Furthermore, they responded significantly slower in the bimodal_{sign} condition compared to the sign condition for familiar sign pairs in the block with minimal novel sign pairs⁴⁰ (bimodal_{sign}: $M=1726$ msec, sign: $M=1173$ msec, $t(7)=-2.87$, $p<.05$). None of the other planned paired samples comparisons approached significance.

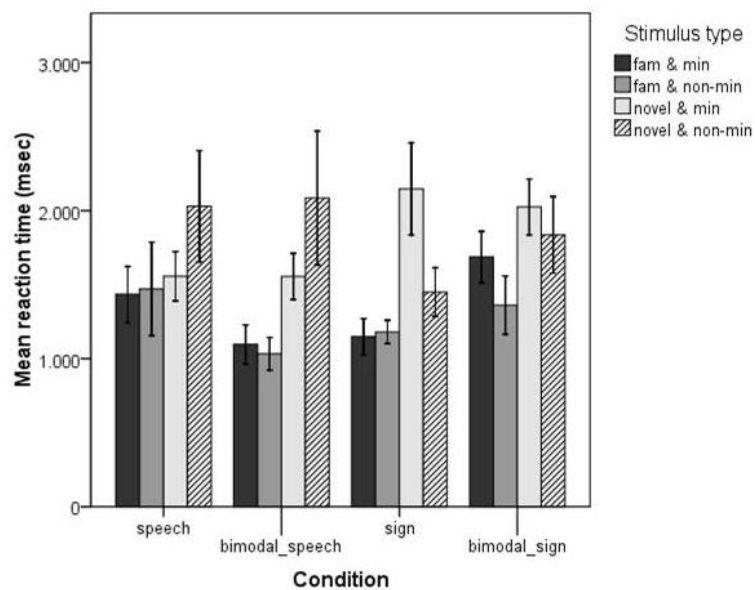


Figure 7.3. Mean reaction times for the children with a CI in the four conditions according to stimulus type: familiar (fam) or novel, and minimal pairs (min) or non-minimal pairs (non-min).

As in the studies reported in Chapters 4-6, our sample of children with a CI in this study included both Dutch children and Flemish children and that the former received more signed input than the latter and may be considered to have more

⁴⁰ Recall that the familiar sign pairs in the experiment were all non-minimal sign pairs (see §7.2.2).

signing experience (see §3.1.1). It is therefore possible that especially the Dutch children experienced positive effects from bimodal exposure. In order to examine this possibility, we analyzed the reaction time data on the familiar minimal pair in the $\text{bimodal}_{\text{speech}}$ and speech conditions for the Dutch ($n=5$) and Flemish ($n=3$) children separately. Indeed, whereas the Dutch children responded significantly faster in the $\text{bimodal}_{\text{speech}}$ condition compared to the speech condition for familiar minimal word pairs ($\text{bimodal}_{\text{speech}}$: $M=1040$ msec, speech: $M=1602$ msec, $t(4)=-3.75$, $p<.05$), the Flemish children did not ($\text{bimodal}_{\text{speech}}$: $M=1190$ msec, speech: $M=1155$ msec, $t(2)=-.21$, $p=.85$). Importantly, although the Flemish children with a CI did not experience facilitation from the bimodal exposure, they also did not experience interference from it. These results therefore suggest that bimodal input does not interfere with speech perception in children with a CI and can even facilitate speech perception in those children with relatively much signing experience⁴¹.

7.3.3 CORRELATIONS

For the children with a CI, correlations of age at implantation, length of CI use and chronological age with scores and reaction times in the four different test conditions were examined. As in previous chapters, longer CI use was associated with earlier implantation ($r=.75$, $p<.05$). In addition, longer CI use was associated with higher scores in the $\text{bimodal}_{\text{sign}}$ condition ($r=.91$, $p<.01$), and faster reaction times in the speech ($r=-.89$, $p<.01$), the sign ($r=-.74$, $p<.05$) and the $\text{bimodal}_{\text{speech}}$ conditions ($r=-.81$, $p<.05$). Neither age at implantation nor chronological age correlated with scores or reaction times in any of the four testing conditions.

⁴¹ In order to examine the possibility that a similar bimodal distribution in the data between the Dutch and Flemish children had cancelled out any positive or negative effects of bimodal exposure, we reanalyzed all accuracy and reaction time data separately for the Dutch and Flemish children. In addition to the difference with respect to the familiar minimal word pairs reported in the text, the Dutch and Flemish children also appeared to respond differently to the familiar sign pairs in the block with novel minimal sign pairs. Whereas the Dutch children responded significantly slower in the $\text{bimodal}_{\text{sign}}$ condition compared to the sign condition (sign: $M=1083$ msec, $\text{bimodal}_{\text{sign}}$: $M=1594$ msec, $t(4)=-3.15$, $p<.05$), the Flemish children did not (sign: $M=1257$ msec, $\text{bimodal}_{\text{sign}}$: $M=1843$ msec, $t(2)=-1.20$, $p=.35$). However, given that the absolute difference in reaction times between the two conditions is quite similar for the Flemish and Dutch children (586 msec and 511 msec, respectively), this apparent difference in performance between the two groups more likely reflects a difference in statistical power.

7.4 DISCUSSION

In this chapter, we have directly assessed the effects of bimodal (i.e., speech and sign) input on speech perception in children with a CI. The results clearly show that bimodality in the input had no negative effects on the processing of words, regardless of whether they were phonologically similar or dissimilar, and novel or familiar. Crucially, the fact that we did not find evidence for negative effects of bimodal exposure on speech perception cannot be accounted for by a lack of attention to the signs in the bimodal condition. The absence of significant differences between scores and reaction times in the bimodal_{sign} and sign conditions for all except one stimulus pair shows that the children had looked at the signs during familiarization.

Apparently the children with a CI had no difficulty distributing their visual attention over the speaker's hands and face. In fact, for one stimulus type, bimodal exposure had a positive effect on the creation or retrieval of spoken lexical representations. Reaction times were faster when familiarization of familiar minimal word pairs had been bimodal compared to only spoken, which suggests that they experienced cross-modal facilitation. Mollink et al. (2008) found positive effects of bimodal exposure on word learning in children with a mild-to-moderate hearing loss wearing acoustic hearing aids (see §7.1.2.). Our results suggest that deaf children with a CI may experience similar positive effects from bimodal exposure.

Our finding that the adults with normal hearing did not show cross-modal facilitation is not surprising given their already near-ceiling performance in the speech condition (see Table 7.3). However, for them bimodal exposure actually appeared to hamper speech processing to some extent. Unexpectedly, they responded significantly faster in the bimodal_{sign} condition compared to the bimodal_{speech} condition, although the former had a longer interval between familiarization and testing (see §7.2.2.1). Bimodal exposure thus appeared to interfere with their processing of the spoken words in the bimodal condition. We will now discuss possible explanations for the observed cross-modal facilitation (§7.4.1) and interference (§7.4.2) effects.

7.4.1 CROSS-MODAL FACILITATION

One possible explanation for the observed processing advantage in the bimodal condition is the more general *redundant signals* effect, according to which combined information from two redundant stimuli co-activates a response and results in a processing advantage (e.g. Miller & Ulrich, 2003). That is, the processing advantage in the bimodal condition may have resulted from the co-activation of spoken and

signed lexical representations during encoding or retrieval (see also Emmorey et al., 2010; Hamilton & Holzman, 1989). More specifically, the co-activation of spoken and signed lexical representations during familiarization in the bimodal condition may have resulted in increased lexical activation and subsequent faster retrieval of the spoken lexical representations during testing. A similar explanation has been put forward with respect to nonverbal multisensory learning, namely that multisensory input creates or changes multisensory neural representations that are subsequently also activated by unisensory stimulation, providing a richer representation that can be used in sensory processing (for a review, see Shams & Seitz, 2008).

It remains to be explained, however, why cross-modal facilitation effects were only observed for minimally different word pairs and not for word pairs that were phonologically dissimilar (see Table 7.3). One possible, but speculative, answer to this question is that the encoding or retrieval of phonologically similar words might benefit more from increased lexical activation than phonologically dissimilar words because the former compete more with each other during spoken word recognition (see §2.1.2).

7.4.2 CROSS-MODAL INTERFERENCE

In contrast to the children with a CI, the adults with normal hearing appeared to experience cross-modal interference in the bimodal condition. This may be explained by their limited signing experience and/or lack of familiarity with bimodal language processing. Some of the adults had had no signing exposure at all. Moreover, although some adults had two years of signing experience as second language learners of NGT, it is likely that they were less often exposed to speech-sign combinations as the children with a CI. Processing of the signs in the bimodal stimuli may have been particularly effortful for them and may have interfered with processing of the spoken words in the same stimuli, perhaps due to competition between limited processing resources along the lines of Bergeson et al. (2005).

Furthermore, besides positively or negatively affecting speech perception, bimodal exposure also affected sign perception. More specifically, the children's responses on the familiar "minimal"⁴² sign pairs were slower when familiarization had been bimodal compared to only signed, and the same pattern was observed for the novel minimal sign pairs in the adults. These negative effects could be due to the longer interval between familiarization and testing for the sign pairs in the bimodal condition, or to a form of competition between processing resources in the bimodal condition, as discussed above. Either way, however, it remains unclear why only these specific stimulus pairs were affected.

⁴² Recall that the familiar sign pairs in the experiment were all non-minimal sign pairs (see §7.2.2).

7.4.3 CONCLUSION

To summarize, the results showed that bimodal input does not negatively affect speech perception in children with a CI. In fact, we found that bimodal input appeared to have a *positive* effect on their processing of familiar phonologically similar word pairs. It should be stressed that the sample size was small and that the results should therefore be interpreted with caution, especially because these concern null effects. However, if we visually compare the scores and reaction times in the speech and bimodal_{speech} conditions in Figures 7.2 and 7.3, we see that, if anything, scores in the latter condition tend to be higher (except for novel non-minimal pairs) and reaction times faster. This supports our conclusion that bimodal exposure does not negatively affect speech perception and even suggests that a larger sample size may reveal further evidence for cross-modal facilitation in lexical processing.

Further (longitudinal) studies with larger samples are needed to examine the role of the two language modalities, preferably over time. It is not unlikely, for instance, that the benefit from the signed modality is especially pronounced in the first few years following implantation and becomes smaller over time when children gain more experience with the CI and become more proficient in the spoken modality. Importantly, even when children perform age-appropriately on standardized spoken language tests and accurately perceive speech in quiet one-to-one situations, the signed modality may provide useful and much-needed support in more challenging conditions, such as during classroom discussions, playground activities and birthday parties⁴³. Future studies should also investigate whether the results obtained here with the presentation of isolated words and signs extend to sentences.

Nevertheless, the results reported in this chapter clearly show that exposing children with a CI to speech and sign at the same time does not necessarily negatively affect their speech perception and does not appear to create competition between limited processing resources. In fact, under some circumstances, namely when the auditory information that needs to be processed is particularly challenging, bimodal exposure may be beneficial, for instance, in retrieving lexical representations of phonologically similar words. These findings further our understanding of the effects of signed input on spoken language processing in children with a CI, although evidently much work remains to be done in this area (cf. Leigh, 2008).

⁴³ Research into the benefits that children with a CI can obtain from multimodal information in challenging listening conditions of course should not only concern the benefits of access to manual-visual information, but also of access to audiovisual information (see also §7.1.2). For instance, in collaboration with the Leiden University Medical Center we are currently involved in a study that investigates the relative benefit of visual speech information for speech perception in quiet and in noise in children with a CI and children with normal hearing (Beers & Giezen, in preparation).

8 CONCLUSIONS

In the final chapter of this thesis we will summarize the main findings and their implications. This summary is divided into two parts: underlying processes in speech perception (§8.1) and interactions between language modalities (§8.2). In §8.3 we will briefly consider the role of age effects in explaining the performance of the children with a CI. Finally, in §8.4 we will discuss methodological considerations related to this research and make recommendations for future studies.

8.1 UNDERLYING PROCESSES IN SPEECH PERCEPTION

8.1.1 SUMMARY OF MAIN FINDINGS

Our first research question was whether children with a CI use acoustic cues differently in consonant and vowel perception from age-matched children with normal hearing. We found that the children with a CI used several acoustic cues less effectively than their peers with normal hearing, although it should be noted that some of these effects were only marginally significant after adjusting for multiple comparisons. The effect was most pronounced for the spectral cues in the fricative contrast /fʊ/-/sʊ/, which also turned out to be the contrast that they discriminated most poorly in terms of identification of the endpoint stimuli and classification slope. However, we also found that both groups of children showed similar cue weighting patterns in sound categorization. They weighted the spectral cues as relatively stronger than other available cues such as duration in the vowel contrasts /a/-/ə/ and /ɪ/-/i/, and intensity in the consonant contrast /fʊ/-/sʊ/.

Overall, the children with a CI were able to use acoustic cues quite similarly to their age-matched peers with normal hearing, although somewhat less effectively. The reduced spectrotemporal resolution of sound processing with a CI does not therefore appear to lead to different acoustic cue weighting patterns, at least not for the sound contrasts included in this thesis. Age at implantation was not significantly correlated with sound perception, but length of CI use was. That is, the longer a child had been using the CI the steeper the classification slopes, which means better discrimination of the contrasts.

Our overall finding that the children with a CI tended to discriminate particular vowel and consonant contrasts less well than the children with normal hearing suggests that their sound representations are poorly specified, i.e., are weak and fuzzy. This raises the question as to whether they are able to create new lexical

representations on the basis of these sound representations. More generally, sound perception by six year-old typically developing children is not yet adult-like as evidenced by the performance differences between the children and adults on the sound categorization task in this thesis, and as shown in previous studies (e.g. Gerrits, 2001; Hazan & Barrett, 2000; Nitttrouer & Miller, 1997). Furthermore, it has been suggested in the literature that typically developing children at this age are restructuring their lexical representations, creating greater phonetic detail under the influence of vocabulary growth (e.g. Garlock et al., 2001; Storkel, 2002, 2004). This suggests that they may have difficulties with learning similar sounding words in rapid word learning experiments. Hearing difficulties are likely to present an extra challenge in this respect. We therefore tested children and adults' ability to learn novel minimal word pairs, e.g., the word pair /tat/-/tat/, after a limited amount of exposures to the words and referents. Crucially, the sound contrasts that distinguished the minimal pairs were the same vowel and consonant contrasts as tested in the sound categorization task.

The results showed that whereas both child groups had problems with learning novel minimal pairs in a demanding task, only the children with a CI experienced similar problems with a less demanding and more ecologically valid task. As expected, the scores of the adults approached ceiling. The observed difficulties of the children with normal hearing in the demanding task might relate to the fragile nature of newly created lexical representations. In contrast, the problems for the children with a CI may be more directly related to their hearing difficulties and resulting problems in sound perception.

We found some relationship between the obtained measures: sound perception, as measured by the sound categorization task, correlated with rapid word learning for the children with normal hearing, but not for the children with a CI. Phonological short-term memory, as measured by a digit span task, did not correlate with rapid word learning for either group of children. However, digit span and sound categorization were correlated for the children with a CI, suggesting that limitations in phonological short-term memory may have contributed to their poorer sound perception. Age at implantation and length of CI use did not correlate with rapid word learning performance. Length of CI use correlated significantly with digit span, suggesting that auditory experience is an important factor in the development of phonological short-term memory.

8.1.2 IMPLICATIONS

Spoken word recognition is characterized by competition between word candidates with overlapping phonological representations (Magnuson et al., 2007; see also

§2.1.2). Poor perception of sound contrasts and a lack of phonetic detail in newly created lexical representations can be predicted to increase lexical competition during spoken word recognition. When children with a CI are uncertain about which sounds and words they hear, co-activated word candidates will compete more strongly and/or for a longer time than in children with normal hearing. For instance, if they have difficulty distinguishing between /t/ and /s/, and they hear the sentence ‘It’s a funny day’, they will initially activate all word candidates starting with both /t/ and /s/ instead of only words starting with /t/. Furthermore, if the words *funny* and *sunny* are not clearly distinguished in their mental lexicon, both will remain equally activated until the semantic or pragmatic context decides on the correct interpretation. Word recognition and sentence processing may thus cause a greater cognitive load.

In this respect, the problems children with a CI experience during spoken word recognition may be similar to those experienced in second language (L2) listening. Because languages differ in their sound inventories, L2 learners may initially treat two different L2 sounds as belonging to one category because their first language does not distinguish between them (e.g. Best, McRoberts, & Goodell, 2001; Escudero et al., 2009; Escudero & Boersma, 2004; MacKay, Flege, Piske, & Schirru, 2001). Such inaccurate categorization of L2 phonemes can cause word recognition problems for L2 learners (Cutler, 2005). For instance, there is an increase of pseudo-homophones in their mental lexicon, i.e., words that sound alike but have different meanings. For Dutch learners of English, *cattle* may be activated when hearing *kettle* since they have difficulties distinguishing the vowel contrast /e/-/æ/. In addition, they may experience spurious lexical activation from non-words embedded in longer words or phrases that they confuse with real words as in *chess* in *chastise*. Finally, they have to resolve temporary ambiguity. For instance, upon hearing the first syllable of the word *pencil*, the word *panda* will also remain active. Each of these problems results in a (temporary) increase in lexical competition during spoken word recognition and slower lexical access. Children with a CI may therefore experience a similar increase in lexical competition during spoken word recognition because of inaccurate sound categorization. Indeed, two recent studies have found less efficient lexical access in children with a CI compared to their peers with normal hearing (Wass et al., 2009; Wechsler-Kashi, Schwartz, Cleary, & Madell, 2009).

In addition, our findings help to explain the recurrent finding that children with a CI have difficulties in learning novel words in rapid word learning tasks (Houston et al., 2005; Tomblin et al., 2007; Willstedt-Svensson et al., 2004). As explained in §2.1.2, when children hear novel words, they will initially try to match the input to words in their mental lexicon. Only when recognition fails will they form a new lexical representation. Competition between a novel word and familiar words in the

mental lexicon thus makes it more difficult to detect the novelty status of the word (Hoover et al., 2010; Jarvis, Merriman, Barnett, Hanba, & Van Haitsma, 2004; Storkel et al., 2006; Swingley & Aslin, 2007). Our results suggest that phonological neighborhoods in children with a CI might be larger than those of children with normal hearing. They might therefore experience more competition when encountering novel words.

Our results also have implications for the development of phonological awareness, an important precursor to reading. Several studies have reported poorer phonological awareness and/or word reading ability in children with a CI compared to their peers with normal hearing (e.g. Geers, 2003; James, Rajput, Brinton, & Goswami, 2008; James et al., 2005; Spencer & Tomblin, 2009). Metsala, Stavrinos and Walley (2009) recently showed that in typically developing children performance on a speech gating task⁴⁴ predicted the development of phonological awareness across a one-year span; phonological awareness in turn predicted word reading ability (see also Walley et al., 2003). The difficulties in learning to read that many children with a CI experience may thus be related to poor phonological specificity in their lexical representations.

Finally, poorly specified representations of speech sounds and words may negatively affect verbal working memory processes if phonological information is poorly encoded in short-term memory (e.g. Burkholder-Juhász et al., 2007; Pisoni et al., 1999). Indeed, our results showed a trend towards smaller digit spans in the children with a CI than their peers with normal hearing. Additionally, sound perception correlated positively with phonological short-term memory. It should be mentioned, however, that this relation may also be in the opposite direction (see §4.4.1). Most importantly, less efficient processing in verbal working memory has been associated with poorer spoken language outcomes in children with a CI (e.g. Dawson et al., 2002; Pisoni et al., 1999; Willstedt-Svensson et al., 2004).

Summarizing, increased lexical competition as a result of poor sound discrimination and a lack of phonetic detail in lexical representations can lead to a bottleneck in spoken language processing (see McMurray et al., 2010 for discussion). Language development starts with perceiving sounds and words and if these two processes are disturbed, spoken language acquisition will present a greater challenge, as illustrated by recent studies on the predictive powers of early speech perception abilities for later language development (e.g. Kuhl et al., 2005; Marchman & Fernald, 2008; Newman et al., 2006). Although advances in CI technology and newborn hearing screening have created opportunities for many deaf

⁴⁴ In a speech gating task participants are presented with word fragments of increasing duration and they have to guess the word after each fragment. This task can be used as a measure for the specificity of lexical representations (e.g. Mainela-Arnold, Evans, & Coady, 2008; Metsala et al., 2009).

children to acquire a spoken language and achieve near-to-age-equivalent scores on standardized spoken language tests, CIs do not restore normal hearing, as is also underlined by our results⁴⁵. Spoken communication remains effortful for children with a CI, especially in noisy environments that, unfortunately, characterize many situations in daily life. In addition, despite the fact that many children perform incredibly well with their implants, many others obtain much less or even minimal benefit from it. These children continue to show substantial delays in spoken language development after implantation and may never achieve the means for successful spoken communication. To reduce effortful spoken communication and to allow for alternative means of communication when the CI provides only limited benefits, it would seem important to also provide input in and access to another language modality, namely the signed modality.

8.2 INTERACTIONS BETWEEN LANGUAGE MODALITIES

8.2.1 SUMMARY OF MAIN FINDINGS

Whereas in Chapters 4 and 5 the focus was on the spoken modality and more specifically on speech perception in children with a CI, in Chapters 6 and 7 it was on the relationship between the spoken and the signed modality. The role of signed input in the education of children with a CI is strongly debated in the literature, with some studies reporting that it has profound negative effects on spoken language outcomes, while others report neutral or even positive effects (see §1.4.2 for detailed discussion). Our approach differed from these previous studies, however, because instead of comparing children from different educational settings, we assessed and related both language modalities in the same sample of children. A within-subject approach is less sensitive to confounding variables than a between-subjects approach, because in the latter approach the two groups of subjects may differ in aspects other than the variable of interest alone.

In addition to adopting a within-subject approach, a major difference between the research reported here and previous research is that we used experimental tasks as outcome measures instead of standardized tests. We did not include standardized

⁴⁵ It remains to be seen to which extent poor sound discrimination abilities in children with a CI can be improved by discrimination training and to which extent such training may generalize to phonological processing abilities (see e.g. Moore, Rosenberg, & Coleman, 2005 on typically developing children). Unfortunately, available training studies so far have focused on adult implant users (e.g. Fu & Galvin III, 2008; Loebach, Pisoni, & Svirsky, 2009; Stacey & Summerfield, 2008).

speech perception tests and vocabulary measures because we were interested precisely in the underlying processes that characterize performance on such tests. In addition, standardized speech perception and especially vocabulary tests are highly dependent on previous language experience. Studies with child and adult bilinguals have consistently shown smaller vocabularies in each of their languages than their monolingual counterparts (Bialystok, 2009). Smaller receptive and expressive spoken language vocabularies in children with a CI who receive signed input in addition to spoken input are therefore not unexpected. When spoken and signed vocabulary are considered together, these children may have equal or in fact larger vocabularies than those who receive only spoken input (see e.g. Connor et al., 2000).

To facilitate the comparison between the two language modalities, we assessed performance on a sign categorization task, two rapid sign learning tasks and a phonological short-term memory task for signed digits that were similar in design to their auditory counterparts. The performance of the children with a CI on the sign perception tasks was compared with that of children with normal hearing and no signing experience and adults with 1-2 years of signing experience as second language learners.

Comparison of both language modalities for the three groups of participants showed that the children with a CI performed similarly in both modalities on the picture-matching, object-matching and digit span tasks, while the other two groups, which had no or limited signing experience, were significantly less accurate in the signed modality (except for the adults in the digit span task due to a ceiling-effect). The children with a CI performed more poorly in the signed than the spoken modality on the categorization task in terms of their classification slopes. As we argued in §6.3.1, their relative difficulties with this task may not have been due to a lack of signing experience, but to the particular design of the task.

Despite as a group performing at equal levels in both modalities, inter-individual variation among the children with a CI in the signed modality was relatively large. Importantly, we showed that the observed variation in their sign perception abilities was positively associated with variation in their speech perception abilities. More specifically, we observed significant *positive* correlations between phoneme endpoint identification scores in the sound categorization task and classification slopes in the sign categorization task, between scores in the spoken and signed picture-matching tasks, and between reaction times in the spoken and signed picture-matching tasks. Furthermore, chronological age and length of CI use correlated positively with picture-matching scores in the signed modality. These positive correlations clearly show that relatively good performance in the signed modality does not preclude relatively good performance in the spoken modality. On the contrary, the children that had good speech perception abilities also had good sign perception abilities.

In order to further investigate the relationship between the two language modalities in children with a CI, we examined the interaction between both modalities when children are simultaneously exposed to speech and sign. Does exposing children with a CI to such bimodal input negatively affect speech perception, as suggested by Bergeson et al. (2005), or positively, as observed by Mollink et al. (2008) for hard-of-hearing children? To examine this children were familiarized with and tested on words, signs or simultaneously produced word-sign combinations that were either familiar or novel, and phonologically dissimilar or similar. We were unable to find negative effects of bimodal exposure on spoken word recognition and learning. In fact, for familiar minimal pairs, information from both modalities was beneficial because it resulted in faster reaction times compared to the speech condition.

8.2.2 IMPLICATIONS

Although it cannot be said that signing experience leads to improved speech perception, we were unable to find negative effects. In fact, we obtained positive correlations between performances in both language modalities for the children. Negative effects of signed input have been suggested in several studies comparing speech perception in children in Oral and Total Communication settings (Archbold et al., 2000; Geers et al., 2003a; Kirk et al., 2003; Pisoni et al., 1999; Svirsky et al., 2000). As discussed in §1.4.2, the findings from these studies were difficult to interpret for several reasons: 1) the variation in educational practices subsumed under the label Total Communication; 2) Oral Communication and Total Communication children may have differed in other respects than just communication modality; and 3) specifically those children who are showing less than expected progress may be more prone to end up in Total Communication settings and/or remain there for a longer time.

In Chapter 7, we specifically addressed one account of how simultaneously exposing children with a CI to speech and signs might negatively affect spoken language outcomes, namely the ‘division of visual attention’ account by Bergeson et al. (2005). Our results show, however, that it is very unlikely that bimodal input creates competition in visual attention between the face, for speech reading, and the hands, for sign recognition. If anything, the effect that we observed was positive and suggested cross-modal facilitation, not interference. We caution against generalization of these results, however, because the sample size and observed effects were small, and because we only examined the effects of bimodal input on the recognition and learning of isolated spoken words. Replication and extension of our findings is therefore warranted. Nevertheless, the results are suggestive and in

line with those from Chapter 6, namely that exposure to and use of the signed as well as the spoken modality does not impede development in children with a CI.

On the basis of our findings, we therefore argue in favor of signed input for children with a CI. Signed input before and for at least some time after implantation can provide the means for effective early parent-child interaction and can provide important foundations for cognitive, linguistic and social development (Marschark, 2007). Given that the majority of deaf children are born to hearing parents, achieving natural and effective communication in the signed modality is only possible with substantial effort from parents and encouragement from professionals. However, access to the signed modality will provide the children with the opportunity to use communicative means other than spoken language whenever needed to, for instance, in challenging listening environments, in the case of device malfunctioning or when interacting with deaf peers without a CI. Indeed, many parents think signing support is useful after implantation (Archbold et al., 2006; Christiansen & Leigh, 2004; Watson et al., 2008).

How long parents should provide signed input to their children at home and school and how much input there should be has to be considered for each child individually, but ensuring successful communication should be the main driving force in this decision. Creating access to the spoken modality may be the ultimate goal of cochlear implantation, but this does not necessarily imply that alternative means of communication cannot play a role in the lives of these children, or that speech-sign bilingualism should be discouraged. Regardless of whether a particular child with a CI will go through life relying solely on spoken communication, or will also use signed communication, the opportunities for development in both language modalities should be offered and this can only be achieved by providing input in both modalities from the outset and at least throughout a substantial part of childhood.

On a final note, we would like to mention the possibility that any delays in spoken language development in children with a CI that also receive signed input may not be permanent. Although opinions will surely differ on this matter, temporary delays in spoken language development might be justified in order to stimulate sign language development. More longitudinal studies are needed to determine whether differences in spoken language abilities between children with and without signed input decrease over time and may eventually disappear (see e.g. Bergeson et al., 2005).

8.3 AGE EFFECTS

Throughout Chapters 4 until 7, we have considered the role of age at implantation, length of CI use and chronological age in explaining the performance of the children with a CI. Especially age at implantation has often been found to affect spoken language outcomes in this population (see §1.4.1 for a detailed discussion). However, it did not correlate significantly with any of the outcome measures included in the present thesis. In §5.4.2 it was suggested that this may have been due to the small sample size in combination with the restricted range in age at implantation in our sample and the fact that most children in our sample were implanted in the first two years of life. Most available studies on the role of age at implantation investigated samples with a wider range in age at implantation and thus also included children who were implanted after two years of age (e.g. Anderson et al., 2004; Artieres et al., 2009; Chin et al., 2007; Geers et al., 2003b; Kirk et al., 2003; Nicholas & Geers, 2007; Svirsky et al., 2004; Zwolan et al., 2004).

Although age at implantation and length of CI use were to some extent confounded in our sample (see §3.1.1), we did observe a significant positive correlation between length of CI use and several outcome measures (see §5.3.4, §6.4 and §7.3.3). That is, the longer the child was using the device, the better he or she performed on the tasks, in the spoken as well as the signed modality. These correlations with length of CI use suggest an important role for language input after implantation in the development of speech and sign perception abilities.

To summarize, although age effects only weakly influenced performance on our outcome measures, they suggest that length of CI use is a more important factor than age at implantation in explaining speech perception abilities in a sample of children with a CI that were implanted relatively early. Moreover, length of CI use positively impacted on both speech and sign perception abilities. It is possible that age at implantation is more important in predicting early spoken language development, whereas later outcomes are affected relatively more by length of CI use (see e.g. Artieres et al., 2009; Geers et al., 2009). Alternatively, age at implantation may mainly be found to be an influencing factor in samples that include a wider range in ages at implantation and thus also a substantial number of children that are implanted after two years of age (see e.g. Nicholas & Geers, 2007)⁴⁶.

⁴⁶ However, Coene et al. (in press) recently showed effects of age at implantation on a variety of linguistic measures in a sample of 9 children with a CI implanted between 5 and 19 months of age.

8.4 METHODOLOGICAL CONSIDERATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

In the concluding section of this thesis, we would like to discuss a few methodological considerations regarding generalization of our findings and future research.

8.4.1 SAMPLE REPRESENTATIVENESS

Our sample of children with a CI was relatively small, especially given the large inter-individual variation in this population (§1.3.1). As a consequence, the statistical power in the analyses was low. A larger sample may therefore have revealed further differences between children with a CI and children with normal hearing that we were unable to detect in the present study. It should be noted, however, that despite small numbers the sample was relatively homogenous (§3.1.1). The children were all pre-lingual profoundly deaf and ten out of 15 children had been implanted in the first two years of life. The surgery had been uneventful and the implants fully inserted for all children. They were also fitted with the latest speech processing algorithm available at the time. Parent involvement was overall average to high and at the time of study all children wore their implant for at least the greater part of the day. All children had at least one hearing parent and Dutch was the only spoken language used at home. Furthermore, at the time of testing no additional disabilities had been diagnosed for any of the children. Because of the relative homogeneity of our sample, several sources of inter-individual variation known to affect outcomes in this population had largely been controlled for, such as the age at onset and severity of hearing loss, the number of languages spoken at home and the presence of any additional disabilities. Especially for small samples, homogeneity can thus be considered an advantage. Evidently many other sources of variation remain that we were unable to control for, such as type of CI, etiology of hearing loss, and frequency and intensity of speech-language therapy.

Homogeneity of a sample can also be considered a disadvantage, however, because it limits the sample representativeness. That is, whereas our sample may have been quite homogenous, the wider population of children with a CI is not and includes children varying widely in age at onset and severity of hearing loss, age at diagnosis, age at implantation, success of the surgery, nonverbal IQ, family support, classroom placement and so on (Geers et al., 2007). Ideally, outcome studies should include all children consecutively implanted at an implant center in a specific time period, regardless of background, success of the surgery and fitting, consistency of CI use or educational setting. Only few studies so far have accomplished that,

however (Marschark et al., 2007). In addition, there is a need for research projects involving multiple CI centers, allowing for large representative samples (e.g. Fink et al., 2007). In the European context, this may also be achieved with collaborations between centers from different countries and support from supranational funding agencies. Such international studies may also allow more fine-grained distinctions in assessing effects of communication modality and educational approaches than has hitherto been possible (e.g., distinguishing between Auditory-Verbal, Bilingual-Bicultural, Simultaneous Communication, and Total Communication approaches).

8.4.2 ECOLOGICAL VALIDITY

The outcome measures included in this thesis were all experimental tasks specifically designed to answer our research questions. The advantage of using experimental measures is that it allows for methodological control of variables. For instance, in order to exclude the role of previous language experience, we opted for rapid word learning tasks instead of standardized vocabulary tests to examine lexical learning in this thesis. However, an increase in methodological control usually comes at the cost of a decrease in *ecological validity*. That is, the participants had to perform tasks that were not necessarily representative of natural behavior. Although children, and to a lesser extent adults, are frequently exposed to novel words, these are usually not minimal pairs and they are usually not produced in the absence of semantic context that provides clues as to their meaning.

This concern applies to much experimental research in general, but in the case of children with a CI two additional concerns should be noted. Assessing children in quiet testing rooms under laboratory-like experimental conditions does not reflect their performance in more naturalistic, noisy environments (see also §1.3.1). Moreover, neither experimental sound perception or word learning tasks nor standardized spoken language tests reflect their communicative functioning (Beadle et al., 2005; Lin et al., 2008). There is therefore a strong need for studies that examine the functional listening performance of children with a CI in more natural environments, e.g., at home or in their classrooms, and for the development of measures of communicative functioning specifically targeted to this population (e.g. Lin et al., 2007).

8.4.3 MOVING TARGETS

The rapidly changing face of cochlear implantation and thus also of the population of children with a CI (see also §1.2) is a major challenge for research. The continuing technological improvement of the CI and the processing algorithms

provides children implanted today with a better starting position than those implanted six years ago, such as the children in this thesis. In addition, more children with a CI receive bilateral implants now than six years ago, either sequentially or simultaneously⁴⁷. Furthermore, children with severe hearing loss and not only profound hearing loss are now also implanted (e.g. Fitzpatrick et al., 2009). Finally, although the children in our sample were implanted relatively early (1;8 on average), this can still be considered fairly late according to today's standards (e.g. Archbold & O'Donoghue, 2009; Eter & Balkany, 2009; Holt & Svirsky, 2008; Papsin & Gordon, 2007). The results we have presented here might therefore not apply to children that have been implanted more recently. As discussed by Geers (2006), children with a CI form a rapidly moving target and outcome research is soon outdated. However, we should not forget that the children who received their implants six years ago have to learn to read today and present their teachers with challenges on how to best help them in this process. These children should therefore not be neglected in pediatric CI research.

8.4.4 INTER-INDIVIDUAL VARIATION IN PERFORMANCE

A final issue concerns inter-individual variation. Large inter-individual variation has been reported often in the pediatric CI literature (Belzner & Seal, 2009; Bond et al., 2009; Peterson et al., 2010; Schauwers et al., 2005; Thoutenhoofd et al., 2005), and the research presented here is no exception. All analyses presented in Chapters 4 to 7 involved group results and comparisons. However, as can be judged from the standard errors in the bar charts and the individual results listed in Appendices C and E, performance by the children with a CI was characterized by substantial inter-individual variation. To illustrate this point, we will review the performance of three children in some detail here, relative to that as a group⁴⁸.

For instance, child A1, a Flemish child implanted at 0;9, was in a mainstream school at the time of study. His performance in the spoken modality resembled that of the group (e.g., 63% correct for sound categorization, 75% for picture-matching and 50% for object-matching). As expected given his limited signing experience, he performed relatively poorly in the signed modality (e.g., 25% correct for sign categorization, 69% for picture-matching task and only 25% for object-matching). In the study from Chapter 7, he was one of the children that benefited most from the bimodal input. His overall percentage correct scores were 79% in the speech

⁴⁷ In our sample three children had received a second implant. In addition, one child used an implant on one side and an acoustic hearing aid on the other; this has also become more common in recent years and is called electric-acoustic or bimodal hearing (for reviews, see Ching et al., 2007; Firszt et al., 2008; Nittrouer & Chapman, 2009; Schafer et al., 2007).

⁴⁸ Background characteristics of these children can be found in §3.1 (Table 3.1).

condition, 88% in the sign condition and 96% for the words in the bimodal condition.

Child *D8*, a Dutch child implanted at 2;1, was also in a mainstream school at the time of study. He performed relatively well in the spoken modality (e.g., 63% correct for sound categorization, 72% for picture-matching and 88% for object-matching) and also in the signed modality (e.g., 100% correct for sign categorization, 100% for picture-matching and 75% for object-matching). His overall percentage correct scores in study from Chapter 7 approached ceiling (96% correct in the speech condition, 92% in the sign condition and 96% for the words in the bimodal condition).

Child *S5*, a Dutch child implanted at a relatively late age, namely 3;9, was at a school of the deaf at the time of the study. He performed relatively poorly in the spoken modality (e.g., 50% correct for sound categorization, 53% for picture-matching, but surprisingly, 100% for object-matching) as well as the signed modality (e.g., 50% correct for sign categorization, 38% for picture-matching, but again surprisingly, 75% for object-matching). His overall percentage correct scores in the study from Chapter 7 were relatively low and he did not appear to benefit much from bimodal input (83% correct in the speech condition, 88% in the sign condition and 83% for the words in the bimodal condition).

The observed variation in performance among these three children underlines that any conclusions based on group results should be interpreted with caution and should take into account the inter-individual variation in the group. Moreover, there is the issue of incomplete or missing data. Not all children completed each of our tasks and a few children failed to complete some tasks in their entirety. This is not very surprising given that experimental data from young children, typically or atypically developing, is often characterized by missing data. However, the children with a CI in our sample more often did not complete a task than the age-matched children with normal hearing, suggesting that there is more to the problem than just chronological age or general cognitive ability. Unfortunately, incomplete data is very difficult to interpret. For instance, it may be that, because they are generally more often tested than children with normal hearing, they felt less constrained in indicating that they did not want to continue anymore. Alternatively, it may be that they got tired earlier than their peers with normal hearing because attentive listening is more difficult for them.

More importantly, however, two children had to be excluded from all analyses in Chapters 4 to 6 because they failed to complete *several* of the tasks. As such, they did not contribute to the group results and the variation in those results, but they are relevant to the present discussion. For one of these children, implanted at 1;8, fitting and programming of the CI had been problematic. In general, she was considered a low performer with the implant and mainly communicated in sign language. These circumstances likely contributed to her difficulties with completing the speech

perception tasks. She was however able to complete the sign perception tasks. The second child, implanted at 0;8, was very inattentive on both testing days, resulting in difficulties in completing our tasks. This child was generally considered a good performer with the implant. It is possible that we simply tested the child at an unfavorable moment. Alternatively, this child may have clinically relevant attention difficulties. For instance, Pisoni et al. (2008) discuss preliminary results showing that children with a CI are rated more poorly than children with normal hearing on several scales of executive functioning, including attention and behavioral regulation (see also Barker et al., 2009).

Large inter-individual variation in outcomes among children with a CI stresses the need for individually based intervention. More specifically, the population of children with a CI includes children who rapidly catch up with their peers with normal hearing, children who develop their spoken language with the same rate and therefore maintain a constant language delay, and children whose language delay increases over time (see e.g. Nicholas & Geers, 2007). Thus, varied educational choices have to be made regarding special education or mainstreaming in terms of the type and amount of additional support a child should receive. More specifically, some children may do very well in mainstream settings and not need additional signed support, while others may need such support. The problem with waiting until it becomes clear that a child does not make sufficient progress and therefore needs additional support is that a delay in social-emotional, cognitive and linguistic development might already have occurred (Leigh, 2008).

This thesis has provided evidence that the spoken and the signed modality do not interfere with each other and that they may even enhance one another under specific circumstances. Clearly, further research that examines the relation and interaction between both modalities in this population is needed before the debate on the effects of signed input on spoken language outcomes can be settled. However, if future studies corroborate the findings presented here, we see no reason why children with a CI should not receive signed input in addition to spoken input. This would ensure successful communication at all times and give them the opportunity to profit from the best of both modalities as they become successful speech-sign bilinguals.

APPENDICES

Appendix A. Acoustic values of the stimuli for each contrast included in the categorization task.

Contrast					Contrast				
Manipulated cues					Manipulated cues				
/a/-/a/ Spectrum (Hz (Mel)) Duration (msec)					/bu/-/pu/ VOT				

Appendix B. Means and medians (between parentheses) of the dependent variables for the children with a CI (CI), the children with normal hearing (NH) and the adults (A) for each contrast in the sound categorization task.

Contrast	Group	Endpoints	Individual cue reliance				Cue ratio	Slope
		%	spectrum	duration	VOT	intensity		
/a/-/a/	CI, <i>n</i> =5	75 (75)	1.12 (.44)	.05 (-.11)			.78 (.76)	1.18 (.45)
	NH, <i>n</i> =11	84 (100)	20.47 (1.98)	8.04 (.63)			.68 (.67)	22.31 (2.00)
	A, <i>n</i> =20	94 (100)	41.07 (57.56)	28.49 (34.24)			.56 (.60)	50.32 (68.07)
/i/-/i/	CI, <i>n</i> =5	60 (50)	-.03 (-.11)	-.03 (.00)			.74 (.75)	.26 (.27)
	NH, <i>n</i> =9	78 (75)	-7.20 (-.90)	-1.26 (-.34)			.67 (.74)	7.36 (.99)
	A, <i>n</i> =21	93 (100)	-29.11 (-3.39)	15.66 (1.39)			.72 (.67)	33.11 (3.41)
/bu/-/pi/	CI, <i>n</i> =5	65 (75)			.09 (.23)			.06 (.06)
	NH, <i>n</i> =8	75 (75)			4.13 (.70)			1.03 (.18)
	A, <i>n</i> =21	96 (100)			25.99 (28.24)			6.50 (7.06)
/fu/-/su/	CI, <i>n</i> =6	54 (50)	.03 (.00)			.07 (.00)	.73 (.75)	.37 (.31)
	NH, <i>n</i> =10	98 (100)	7.16 (1.89)			1.18 (.11)	.88 (.92)	7.29 (1.90)
	A, <i>n</i> =20	94 (100)	20.83 (3.06)			5.40 (.95)	.76 (.75)	22.21 (3.22)

Note. Endpoints=phoneme endpoint identification, VOT=voice onset time

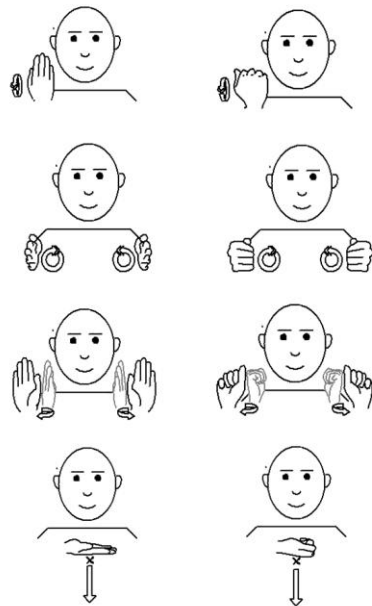
Appendix C. Individual results of the children with a CI on the categorization, lexical learning tasks and pSTM tasks in both language modalities.

Child	Spoken modality					Signed modality				
	XAB		PICT	OBJ	pSTM	XAB		PICT	OBJ	pSTM
	%	slope	%	%	span	%	slope	%	%	span
N7	50.0	.18	62.5	25.0	3	--	--	68.8	50.0	2
X5	50.0	.27	75.0	50.0	4	50.0	.01	100.0	100.0	2
A1	62.5	.88	75.0	50.0	4	25.0	.04	68.8	25.0	--
J3	50.0	.39	59.4	62.5	--	75.0	.02	50.0	--	--
V4	75.0	1.69	75.0	50.0	4	50.0	.04	100.0	0.0	3
S7	62.5	.17	78.1	75.0	3	--	--	--	100.0	2
T1	50.0	.16	79.1	25.0	2	50.0	.01	87.5	--	3
L2	75.0	.19	65.6	37.5	3	--	--	68.8	100.0	3
D8	62.5	.63	71.8	50.0	3	100.0	.08	100.0	75.0	4
K3	75.0	.09	71.8	87.5	3	50.0	.11	87.5	75.0	2
L6	75.0	.45	71.8	62.5	3	25.0	.03	87.5	50.0	2
L4	--	--	84.4	50.0	--	--	--	81.3	75.0	--
S5	50.0	.19	53.1	100.0	--	50.0	.01	38.5	75.0	--

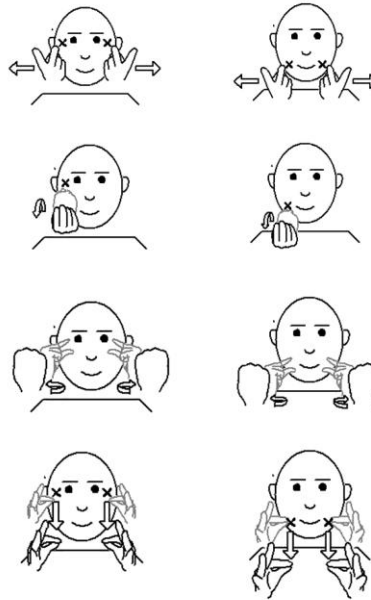
Note. XAB= categorization task (%=phoneme endpoint identification), PICT=picture-matching, OBJ=object-matching, pSTM=phonological short-term memory

Appendix D. Illustrations of the non-signs used in this thesis.

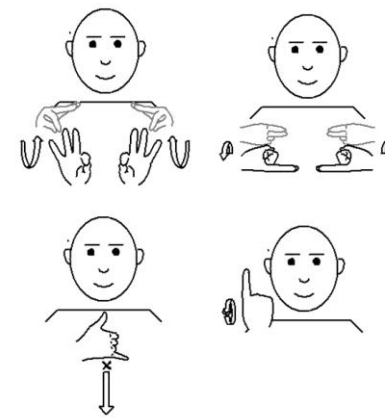
/open/-/closed/ contrast



/eye/-/chin/ contrast



other



Appendix E. Percentage correct scores (%) and reaction times (RT, msec) of the individual children with a CI in the speech, sign, bimodal_{speech} and bimodal_{sign} conditions.

ID		Speech	Sign	Bimodal _{speech}	Bimodal _{sign}
N7	%	95.8	100.0	79.2	95.8
	RT	1361	1464	1423	1325
A1	%	79.2	87.5	95.8	95.8
	RT	1350	1288	1099	2110
J3	%	91.7	95.8	95.8	87.5
	RT	1553	1791	1515	1836
S7	%	95.8	91.7	95.8	95.8
	RT	1068	1073	1488	1600
L2	%	91.7	100.0	95.8	91.7
	RT	1411	1174	1178	1435
D8	%	95.8	91.7	95.8	91.7
	RT	1236	1149	1301	1395
L4	%	91.7	91.7	87.5	91.7
	RT	1725	1531	1042	1815
S5	%	83.3	87.5	83.3	79.2
	RT	2770	2083	2331	1883

BIBLIOGRAPHY

- Adank, P., Van Hout, R., & Smits, R. (2004). An acoustic description of the vowels of Northern and Southern Standard Dutch. *Journal of the Acoustical Society of America*, 116, 1729-1738.
- Adank, P., Van Hout, R., & Van de Velde, H. (2007). An acoustic description of the vowels of northern and southern standard Dutch II: regional varieties. *Journal of the Acoustical Society of America*, 121, 1130-1141.
- Anderson, I., Weichbold, V., D'Haese, P. S. C., Szuchnik, J., Quevedo, M. S., Martin, J., et al. (2004). Cochlear implantation in children under the age of two- what do the outcomes show us? *International Journal of Pediatric Otorhinolaryngology*, 68, 425-431.
- Apoussidou, D. (2006). *The learnability of metrical phonology*. Utrecht: LOT Dissertation Series 148.
- Archbold, S. M., Nikolopoulos, T. P., & Lloyd-Richmond, H. (2009). Long-term use of cochlear implant systems in paediatric recipients and factors contributing to non-use. *Cochlear Implants International*, 10, 25-40.
- Archbold, S. M., Nikolopoulos, T. P., Tait, D. M., O'Donoghue, G. M., Lutman, M. E., & Gregory, S. (2000). Approach to communication, speech perception and intelligibility after paediatric cochlear implantation. *British Journal of Audiology*, 34, 257-264.
- Archbold, S. M., & O'Donoghue, G. M. (2009). Cochlear implantation in children: current status. *Paediatrics and Child Health*, 19, 457-463.
- Archbold, S. M., Sach, T. H., O'Neill, C., Lutman, M. E., & Gregory, S. (2006). Deciding to have a cochlear implant and subsequent after-care: parental perspectives. *Deafness and Education International*, 8, 190-206.
- Archbold, S. M., Sach, T. H., O'Neill, C., Lutman, M. E., & Gregory, S. (2008). Outcomes from cochlear implantation for child and family: parental perspectives. *Deafness and Education International*, 10, 120-142.
- Artieres, F., Vieu, A., Mondain, M., Uziel, A., & Venail, F. (2009). Impact of early cochlear implantation on the linguistic development of the deaf child. *Otology and Neurotology*, 30, 736-742.
- Baayen, H., Piepenbrock, R., & Van Rijn, H. (1993). The CELEX lexical database [CD-ROM]. Philadelphia, PA: University of Pennsylvania Linguistics Data Consortium.
- Baddeley, A. D. (2003). Working memory and language: an overview. *Journal of Communication Disorders*, 36, 189-208.
- Bahng, J. (2008). Acoustic cue weighting in children wearing cochlear implants. Unpublished Doctoral dissertation. University of Tennessee.
- Bahrick, L. E., Lickliter, R., & Flom, R. (2004). Intersensory redundancy guides the development of selective attention, perception, and cognition in infancy. *Current Directions in Psychological Science*, 13, 99-102.
- Baker, A. E., & Van den Bogaerde, B. (2008). Code mixing in signs and words in input to and output from children. In C. Plaza Pust & E. Morales Lopez (Eds.), *Sign bilingualism: language development, interaction and maintenance in language contact situations* (pp. 1-27). Amsterdam: John Benjamins.

- Baker, A. E., Van den Bogaerde, B., Pfau, R., & Schermer, G. T. (Eds.). (in preparation). *Sign linguistics: an introduction*. Amsterdam: John Benjamins.
- Baker, A. E., Van den Bogaerde, B., & Woll, B. (2005a). Methods and procedures in sign language acquisition studies. *Sign Language and Linguistics*, 8, 7-59.
- Baker, S. A., Golinkoff, R. M., & Petitto, L.-A. (2006). New insights into old puzzles from infants' categorical discrimination of soundless phonetic units. *Language Learning and Development*, 2, 147-162.
- Baker, S. A., Isardi, W. J., Golinkoff, R. M., & Petitto, L.-A. (2005b). The perception of handshapes in American Sign Language. *Memory and Cognition*, 33, 887-904.
- Barker, D. H., Quittner, A. L., Fink, N. E., Eisenberg, L. S., Tobey, E. A., Niparko, J. K., et al. (2009). Predicting behavior problems in deaf and hearing children: the influences of language, attention and parent-child communication. *Development and Psychopathology*, 21, 373-392.
- Baskent, D. (2006). Speech recognition in normal hearing and sensorineural hearing loss as a function of the number of spectral channels. *Journal of the Acoustical Society of America*, 120, 2908-2925.
- Bat-Chava, Y., Martin, D., & Kosciw, J. G. (2005). Longitudinal improvements in communication and socialization of deaf children with cochlear implants and hearing aids: evidence from parental reports. *Journal of Child Psychology and Psychiatry*, 46, 1287-1296.
- Battison, R. (1978). *Lexical borrowing in American Sign Language*. Silver Spring, MD: Linstok.
- Baus, C., Gutierrez-Sigut, E., Quer, J., & Carreiras, M. (2008). Lexical access in Catalan Signed Language production. *Cognition*, 108, 856-865.
- Bavelier, D., & Neville, H. J. (2002). Cross-modal plasticity: where and how? *Nature Reviews: Neurosciences*, 3, 443-452.
- Bavelier, D., Newport, E. L., Hall, M., Supalla, T., & Boutla, M. (2008). Ordered short-term memory differs in signers and speakers: implications for models of short-term memory. *Cognition*, 107, 433-549.
- Bavelier, D., Newport, E. L., Hall, M. L., Supalla, T., & Boutla, M. (2006). Persistent differences in short-term memory span between sign and speech: implications for cross-linguistic comparisons. *Psychological Science*, 17, 1090-1092.
- Beadle, E. A. R., McKinley, D. J., Nikolopoulos, T. P., Brough, J., O'Donoghue, G. M., & Archbold, S. M. (2005). Long-term functional outcomes and academic-occupational status in implanted children after 10 to 14 years of cochlear implant use. *Otology and Neurotology*, 26, 1152-1160.
- Beckman, M. E., & Edwards, J. (2000). The ontogeny of phonological categories and the primacy of lexical learning in linguistic development. *Child Development*, 71, 240-249.
- Beers, W., & Giezen, M. R. (in preparation). Audiovisual integration in children with a CI in quiet and noise.
- Belzner, K. A., & Seal, B. C. (2009). Children with cochlear implants: a review of demographics and communication outcomes. *American Annals of the Deaf*, 154, 311-333.

- Berg, A. L., Ip, S. C., Hurst, M., & Herb, A. (2007). Cochlear implants in young children: informed consent as a process and current practices. *American Journal of Audiology*, 16, 13-28.
- Bergeson, T. R., Houston, D. M., & Miyamoto, R. T. (2010). Effects of congenital hearing loss and cochlear implantation on audiovisual speech perception in infants and children. *Restorative Neurology and Neuroscience*, 28, 157-165.
- Bergeson, T. R., Pisoni, D. B., & Davis, R. O. A. (2005). Development of audiovisual comprehension skills in prelingually deaf children with cochlear implants. *Ear and Hearing*, 26, 149-164.
- Bernhardt, B. M., Kemp, N., & Werker, J. F. (2007). Early word-object associations and later language development. *First Language*, 27, 315-328.
- Best, C. T., Mathur, G., Miranda, K. A., & Lillo-Martin, D. (2010). Effects of sign language experience on categorical perception of dynamic ASL pseudosigns. *Attention, Perception, & Psychophysics*, 72, 742-762.
- Best, C. T., McRoberts, G. W., & Goodell, E. (2001). Discrimination of non-native consonant contrasts varying in perceptual assimilation to the listener's native phonological system. *Journal of the Acoustical Society of America*, 109, 775-794.
- Bialystok, E. (2001). *Bilingualism in development: language, literacy and cognition*. Cambridge: Cambridge University Press.
- Bialystok, E. (2009). Bilingualism: the good, the bad, and the indifferent. *Bilingualism: Language and Cognition*, 1, 3-11.
- Birdsong, D. (2006). Age and second language acquisition and processing: a selective overview. *Language Learning*, 56, 9-49.
- Bischof, H. J. (2007). Behavioral and neuronal aspects of developmental sensitive periods. *Neuroreport*, 18, 461-465.
- Bishop, M. (2006a). Bimodal bilingualism in hearing, native users of American Sign Language.
- Bishop, M. (2006b). Bimodal bilingualism in hearing, native users of American Sign Language. Unpublished Doctoral dissertation. Gallaudet University.
- Bishop, M., & Hicks, S. L. (2005). Orange eyes: bimodal bilingualism in hearing adults from deaf families *Sign Language Studies*, 5, 188-230.
- Blamey, P. J., Sarant, J. Z., Paatsch, L. E., Barry, J. G., Bow, C. P., Wales, R. J., et al. (2001). Relationships among speech perception, production, language, hearing loss, and age in children with impaired hearing. *Journal of Speech, Language and Hearing Research*, 44, 264-285.
- Boersma, P. (1998). *Functional phonology*. The Hague: Holland Academics Graphics.
- Boersma, P., & Escudero, P. (2005). Measuring relative cue weighting: a reply to Morrison. *Studies in Second Language Acquisition*.
- Boersma, P., Escudero, P., & Hayes, R. (2003). *Learning abstract phonological from auditory phonetic categories: an integrated model for the acquisition of language-specific sound categories*. Paper presented at the 15th International Congress of Phonetic Sciences, Barcelona.
- Boersma, P., & Weenink, D. (2008). Praat: doing phonetics by computer (Version 5.0.23) [Computer Program]. Retrieved 10 May 2008 from < www.praat.org >.

- Bollard, P. M., Chute, P. M., Popp, A., & Parisier, S. C. (1999). Specific language growth in young children using the Clarion cochlear implant. *Annals of Otology, Rhinology and Laryngology*, 108, 119-123.
- Bond, M., Elston, J., Mealing, S., Anderson, R., Weiner, G., Taylor, R. S., et al. (2009). Effectiveness of multi-channel unilateral cochlear implants for profoundly deaf children: a systematic review. *Clinical Otolaryngology*, 34, 199-211.
- Bortfeld, H., & Whitehurst, G. J. (2001). Sensitive periods in first language acquisition. In D. B. Bailey-jr., J. T. Bruer, F. J. Symons & J. W. Lichtman (Eds.), *Critical thinking about critical periods* (pp. 173-192). Baltimore: Paul H. Brookes Publishing.
- Boutla, M., Supalla, T., Newport, E. L., & Bavelier, D. (2004). Short-term memory span: insights from sign language. *Nature Neuroscience*, 7, 997-1002.
- Brackenbury, T., Ryan, T., & Messenheimer, T. (2006). Incidental word learning in a hearing child of deaf adults. *Journal of Deaf Studies and Deaf Education*, 11, 76-93.
- Brasileiro, I. (2009). *The effects of bilingualism on children's perception of speech sounds*. Utrecht: LOT.
- Brentari, D. (1990). Theoretical foundations of American Sign Language phonology. Unpublished PhD dissertation. University of Chicago.
- Brentari, D. (1998). *Prosodic model of sign language phonology*. Cambridge, MA: MIT Press.
- Bruer, J. T. (2001). A critical and sensitive period primer. In D. B. Bailey-jr., J. T. Bruer, F. J. Symons & J. W. Lichtman (Eds.), *Critical thinking about critical periods* (pp. 3-26). Baltimore: Paul H. Brookes Publishing.
- Burkholder-Juhasz, R. A., Levi, S. V., Dillon, C. M., & Pisoni, D. B. (2007). Nonword repetition with spectrally reduced speech: some developmental and clinical findings from pediatric cochlear implantation. *Journal of Deaf Studies and Deaf Education*, 12, 472-485.
- Burkholder, R. A., & Pisoni, D. B. (2003). Speech timing and working memory in profoundly deaf children after cochlear implantation. *Journal of Experimental Child Psychology*, 85, 63-88.
- Burkholder, R. A., & Pisoni, D. B. (2006). Working memory capacity, verbal rehearsal speed and scanning in deaf children with cochlear implants. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children* (pp. 328-357). Oxford: Oxford University Press.
- Campbell, R., MacSweeney, M., & Waters, D. (2008). Sign language and the brain: a review. *Journal of Deaf Studies and Deaf Education*, 13, 3-20.
- Capek, C. M., Grossi, G., Newman, A. J., McBurney, S. L., Corina, D. P., Roeder, B., et al. (2009). Brain systems mediating semantic and syntactic processing in deaf native signers: biological invariance and modality specificity. *Proceedings of the National Academy of Sciences of the United States of America*, 106, 8784-8789.
- Capek, C. M., Woll, B., MacSweeney, M., Waters, D., McGuired, P. K., David, A. S., et al. (2010). Superior temporal activation as a function of linguistic

- knowledge: Insights from deaf native signers who speechread. *Brain and Language*, 112, 129-134.
- Capone, N. C., & McGregor, K. K. (2004). Gesture development: a review for clinical and research practices. *Journal of Speech, Language and Hearing Research*, 47, 173-186.
- Carreiras, M., Gutierrez-Sigut, E., Baquero, S., & Corina, D. P. (2008). Lexical processing in Spanish Signed Language (LSE). *Journal of Memory and Language*, 58, 100-122.
- Casey, S., & Emmorey, K. (2009). Co-speech gesture in bimodal bilinguals. *Language and Cognitive Processes*, 24, 290-312.
- Cassandro, E., Nicastrì, G., Chiarella, G., Genovese, E., & Gallo, M. C. (2003). Development of communication and speech skills after cochlear implant in a sign language child. *Acta Otorhinolaryngologica Italica*, 23, 88-93.
- Chin, S. B., Svirsky, M. A., & Jester, A. (2007). The effects of age at implantation on speech intelligibility in pediatric cochlear implant users: clinical outcomes and sensitive periods. *Audiological Medicine*, 5, 293-306.
- Ching, T. Y. C., Van Wanrooy, E., & Dillon, H. (2007). Binaural-bimodal fitting or bilateral implantation for managing severe to profound deafness: a review. *Trends in Amplification*, 11, 161-192.
- Christiansen, J. B., & Leigh, I. W. (2004). Children with cochlear implants: changing parent and Deaf community perspectives. *Archives of Otolaryngology: Head and Neck Surgery*, 130, 673-677.
- Cleary, M., Pisoni, D. B., & Geers, A. E. (2001). Some measures of verbal and spatial working memory in eight- and nine-year old hearing-impaired children with cochlear implants. *Ear and Hearing*, 22, 395-411.
- Coene, M., Schauwers, K., Gillis, S., Rooryck, J., & Govaerts, P. J. (in press). Genetic predisposition and sensory experience in language development: evidence from cochlear-implanted children. *Language and Cognitive Processes*.
- Coerts, J. A., Mills, A. E., Van den Broek, P., & Brokx, J. (1994). De taalontwikkeling van dove kinderen met een cochleaire implant. *Stem-, Spraak- en Taalpathologie*, 3, 42-62.
- Cohen, J. D., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: a new graphic interactive environment for designing psychology experiments. *Behavioral Research Methods, Instruments, and Computers*, 25, 257-271.
- Colletti, L. (2009). Long-term follow-up of infants (4-11 months) fitted with cochlear implants. *Acta Oto-Laryngologica*, 129, 361-366.
- Connor, C. M., Craig, H. K., Raudenbush, S. W., Heavner, K., & Zwolan, T. A. (2006). The age at which young deaf children receive cochlear implants and their vocabulary and speech-production growth: Is there an added value for early implantation? *Ear and Hearing*, 27, 628-644.
- Connor, C. M., Hieber, S., Arts, H. A., & Zwolan, T. A. (2000). Speech, vocabulary, and the education of children using cochlear implants: oral or total communication? *Journal of Speech, Language and Hearing Research*, 43, 1185-1204.
- Connor, C. M., & Zwolan, T. A. (2004). Examining multiple sources of influence on the reading comprehension skills of children who use cochlear implants. *Journal of Speech, Language and Hearing Research*, 47, 509-526.

- Corina, D. P., & Hildebrandt, U. C. (2002). Psycholinguistic investigations of phonological structure in ASL. In R. P. Meier, K. Cormier & D. Quinto-Pozos (Eds.), *Modality and structure in signed and spoken languages* (pp. 88-111). Cambridge: Cambridge University Press.
- Corina, D. P., & Sandler, W. (1993). On the nature of phonological structure in sign language. *Phonology*, 10, 165-207.
- Corina, D. P., & Singleton, J. (2009). Developmental social cognitive neuroscience: insights from deafness. *Child Development*, 80, 952-967.
- Crosson, J., & Geers, A. E. (2001). Analysis of narrative ability in children with cochlear implants. *Ear and Hearing*, 22, 381-394.
- Cullington, H., Hodges, A. V., Butts, S. L., Dolan-Ash, S., & Balkany, T. J. (2000). Comparison of language abilities in children with cochlear implants placed in oral and total communication educational settings. *Annals of Otology, Rhinology and Laryngology*, 185, 121-123.
- Curtin, S., Fennell, C., & Escudero, P. (2009). Weighting of vowel cues explains patterns of word-object associative learning. *Developmental Science*, 12, 725-731.
- Cutler, A. (2005). *The lexical statistics of word recognition problems caused by L2 phonetic confusion*. Paper presented at the INTERSPEECH-2005, Lisbon, Portugal.
- Cutler, A. (2008). The abstract representations in speech processing. *The Quarterly Journal of Experimental Psychology*, 61, 1601-1619.
- Dawson, P. W., Busby, P. A., McKay, C. M., & Clark, G. M. (2002). Short-term auditory memory in children using cochlear implants and its relevance to receptive language. *Journal of Speech, Language and Hearing Research*, 45, 789-801.
- De Gelder, B., & Bertelson, P. (2003). Multisensory integration, perception and ecological validity. *Trends in Cognitive Sciences*, 7, 460-467.
- De Raeve, L., Spaai, G., Wiefferink, K., Uilenburg, N., Vermeij, B., Bammens, M., et al. (2009). Invloed van het taalaanbod op de ontwikkeling van jonge dove kinderen met een cochleair implantaat. *Logopedie en Foniatrie*, 1, 16-23.
- Delore, C., Robier, A., Bremond, M., Beutter, P., & Ployet, M. J. (1999). Cochlear implants and sign language. *International Journal of Pediatric Otorhinolaryngology*, 47, 209-211.
- DesJardin, J. L., Ambrose, S. E., Martinez, A. S., & Eisenberg, L. S. (2009). Relationships between speech perception abilities and spoken language skills in young children with hearing loss. *International Journal of Audiology*, 48, 248-259.
- Dettman, S. J., Pinder, D., Briggs, R. J. S., Dowell, R. C., & Leigh, J. R. (2007). Communication development in children who receive the cochlear implant younger than 12 months: risks versus benefits. *Ear and Hearing*, 28, 11-18.
- Dietrich, C., Swingle, D., & Werker, J. F. (2007). Native language governs interpretation of salient speech sounds differences at 18 months. *Proceedings of the 16th International Congress of Phonetic Sciences*, 104, 16027-16031.
- Dorman, M. F., Loizou, P. C., Spahr, A. J., & Maloff, E. (2002). Factors that allow a high level of speech understanding by patients fit with cochlear implants. *American Journal of Audiology*, 11, 119-123.

- Dowell, R. C., Dettman, S. J., Blamey, P. J., Barker, E. J., & Clark, G. M. (2002). Speech perception in children using cochlear implants: predictions of long-term outcomes. *Cochlear Implants International*, 3, 1-18.
- Duchesne, L., Sutton, A., & Bergeron, F. (2009). Language achievement in children who received cochlear implants between 1 and 2 years of age: group trends and individual patterns. *Journal of Deaf Studies and Deaf Education*, 14, 465-485.
- Dunham, B., & Limb, C. J. (2007). Cochlear implants: a brief overview. In R. S. Ackley, T. N. Decker & C. J. Limb (Eds.), *An essential guide to hearing and balance disorders* (pp. 171-201). Mahwah: Lawrence Erlbaum Associates.
- Duyck, W., Desmet, T., Verbeke, L. P. C., & Brysbaert, M. (2004). WordGen: a tool for word selection and nonword generation in Dutch, English, German, and French. *Behavior Research Methods, Instruments, & Computers*, 36, 488-499.
- Dye, M. W. G., Hauser, P. C., & Bavelier, D. (2008). Visual attention in deaf children and adults. In M. Marschark & P. C. Hauser (Eds.), *Deaf cognition: foundations and outcomes* (pp. 250-263). Oxford: Oxford University Press.
- Edwards, B. (2007a). The future of hearing aid technology. *Trends in Amplification*, 11, 31-45.
- Edwards, L. C. (2007b). Children with cochlear implants and complex needs: a review of outcome research and psychological practice. *Journal of Deaf Studies and Deaf Education*, 12, 258-268.
- Edwards, L. C., Khan, S., Broxholme, C., & Langdon, D. (2006). Exploration of the cognitive and behavioural consequences of paediatric cochlear implantation. *Cochlear Implants International*, 7, 61-76.
- Eisenberg, L. S., Martinez, A. S., & Boothroyd, A. (2007). Assessing auditory capabilities in young children. *International Journal of Pediatric Otorhinolaryngology*, 71, 1339-1350.
- Eisenberg, L. S., Martinez, A. S., Holowecky, S. R., & Pogorelsky, S. (2002). Recognition of lexically controlled words and sentences by children with normal hearing and children with cochlear implants. *Ear and Hearing*, 23, 450-462.
- Eisenberg, L. S., Shannon, R. V., Martinez, A. S., Wygonski, J., & Boothroyd, A. (2000). Speech recognition with reduced spectral cues as a function of age. *Journal of the Acoustical Society of America*, 107, 2704-2710.
- El-Hakim, H., Levasseur, J., Papsin, B. C., Panesar, J., Mount, R. J., Stevens, D., et al. (2001). Assessment of vocabulary development in children after cochlear implantation. *Archives of Otolaryngology: Head and Neck Surgery*, 127, 1053-1059.
- Emmorey, K. (2002). *Language, cognition and the brain: insights from sign language research*. Mahwah: Lawrence Erlbaum Associates.
- Emmorey, K. (2007). The psycholinguistics of signed and spoken languages: how biology affects processing. In G. Gaskell (Ed.), *Oxford Handbook of Psycholinguistics* (pp. 703-721). Oxford: Oxford University Press.
- Emmorey, K., Borinstein, H. B., Thompson, R., & Gollan, T. H. (2008). Bimodal bilingualism. *Bilingualism: Language and Cognition*, 11, 43-61.
- Emmorey, K., & Corina, D. P. (1990). Lexical recognition in sign language: effects of phonetic structure and morphology. *Perceptual and Motor Skills*, 71, 1227-1252.

- Emmorey, K., McCullough, S., & Brentari, D. (2003). Categorical perception in American Sign Language. *Language and Cognitive Processes*, 18, 21-45.
- Emmorey, K., Petrich, J., & Gollan, T. H. (2010). *Simultaneous production of ASL and English costs the speaker but benefits the listener*. Paper presented at the Poster presented at Theoretical Issues in Sign Language Research 10.
- Emmorey, K., & Wilson, M. (2005). The puzzle of working memory for sign language. *Trends in Cognitive Sciences*, 8, 521-523.
- Ertmer, D. J., Young, N., Grohne, K., Mellon, J. A., Johnson, C., Corbett, K., et al. (2002). Vocal development in young children with cochlear implants: profiles and implications for intervention. *Language, Speech and Hearing Services in Schools*, 3, 184-195.
- Escudero, P. (2005). *Linguistic perception and second language acquisition: explaining the attainment of optimal phonological categorization*. Utrecht: LOT.
- Escudero, P., & Benders, A. T. (2010). Phonetic and phonological approaches to early word recognition: empirical findings, methodological issues, and theoretical implications. In T. Lentz, H. De Mulder, O. Nilsen & A. Zondervan (Eds.), *The Linguistics Enterprise: from knowledge of language to knowledge in linguistics*. Amsterdam: John Benjamins.
- Escudero, P., Benders, T., & Lipski, S. C. (2009). Native, non-native and L2 perceptual cue weighting for Dutch vowels: the case of Dutch, German, and Spanish listeners. *Journal of Phonetics*, 37, 452-466.
- Escudero, P., & Boersma, P. (2004). Bridging the gap between L2 perception research and phonological theory. *Studies in Second Language Acquisition*, 26, 551-585.
- Escudero, P., Hayes-Harb, R., & Mitterer, H. (2008). Novel second-language words and asymmetric lexical access. *Journal of Phonetics*, 36, 345-360.
- Escudero, P., & Wanrooij, K. (2010). The effect of L1 orthography on L2 vowel perception. *Language and Speech*, 53, 343-365.
- Eter, E. G., & Balkany, T. J. (2009). Pediatric cochlear implant surgery. *Operative Techniques in Otolaryngology*, 20, 202-205.
- Fagan, M. K., & Pisoni, D. B. (2009). Perspectives on multisensory experience and cognitive development in infants with cochlear implants. *Scandinavian Journal of Psychology*, 50, 457-462.
- Fagan, M. K., Pisoni, D. B., Horn, D. L., & Dillon, C. M. (2007). Neuropsychological correlates of vocabulary, reading, and working memory in deaf children with cochlear implants *Journal of Deaf Studies and Deaf Education*, 12, 461-471.
- Fallon, J. B., Irvine, D. R. F., & Shepherd, R. K. (2008). Cochlear implants and brain plasticity. *Hearing Research*, 238, 110-117.
- Fant, G. (1973). *Speech sounds and features*. The Hague: Mouton.
- Fennell, C., & Waxman, S. R. (2010). What paradox? Referential cues allow for infant use of phonetic detail in word learning. *Child Development*, 81, 1376-1383.
- Fenson, L., Dale, P., Reznick, J., Thal, D., Bates, E., & Hartung, J. (1993). *MacArthur Communicative Development Inventories: User's guide and technical manual*. San Diego: Singular Publishing Group.

- Fenson, L., Dale, P. S., Reznick, J. S., Bates, E., Thal, D., & Pethick, S. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development*, 59.
- Fikkert, P. (2010). Developing representations and the emergence of phonology: evidence from perception and production. In C. Fougeron, B. Kuhnert, M. D'Imperio & N. Vallee (Eds.), *Laboratory Phonology* (Vol. 10, pp. 227-260). Berlin: Mouton de Gruyter.
- Fink, N. E., Wang, N.-Y., Visaya, J., Niparko, J. K., Quittner, A. L., Eisenberg, L. S., et al. (2007). Childhood Development after Cochlear Implantation (CDaCI) Study: design and baseline characteristics. *Cochlear Implants International*, 8, 92-116.
- Firszt, J. B., Reeder, R. M., & Skinner, M. W. (2008). Restoring hearing symmetry with two cochlear implants or one cochlear implant and a contralateral hearing aid. *Journal of Rehabilitation Research & Development*, 45, 749-768.
- Fitzpatrick, E., Olds, J., Durieux-Smith, A., McCrae, R., Schramm, D., & Gaboury, I. (2009). Pediatric cochlear implantation: how much hearing is too much? *International Journal of Audiology*, 48, 91-97.
- Flege, J. E., Bohn, O.-S., & Jang, S. (1997). Effects of experience on non-native speakers' production and perception of English vowels. *Journal of Phonetics*, 25, 437-470.
- Flipsen Jr., P., & Parker, R. G. (2008). Phonological patterns in the conversational speech of children with cochlear implants. *Journal of Communication Disorders*, 41, 337-357.
- Friesen, L. M., Shannon, R. V., Baskent, D., & Wang, X. (2001). Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hearing and cochlear implants. *Journal of the Acoustical Society of America*, 110, 1150-1163.
- Frisch, S., & Pisoni, D. B. (2000). Modelling spoken word recognition performance by pediatric cochlear implant users using feature identification. *Ear and Hearing*, 21, 578-589.
- Fu, Q.-J., & Galvin III, J. J. (2008). Maximizing cochlear implant patients' performance with advanced speech training procedures. *Hearing Research*, 242, 198-208.
- Fu, Q.-J., & Nogaki, G. (2005). Noise susceptibility of cochlear implant users: the role of spectral resolution and smearing. *Journal of the Association for Research in Otolaryngology*, 6, 19-27.
- Garlock, V. M., Walley, A. C., & Metsala, J. L. (2001). Age-of-acquisition, word frequency, and neighborhood density effects on spoken word recognition by children and adults: implications for the development of phoneme awareness and early reading ability. *Journal of Memory and Language*, 45, 468-492.
- Gaskell, M. G., Quinlan, P. T., Tamminen, J., & Cleland, A. A. (2008). The nature of phoneme representation in spoken word recognition. *Journal of Experimental Psychology: General*, 137, 282-302.
- Gathercole, S. E. (1999). Cognitive approaches to phonological short-term memory. *Trends in Cognitive Sciences*, 3, 410-419.
- Gathercole, S. E. (2006). Non-word repetition and word learning: the nature of the relationship. *Applied Psycholinguistics*, 27, 513-543.

- Geers, A. E. (2002). Factors affecting the development of speech, language and literacy in children with early cochlear implantation. *Language, Speech and Hearing Services in Schools*, 33, 172-183.
- Geers, A. E. (2003). Predictors of reading skill development in children with early cochlear implantation. *Ear and Hearing*, 24, S59-S68.
- Geers, A. E. (2004). Speech, language, and reading skills after early cochlear implantation. *Archives of Otolaryngology: Head and Neck Surgery*, 130, 634-638.
- Geers, A. E. (2006). Spoken language in children with cochlear implants. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children* (pp. 244-270). Oxford: Oxford University Press.
- Geers, A. E., Brenner, C., & Davidson, L. (2003a). Factors associated with development of speech perception skills in children implanted by age five. *Ear and Hearing*, 24, 24-35.
- Geers, A. E., Brenner, C., Nicholas, J. G., Uchanski, R., Tye-Murray, N., & Tobey, E. A. (2002). Rehabilitation factors contributing to implant benefit in children. *Annals of Otology, Rhinology and Laryngology*, 111, 127-130.
- Geers, A. E., Moog, J. S., Biedenstein, J., Brenner, C., & Hayes, H. (2009). Spoken language scores of children using cochlear implants compared to hearing age-mates at school entry. *Journal of Deaf Studies and Deaf Education*, 14, 371-385.
- Geers, A. E., Nicholas, J. G., & Moog, J. S. (2007). Estimating the influence of cochlear implantation on language development in children. *Audiological Medicine*, 5, 262-273.
- Geers, A. E., Nicholas, J. G., & Sedey, A. L. (2003b). Language skills of children with early cochlear implantation. *Ear and Hearing*, 24, 46-58.
- Geers, A. E., Nicholas, J. G., Tye-Murray, N., Uchanski, R., Brenner, C., Davidson, L., et al. (2000). Effects of communication mode on skills of long-term cochlear implant users. *Annals of Otology, Rhinology and Laryngology*, 109, 89-91.
- Geers, A. E., Strube, M. J., Tobey, E. A., Pisoni, D. B., & Moog, J. S. (2011). Epilogue: factors contributing to long-term outcomes of cochlear implantation in early childhood. *ear and Hearing*, 32, S84-92.
- Geers, A. E., Tobey, E. A., Moog, J. S., & Brenner, C. (2008). Long-term outcomes of cochlear implantation in the preschool years: from elementary grades to high school. *International Journal of Audiology*, 47 (S2), 21-30.
- Genesee, F., Paradis, J., & Crago, M. B. (2004). *Dual development and language disorders: a handbook on bilingualism and second language learning*. Baltimore: Paul H. Brookes Publishing.
- Gerrits, E. (2001). *The categorisation of speech sounds by adults and children: a study of the categorical perception hypothesis and the developmental weighting of acoustic speech cues*. Utrecht: LOT Dissertation series 42.
- Gerrits, E. (2006). Spraakperceptie van dove baby's met een cochleair implantaat: een overzicht. *Stem-, Spraak- en Taalpathologie*, 14, 29-39.
- Gerrits, E., Brokx, J., & Rozier, E. (2005). Vroegtijdige interventie na neonatale gehoorscreening. *Logopedie en Foniatrie*, 77, 311-320.
- Giraud, A. L., & Lee, H.-J. (2007). Predicting cochlear implant outcome from brain organisation in the deaf. *Restorative Neurology and Neuroscience*, 25, 381-390.

- Gordon, K. A., & Papsin, B. C. (2009). Benefits of short interimplant delays in children receiving bilateral cochlear implants. *Otology and Neurotology*, 30, 319-331.
- Gray, S. (2003a). Diagnostic accuracy and test-retest reliability of nonword repetition and digit span tasks administered to preschool children with Specific Language Impairment. *Journal of Communication Disorders*, 36, 129-151.
- Gray, S. (2003b). Word-learning by preschoolers with Specific Language Impairment: what predicts success? *Journal of Speech, Language and Hearing Research*, 46, 56-67.
- Gray, S. (2005). Word learning by preschoolers with Specific Language Impairment: effect of phonological or semantic cues. *Journal of Speech, Language and Hearing Research*, 48, 1452-1467.
- Gray, S. (2006). The relationship between phonological memory, receptive vocabulary, and fast mapping in young children with Specific Language Impairment. *Journal of Speech, Language and Hearing Research*, 49, 955-969.
- Green, D. M. (1995). Maximum-likelihood procedures and the inattentive observer. *Journal of the Acoustical Society of America*, 97, 3749-3760.
- Grieco-Calub, T. M., Saffran, J. R., & Litovsky, R. Y. (2009). Spoken word recognition in toddlers who use cochlear implants. *Journal of Speech, Language and Hearing Research*, 52, 1390-1400.
- Gullberg, M., De Bot, K., & Volterra, V. (2008). Gestures and some key issues in the study of language development. *Gesture*, 8, 149-179.
- Gupta, P. (2003). Examining the relationship between word learning, nonword repetition, and immediate serial recall in adults. *The Quarterly Journal of Experimental Psychology*, 56, 1213-1236.
- Gupta, P., & MacWhinney, B. (1997). Vocabulary acquisition and verbal short-term memory: computational and neural bases. *Brain and Language*, 59, 267-333.
- Hakuta, K. (2001). A critical period for second language acquisition? In D. B. Bailey-jr., J. T. Bruer, F. J. Symons & J. W. Lichtman (Eds.), *Critical thinking about critical periods* (pp. 193-205). Baltimore: Paul H. Brookes Publishing.
- Hall, G., & Waxman, S. (Eds.). (2004). *Weaving a lexicon*. Cambridge: MIT Press.
- Hamilton, H., & Holzman, T. G. (1989). Linguistic encoding in short-term memory as a function of stimulus type. *Memory and Cognition*, 17, 541-550.
- Harrison, R. V., Gordon, K. A., & Mount, R. J. (2005). Is there a critical period for cochlear implantation in congenitally deaf children? Analyses of hearing and speech perception performance after implantation. *Developmental Psychobiology*, 46, 252-261.
- Hayes-Harb, R. (2007). Lexical and statistical evidence in the acquisition of second language phonemes. *Second Language Research*, 23, 65-94.
- Hazan, V., & Barrett, S. (2000). The development of phonemic categorization in children aged 6-12. *Journal of Phonetics*, 28, 377-396.
- Hedrick, M. S., & Carney, A. E. (1997). Effect of relative amplitude and formant transitions on perception of place of articulation by adult listeners with cochlear implants. *Journal of Speech, Language and Hearing Research*, 40, 1445-1457.
- Henry, B. A., Turner, C. W., & Behrens, A. (2005). Spectral peak resolution and speech recognition in quiet: normal hearing, hearing impaired and cochlear implant listeners. *Journal of the Acoustical Society of America*, 118, 1111-1121.

- Hickok, G., Bellugi, U., & Klima, E. S. (1998). What's right about the neural organization of sign language? A perspective on recent neuroimaging results. *Trends in Cognitive Sciences*, 2, 465-468.
- Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews: Neurosciences*, 8, 393-402.
- Hicks, C. B., & Ohde, R. N. (2005). Developmental role of static, dynamic, and contextual cues in speech perception. *Journal of Speech, Language and Hearing Research*, 48, 960-974.
- Hildebrandt, U. C., & Corina, D. P. (2002). Phonological similarity in American Sign Language. *Language and Cognitive Processes*, 17, 593-612.
- Hohenberger, A., Happ, D., & Leuniger, H. (2002). Modality-dependent aspects of sign language production: evidence from slips of the hands and their repairs in German Sign Language. In R. P. Meier, K. Cormier & D. Quinto-Pozos (Eds.), *Modality and structure in signed and spoken languages* (pp. 112-142). Cambridge: Cambridge University Press.
- Holt, R. F., & Svirsky, M. A. (2008). An exploratory look at pediatric cochlear implantation: is earliest always the best? *Ear and Hearing*, 29, 492-511.
- Hoover, J. R., Storkel, H. L., & Hogan, T. P. (2010). A cross-sectional comparison of the effects of phonotactic probability and neighborhood density on word learning by preschool children. *Journal of Memory and Language*, 63, 100-116.
- Horn, D. L., Davis, R. A. O., Pisoni, D. B., & Miyamoto, R. T. (2005). Development of visual attention skills in prelingually deaf children who use cochlear implants. *Ear and Hearing*, 26, 389-408.
- Horn, D. L., Fagan, M. K., Dillon, C. M., Pisoni, D. B., & Miyamoto, R. T. (2007a). Visual-motor integration skills of prelingually deaf children: implications for pediatric cochlear implantation. *The Laryngoscope*, 117, 2017-2025.
- Horn, D. L., Houston, D. M., & Miyamoto, R. T. (2007b). Speech discrimination skills in deaf infants before and after cochlear implantation. *Audiological medicine*, 5, 232-241.
- Houston, D. M. (2005). Speech perception in infants. In D. B. Pisoni & R. E. Remez (Eds.), *The handbook of speech perception* (pp. 417-448). Malden: Blackwell Publishing.
- Houston, D. M., Carter, A. K., Pisoni, D. B., Kirk, K. I., & Ying, E. A. (2005). Word learning in children following cochlear implantation. *The Volta Review*, 105, 41-72.
- Houston, D. M., Ying, E. A., Pisoni, D. B., & Kirk, K. I. (2004). Development of pre-word-learning skills in infants with cochlear implants. *Volta Review*, 103, 303-326.
- Hwa-Froelich, D. A., & Matsuo, H. (2005). Vietnamese children and language-based processing tasks. *Language, Speech, and Hearing Services in Schools*, 36, 230-243.
- Ibertsson, T., Hansson, K., Maki-Torkko, E., Willstedt-Svensson, U., & Sahlen, B. (2009). Deaf teenagers with cochlear implants in conversation with hearing peers. *International Journal of Language and Communication Disorders*, 44, 319-337.
- Iverson, J. M., & Goldin-Meadow, S. (2005). Gesture paves the way for language development. *Psychological Science*, 16, 367-371.

- Iverson, P. (2003). Evaluating the function of phonetic perceptual phenomena within speech recognition: an examination of the perception of /d/-/t/ by adult cochlear implant users. *Journal of the Acoustical Society of America*, 113, 1056-1064.
- Iverson, P., & Evans, B. G. (2007). Learning English vowels with different first-language vowel systems: perception of formant targets, formant movement, and duration. *Journal of the Acoustical Society of America*, 122, 2842-2854.
- Iverson, P., Smith, C. A., & Evans, B. G. (2006). Vowel recognition via cochlear implants and noise vocoders: effects of formant movement and duration. *Journal of the Acoustical Society of America*, 120, 3998-4006.
- James, D., Rajput, K., Brinton, J., & Goswami, U. (2008). Phonological awareness, vocabulary, and word reading in children who use cochlear implants: does age of implantation explain interindividual variability in performance of outcomes and growth? *Journal of Deaf Studies and Deaf Education*, 13, 117-137.
- James, D., Rajput, K., Brown, T., Sirimanna, T., Brinton, J., & Goswami, U. (2005). Phonological awareness in deaf children who use cochlear implants. *Journal of Speech, Language and Hearing Research*, 48, 1511-1528.
- Jarvis, L. H., Merriman, W. E., Barnett, M., Hanba, J., & Van Haitsma, K. S. (2004). Input that contradicts young children's strategy for mapping novel words affects their phonological and semantic interpretation of other novel words. *Journal of Speech, Language and Hearing Research*, 47, 392-406.
- Jerger, S. (2007). Current state of knowledge: perceptual processing by children with hearing impairment. *Ear and Hearing*, 28, 754-765.
- Johnston, J. C., Durieux-Smith, A., Angus, D., O'Connor, A., & Fitzpatrick, E. (2009). Bilateral cochlear paediatric implants: a critical review. *International Journal of Audiology*, 48, 601-617.
- Jusczyk, P. W. (1993). From general to language specific capacities: the WRAPSA model of how speech perception develops. *Journal of Phonetics*, 21, 3-28.
- Jusczyk, P. W. (1997). *The discovery of spoken language*. Cambridge: MIT Press.
- Kan, P. F., & Kohnert, K. (2008). Fast mapping by bilingual preschool children. *Journal of Child Language*, 35, 495-514.
- Kelly, S. D., Manning, S. M., & Rodak, S. (2008). Gesture gives a hand to language and learning: perspectives from cognitive neuroscience, developmental psychology and education. *Language and Linguistics Compass*, 2.
- Kelly, S. D., McDevitt, T., & Esch, M. (2009). Brief training with co-speech gesture lends a hand to word learning in a foreign language. *Language and Cognitive Processes*, 24, 313-334.
- Kelly, S. D., Ozyurek, A., & Maris, E. (2010). Two sides of the same coin: speech and gesture mutually interact to enhance comprehension. *Psychological Science*, 21, 260-267.
- Kennedy, C. R., McCann, D. C., Campbell, M. J., Law, C. N., Mullee, M., Petrou, S., et al. (2006). Language ability after early detection of permanent childhood hearing impairment. *New England Journal of Medicine*, 354, 2131-2141.
- Kirk, K. I., Hay-McCutcheon, M. J., Holt, R. F., Gao, S., Qi, R., & Gerlain, B. L. (2007). Audiovisual spoken word recognition by children with cochlear implants. *Audiological Medicine*, 5, 250-261.

- Kirk, K. I., Miyamoto, R. T., Ying, E., Perdew, A. E., & Zuganelis, H. (2003). Cochlear implantation in young children: effects of age at implantation and communication mode. *Volta Review*, 102, 127-144.
- Kishon-Rabin, L., Taitelbaum, R., Muchnik, C., Gehtler, I., Kronenberg, J., & Hildesheimer, M. (2002). Development of speech perception and production in children with cochlear implants. *The annals of otology, rhinology and laryngology*, 189, 85-90.
- Kissine, M., Van de Velde, H., & Van Hout, R. (2003). An acoustic study of standard Dutch /v/, /f/, /z/ and /s/. *Linguistics in the Netherlands*(93-104).
- Klatter-Folmer, J., Van Hout, R., Kolen, E., & Verhoeven, L. (2006). Language development in deaf children's interactions with deaf and hearing adults: a Dutch longitudinal study. *Journal of Deaf Studies and Deaf Education*, 11, 238-251.
- Klima, E. S., & Bellugi, U. (1979). *The signs of language*. Cambridge: Harvard University Press.
- Knapp, H. P., & Corina, D. P. (2010). A human mirror neuron system for language: perspectives from signed languages of the deaf. *Brain and Language*, 112, 36-43.
- Knoors, H. (2006). Cochleaire implantatie bij dove kinderen: effecten op de ontwikkeling en mogelijke gevolgen voor pedagogisch beleid. Unpublished Paper in kader symposium 'Effecten van CI bij kinderen: een breed perspectief', Amsterdam, 10 november 2006.
- Knoors, H. (2007). Educational responses to varying objectives of parents of deaf children: a Dutch perspective. *Journal of Deaf Studies and Deaf Education*, 12, 243-253.
- Knudsen, E. I. (2004). Sensitive periods in the development of brain and behavior. *Journal of Cognitive Neuroscience*, 16, 1412-1425.
- Kral, A., & Eggermont, J. J. (2007). What's to lose and what's to learn: development under auditory deprivation, cochlear implants and limits of cortical plasticity. *Brain Research Reviews*, 56, 259-269.
- Krentz, U. C., & Corina, D. P. (2008). Preference for language in early infancy: the human language bias is not speech-specific. *Developmental Science*, 11, 1-9.
- Kuhl, P. K. (2004). Early language acquisition: cracking the speech code. *Neuroscience*, 5831-843.
- Kuhl, P. K., Conboy, B. T., Padden, D., Nelson, T., & Pruitt, J. (2005). Early speech perception and later language development: implications for the "critical period". *Language Learning and Development*, 1, 237-264.
- Kuijpers, C. T. L. (1996). Perception of the voicing contrast by Dutch children and adults. *Journal of Phonetics*, 24, 367-382.
- Lane, H., Denny, M., Guenther, F. H., Hanson, H. M., Marrone, N., Matthies, M. L., et al. (2007). On the structure of phoneme categories in listeners with cochlear implants. *Journal of Speech, Language and Hearing Research*, 50, 2-14.
- Leach, L., & Samuel, A. G. (2007). Lexical configuration and lexical engagement: when adults learn new words *Cognitive Psychology*, 55, 306-353.
- Lederberg, A. R., & Spencer, P. E. (2009). Word-learning abilities in deaf and hard-of-hearing preschoolers: effect of lexicon size and language modality. *Journal of Deaf Studies and Deaf Education*, 14, 44-62.

- Lederberg, A. R., Spencer, P. E., & Prezbindowski, A. K. (2000). Word learning skills of deaf preschoolers: the development of novel mapping and rapid word learning strategies. *Child Development*, 71, 1571-1585.
- Lee, S., Potamianos, A., & Narayanan, S. (1999). Acoustics of children's speech: developmental changes of temporal and spectral parameters. *Journal of the Acoustical Society of America*, 105, 1455-1468.
- Leigh, G. (2008). Changing parameters in deafness and deaf education. In M. Marschark & P. C. Hauser (Eds.), *Deaf cognition: foundations and outcomes* (pp. 24-51). Oxford: Oxford University Press.
- Leigh, I. W., Maxwell-McCaw, D., Bat-Chava, Y., & Christiansen, J. B. (2008). Correlates of psychosocial adjustment in deaf adolescents with and without cochlear implants: a preliminary investigation. *Journal of Deaf Studies and Deaf Education*, 14, 244-259.
- Liddell, S. (1980). *American Sign Language syntax*. The Hague: Mouton.
- Liddell, S. (1990). Four functions of a locus: re-examining the structure of space in ASL.
- Lin, F. R., Ceh, K., Bervinchak, D., Riley, A., Miech, R., & Niparko, J. K. (2007). Development of a communicative performance scale for pediatric cochlear implantation. *Ear and Hearing*, 28, 703-712.
- Lin, F. R., Wang, N.-Y., Fink, N. E., Quittner, A. L., Eisenberg, L. S., Tobey, E. A., et al. (2008). Assessing the use of speech and language measures in relation to parental perceptions of development after early cochlear implantation. *Otology and Neurotology*, 29, 208-213.
- Loebach, J. L., Pisoni, D. B., & Svirsky, M. A. (2009). Transfer of auditory perceptual learning with spectrally reduced speech to speech and nonspeech tasks: implications for cochlear implants. *Ear and Hearing*, 30, 662-674.
- Lynas, W. (2005). Controversies in the education of deaf children. *Current Paediatrics*, 15, 200-206.
- MacKay, I. R. A., Flege, J. E., Piske, T., & Schirru, C. (2001). Category restructuring during second-language speech acquisition. *Journal of the Acoustical Society of America*, 110, 516-528.
- MacSweeney, M., Capek, C. M., Campbell, R., & Woll, B. (2008). The signing brain: the neurobiology of sign language. *Trends in Cognitive Sciences*, 12, 432-440.
- Magnuson, J. S., Dixon, J. A., Tanenhaus, M. K., & Aslin, R. N. (2007). The dynamics of lexical competition during spoken word recognition. *Cognitive Science*, 31, 133-156.
- Mainela-Arnold, E., Evans, J. L., & Coady, J. A. (2008). Lexical representations in children with SLI: evidence from a frequency-manipulated gating task. *Journal of Speech, Language and Hearing Research*, 51, 381-393.
- Mani, N., & Plunkett, K. (2008). Fourteen-month-olds pay attention to vowels in novel words. *Developmental Science*, 11, 53-59.
- Marchman, V. A., & Fernald, A. (2008). Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Developmental Science*, 11, 9-16.

- Marco-Algarra, J., Martinez-Beneyto, P., Morant-Ventura, A., Platero-Zamarreno, A., Latorre-Monteagudo, E., & Pitarch-Ribas, I. (2009). Cortical neuroplasticity in children after early cochlear implantation. *Audiological Medicine*, 7, 40-46.
- Marschark, M. (2007). *Raising and educating a deaf child* (Second edition ed.). Oxford: Oxford University Press.
- Marschark, M., & Hauser, P. C. (Eds.). (2008). *Deaf cognition: foundations and outcomes*. Oxford: Oxford University Press.
- Marschark, M., Rhoten, C., & Fabich, M. (2007). Effects of cochlear implants on children's reading and academic achievement. *Journal of Deaf Studies and Deaf Education*, 12, 269-282.
- Marschark, M., Schick, B., & Spencer, P. E. (2005). Understanding sign language development of deaf children. In B. Schick, M. Marschark & P. E. Spencer (Eds.), *Advances in the sign language development of deaf children* (pp. 3-19). Oxford: Oxford University Press.
- Marschark, M., & Spencer, P. E. (2006). Spoken language development of deaf and hard-of-hearing children: historical and theoretical perspectives. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children* (pp. 3-21). Oxford: Oxford University Press.
- Mayberry, R. I., & Lock, E. (2003). Age constraints on first versus second language acquisition: evidence for linguistic plasticity and epigenesis. *Brain and Language*, 87, 369-384.
- Maye, J., Weiss, D. J., & Aslin, R. N. (2008). Statistical phonetic learning in infants: facilitation and feature generalization. *Developmental Science*, 11, 122-134.
- Maye, J., Werker, J. F., & Gerken, L. (2002). Infant sensitivity to distributional information can affect phonetic discrimination. *Cognition*, 82, 101-111.
- Mayo, C., Scobbie, J. M., Hewlett, N., & Waters, D. (2003). The influence of phonemic awareness development on acoustic cue weighting strategies in children's speech perception. *Journal of Speech, Language and Hearing Research*, 46, 1184-1196.
- Mayo, C., & Turk, A. (2005). The influence of spectral distinctiveness on acoustic cue weighting in children's and adults' speech perception. *Journal of the Acoustical Society of America*, 118, 1730-1741.
- McClelland, J. L., Mirman, D., & Holt, L. L. (2006). Are there interactive processes in speech perception? *Trends in Cognitive Sciences*, 10, 363-369.
- McConkey Robbins, A. M., Bollard, P. M., & Green, J. (1999). Language development in children implanted with the CLARION implant. *Annals of Otology, Rhinology and Laryngology*, 177, 113-118.
- McConkey Robbins, A. M., Svirsky, M. A., & Kirk, K. I. (1997). Children with implants can speak, but can they communicate? *Archives of Otolaryngology - Head and Neck Surgery*, 117, 155-160.
- McCullough, S., & Emmorey, K. (2009). Categorical perception of affective and linguistic facial expressions. *Cognition*, 110, 208-221.
- McGurk, H., & MacDonald, J. (1976). Hearing lips and seeing voices. *Nature*, 264, 746-748.
- McMurray, B., Samuelson, S. M., Lee, S. H., & Tomblin, J. B. (2010). Individual differences in online spoken word recognition: implications for SLI. *Cognitive Psychology*, 60, 1-39.

- McMurray, B., Tanenhaus, M. K., & Aslin, R. N. (2009). Within-category VOT affects recovery from “lexical” garden-paths: evidence against phoneme-level inhibition *Journal of Memory and Language*, 60, 65-91.
- Meier, R. P., Cormier, K., & Quinto-Pozos, D. (Eds.). (2002). *Modality and structure in signed and spoken languages*. Cambridge: Cambridge University Press.
- Mendel, L. L. (2008). Current considerations in pediatric speech audiometry. *International Journal of Audiology*, 47, 546-553.
- Metsala, J. L. (1999). Young children's phonological awareness and nonword repetition as a function of vocabulary development. *Journal of Educational Psychology*, 91, 3-19.
- Metsala, J. L., Stavrinou, D., & Walley, A. C. (2009). Children's spoken word recognition and contributions to phonological awareness and nonword repetition: a 1-year follow-up. *Applied Psycholinguistics*, 30, 101-121.
- Metsala, J. L., & Walley, A. C. (1998). Spoken vocabulary growth and the segmental restructuring of lexical representations: precursors to phonemic awareness and early reading ability. In J. L. Metsala & L. C. Ehri (Eds.), *Word recognition in beginning literacy* (pp. 89-120). Mahwah: Lawrence Erlbaum Associates.
- Mildner, V., Sindija, B., & Zrinski, K. V. (2006). Speech perception of children with cochlear implants and children with traditional hearing aids. *Clinical Linguistics and Phonetics*, 20, 219-229.
- Miller, J., & Ulrich, R. (2003). Simple reaction time and statistical facilitation: a parallel grains model. *Cognitive Psychology*, 46, 101-151.
- Mitchell, T. V., & Maslin, M. T. (2007). How vision matters for individuals with hearing loss. *International Journal of Audiology*, 46, 500-511.
- Mollink, I., Hermans, D., & Knoors, H. (2008). Vocabulary training of words in hard-of-hearing children. *Deafness and Education International*, 10, 80-92.
- Moore, B. C. J. (2003). Coding of sounds in the auditory system and its relevance to signal processing and coding in cochlear implants. *Otology and Neurotology*, 24, 243-254.
- Moore, D. R., Rosenberg, J. F., & Coleman, J. S. (2005). Discrimination training of phonemic contrasts enhances phonological processing in mainstream school children. *Brain and Language*, 94, 72-85.
- Moore, D. R., & Shannon, R. V. (2009). Beyond cochlear implants: awakening the deafened brain. *Nature Neuroscience*, 12, 686-691.
- Morford, J. P., Grieve-Smith, A. B., MacFarlane, J., Staley, J., & Waters, G. (2008). Effects of sign language experience on the perception of American Sign Language. *Cognition*, 109, 41-53.
- Morrison, G. S. (2005). An appropriate metric for cue weighting in L2 speech perception. *Studies in Second Language Acquisition*, 27, 597-606.
- Morrison, G. S. (2007). Logistic regression modelling for first- and second-language perception data. In M. J. Sole, P. Prieto & J. Mascaró (Eds.), *Segmental and prosodic issues in Romance phonology* (pp. 119-136). Amsterdam: John Benjamins.

- Munson, B., & Nelson, P. B. (2005). Phonetic identification in quiet and in noise by listeners with cochlear implants. *Journal of the Acoustical Society of America*, 118, 2607-2617.
- Nazzi, T. (2005). Use of phonetic specificity during the acquisition of new words: differences between consonants and vowels. *Cognition*, 98, 13-30.
- Newkirk, D., Klima, E. S., Pedersen, C. C., & Bellugi, U. (1980). Linguistic evidence from slips of the hand. In V. Fromkin (Ed.), *Errors in linguistic performance: slips of the tongue, ear, pen, and hand* (pp. 165-198). New York: Academic Press.
- Newman, R. S., Bernstein Ratner, N., Jusczyk, A. M., Jusczyk, P. W., & Ayala Dow, K. (2006). Infants' early ability to segment the conversational speech signal predicts later language development: a retrospective analysis. *Developmental Psychology*, 42, 643-655.
- Nicholas, J. G., & Geers, A. E. (2003). Hearing status, language modality, and young children's communicative and linguistic behavior. *Journal of Deaf Studies and Deaf Education*, 8, 422-437.
- Nicholas, J. G., & Geers, A. E. (2007). Will they catch up? The role of age at cochlear implantation in the spoken language development of children with severe to profound hearing loss. *Journal of Speech, Language and Hearing Research*, 50, 1048-1062.
- Nicholas, J. G., & Geers, A. E. (2008). Expected test scores for preschoolers with a cochlear implant who use spoken language. *American Journal of Speech-Language Pathology*, 17, 121-138.
- Nie, K., Barco, A., & Zeng, F.-G. (2006). Spectral and temporal cues in cochlear implant speech perception. *Ear and Hearing*, 27, 208-217.
- Nikolopoulos, T. P., Archbold, S. M., & Gregory, S. (2005). Young deaf children with hearing aids or cochlear implants: early assessment package for monitoring progress. *International Journal of Pediatric Otorhinolaryngology*, 69, 169-179.
- Niparko, J. K., Tobey, E. A., Thal, D. J., Eisenberg, L. S., Wang, N.-Y., Quittner, A. L., et al. (2010). Spoken language development in children following cochlear implantation. *Journal of the American Medical Association*, 303, 1498-1506.
- Nittrouer, S. (1996). Discriminability and perceptual weighting of some acoustic cues to speech perception by 3-year-olds. *Journal of Speech, Language and Hearing Research*, 39, 278-297.
- Nittrouer, S. (2002a). From ear to cortex: a perspective on what clinicians need to understand about speech perception and language processing. *Language, Speech, and Hearing Services in Schools*, 33, 237-252.
- Nittrouer, S. (2002b). Learning to perceive speech: how fricative perception changes, and how it stays the same. *Journal of the Acoustical Society of America*, 112, 711-719.
- Nittrouer, S. (2007). Dynamic spectral structure specifies vowels for children and adults. *Journal of the Acoustical Society of America*, 122, 2328-2339.
- Nittrouer, S., & Chapman, C. (2009). The effects of bilateral electric and bimodal electric-acoustic stimulation on language development. *Trends in Amplification*, 13, 190-205.

- Nittrouer, S., & Lowenstein, J. H. (2007). Children's weighting strategies for word-final stop voicing are not explained by auditory sensitivities. *Journal of Speech, Language and Hearing Research*, 50, 58-73.
- Nittrouer, S., & Lowenstein, J. H. (2009). Does harmonicity explain children's cue weighting of fricative-vowel syllables? *Journal of the Acoustical Society of America*, 125, 1679-1692.
- Nittrouer, S., & Miller, M. E. (1997). Predicting developmental shifts in perceptual weighting schemes. *Journal of the Acoustical Society of America*, 101, 2253-2266.
- Nordqvist, A., & Nelfelt, K. (2004). *Early bilingual language development in deaf children with cochlear implants - is it possible?* Paper presented at the 20th Danavox Symposium, Copenhagen.
- Norris, D., McQueen, J. M., & Cutler, A. (2000). Merging information in speech recognition: feedback is never necessary. *Behavioral and Brain Sciences*, 23, 299-325.
- Norris, D., McQueen, J. M., & Cutler, A. (2003). Perceptual learning in speech. *Cognitive Psychology*, 47, 204-238.
- Oblaser, J., & Eisner, F. (2009). Pre-lexical abstraction of speech in the auditory cortex. *Trends in Cognitive Sciences*, 13, 14-19.
- Olazaran, J., Jacobs, D. M., & Stern, Y. (1996). Comparative study of visual and verbal short-term memory in English and Spanish speakers: testing a linguistic hypothesis. *Journal of the International Neuropsychological Society*, 2, 105-110.
- Orfanidou, E., Adam, R., McQueen, J. L., & Morgan, G. (2009). Making sense of nonsense in British Sign Language (BSL): The contribution of different phonological parameters to sign recognition. *Memory and Cognition*, 37, 302-315.
- Orfanidou, E., Adam, R., Morgan, G., & McQueen, J. L. (2010). Recognition of signed and spoken language: different sensory inputs, the same segmentation procedure. *Journal of Memory and Language*, 62, 272-283.
- Ormel, E., Hermans, D., Knoors, H., & Verhoeven, L. (2009). The role of sign phonology and iconicity during sign processing: the case of deaf children. *Journal of Deaf Studies and Deaf Education*, 14, 436-448.
- Padden, C. (1990). The relation between space and grammar in ASL in ASL verb morphology. In C. Lucas (Ed.), *Sign language research: theoretical issues* (pp. 118-132). Washington: Gallaudet University Press.
- Papsin, B. C., & Gordon, K. A. (2007). Cochlear implants for children with severe-to-profound hearing loss. *New England Journal of Medicine*, 357, 2380-2387.
- Papsin, B. C., & Gordon, K. A. (2008). Bilateral cochlear implants should be the standard for children with bilateral sensorineural deafness. *Current Opinion in Otolaryngology & Head and Neck Surgery*, 16, 69-74.
- Pascual-Leone, A., Amedi, A., Fregni, F., & Merabet, L. B. (2005). The plastic human brain cortex. *Annual Review of Neuroscience*, 28, 377-401.
- Percy-Smith, L., Caye-Thomasen, P., Gudman, M., Hedegard-Jensen, J., & Thomsen, J. (2008). Self-esteem and social well-being of children with cochlear implant compared to normal-hearing children. *International Journal of Pediatric Otorhinolaryngology*, 72, 1113-1120.

- Peterson, N. R., Pisoni, D. B., & Miyamoto, R. T. (2010). Cochlear implants and spoken language processing abilities: review and assessment of the literature. *Restorative Neurology and Neuroscience*, 28, 237-250.
- Pisoni, D. B. (1973). Auditory and phonetic memory codes in the discrimination of consonants and vowels. *Perception and Psychophysics*, 13, 253-260.
- Pisoni, D. B. (1997). Some thoughts on "normalization" in speech perception. In K. Johnson & J. W. Mullennix (Eds.), *Talker variability in speech processing* (pp. 9-32). San Diego: Academic Press.
- Pisoni, D. B. (2000). Cognitive factors and cochlear implants: some thoughts on perception, learning, and memory in speech perception. *Ear and Hearing*, 21, 70-78.
- Pisoni, D. B. (2005). Speech perception in deaf children with cochlear implants. In D. B. Pisoni & R. E. Remez (Eds.), *The handbook of speech perception* (pp. 494-523). Malden: Blackwell Publishing.
- Pisoni, D. B., & Cleary, M. (2003). Measures of working memory span and verbal rehearsal speed in deaf children after cochlear implantation. *Ear and Hearing*, 24, S106-S120.
- Pisoni, D. B., Cleary, M., Geers, A. E., & Tobey, E. A. (1999). Individual differences in effectiveness of cochlear implants in children who are prelingually deaf: new process measures of performance. *The Volta Review*, 101, 111-164.
- Pisoni, D. B., Conway, C. M., Kronenberger, W. G., Horn, D. L., Karpicke, J., & Henning, S. C. (2008). Efficacy and effectiveness of cochlear implants in deaf children. In M. Marschark & P. C. Hauser (Eds.), *Deaf cognition: foundations and outcomes* (pp. 52-101). Oxford: Oxford University Press.
- Pittman, A. L., Stelmachowicz, P. G., Lewis, D. E., & Hoover, B. M. (2002). Influence of hearing loss on the perceptual strategies of children and adults. *Journal of Speech, Language and Hearing Research*, 45, 1276-1284.
- Poeppl, D., & Monahan, P. J. (2008). Speech perception: cognitive foundations and cortical implementation. *Current Directions in Psychological Science*, 17, 80-85.
- Poizner, H., Klima, E. S., & Bellugi, U. (1987). *What the hands reveal about the brain*. Cambridge: MIT Press.
- Polka, L., & Werker, J. F. (1994). Developmental changes in perception of non-native vowel contrasts. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 745-749.
- Pols, L. C. W., Tromp, H. R. C., & Plomp, R. (1973). Frequency analysis of Dutch vowels from 50 male speakers. *Journal of the Acoustical Society of America*, 53, 1093-1101.
- Preisler, G., Tvingstedt, A.-L., & Ahlstrom, M. (2001). A psychosocial follow-up study of deaf preschool children using cochlear implants. *Child: Care, Health and Development*, 28, 403-418.
- Preisler, G., Tvingstedt, A.-L., & Ahlstrom, M. (2005). Interviews with deaf children about their experience using cochlear implants. *American Annals of the Deaf*, 150, 260-266.
- Prezbindowski, A. K., & Lederberg, A. R. (2003). Vocabulary assessment of deaf and hard-of-hearing children from infancy through the preschool years. *Journal of Deaf Studies and Deaf Education*, 8, 383-400.

- Psarros, C., Plant, K. L., Lee, K., Decker, J. A., Whitford, L. A., & Cowan, R. S. C. (2002). Conversion from the SPEAK to the ACE strategy in children using the Nucleus 24 cochlear implant system: speech perception and speech production outcomes. *Ear and Hearing*, 23, 18-27.
- Quittner, A. L., Barker, D. H., Snell, C., Cruz, I., McDonald, L.-G., Grimley, M. E., et al. (2007). Improvements in visual attention in deaf infants and toddlers after cochlear implantation *Audiological Medicine*, 5, 242-249.
- Rispens, J. E., Baker, A. E., & Duinmeijer, I. (in preparation). Phonological representations in children with language and reading impairment.
- Rogers, C. F., Healy, E. W., & Montgomery, A. A. (2006). Sensitivity to isolated and concurrent intensity and fundamental frequency increments by cochlear implant users under natural listening conditions. *Journal of the Acoustical Society of America*, 119, 2276-2287.
- Rosenblum, L. D. (2005). The primacy of multimodal speech perception. In D. B. Pisoni & R. Remez (Eds.), *Handbook of speech perception* (pp. 51-78). Malden: Blackwell.
- Rosenblum, L. D. (2008). Speech perception as a multimodal phenomenon. *Current Directions in Psychological Science*, 17, 405-409.
- Sach, T. H., & Whynes, D. K. (2005). Paediatric cochlear implantation: the views of parents. *International Journal of Audiology*, 44, 400-407.
- Sandler, W. (1989). *Phonological representation of the sign: linearity and nonlinearity in American Sign Language*. Dordrecht: Foris.
- Sandler, W., & Lillo-Martin, D. (2006). *Sign language and linguistic universals*. Cambridge: Cambridge University Press.
- Sarant, J. Z., Blamey, P. J., Dowell, R. C., Clark, G. M., & Gibson, W. P. R. (2001). Variation in speech perception scores among children with cochlear implants. *Ear and Hearing*, 22, 18-28.
- Sarant, J. Z., Holt, C. M., Dowell, R. C., Rickards, F. W., & Blamey, P. J. (2009). Spoken language development in oral preschool children with permanent childhood deafness. *Journal of Deaf Studies and Deaf Education*, 14, 205-217.
- Schaerlaekens, A., Kohnstamm, D., & Lejaegere, M. (1999). *Streeflijst woordenschat voor zesjarigen: derde herziene versie gebaseerd op nieuw onderzoek in Nederland en België*. Lisse: Swets & Zeitlinger.
- Schafer, E. C., Amlani, A. M., Seibold, A., & Shattuck, P. L. (2007). A meta-analytic comparison of binaural benefits between bilateral cochlear implants and bimodal stimulation. *Journal of the American Academy of Audiology*, 18, 760-776.
- Schafer, E. C., & Thibodeau, L. M. (2006). Speech recognition in noise in children with cochlear implants while listening in bilateral, bimodal, and FM-system arrangements. *American Journal of Audiology*, 14, 114-126.
- Schauwers, K., Gillis, S., Daemers, K., De Beukelaer, C., & Govaerts, P. (2004). Cochlear implantation between 5 and 20 months of age: the onset of babbling and audiological outcome. *Otology and Neuro-otology*, 25, 263-270.
- Schauwers, K., Gillis, S., & Govaerts, P. (2005). Language acquisition in children with a cochlear implant. In P. Fletcher & J. F. Miller (Eds.), *Developmental theory and language disorders* (pp. 95-119). Amsterdam: John Benjamins.

- Scherf, F. W. A. C., Van Deun, L., Van Wieringen, A., Wouters, J., Desloovere, C., Dhooge, I., et al. (2009). Functional outcomes of sequential bilateral cochlear implantation in young children: 36 months postoperative results. *International Journal of Pediatric Otorhinolaryngology*, 73, 723-730.
- Schick, B., Marschark, M., & Spencer, P. E. (Eds.). (2005). *Advances in the sign language development of deaf children*. Oxford: Oxford University Press.
- Schorr, E. A., Fox, N. A., Van Wassenhove, V., & Knudsen, E. I. (2005). Auditory-visual fusion in speech perception in children with cochlear implants. *Proceedings of the National Academy of Sciences of the United States of America*, 102, 18748-18750.
- Schorr, E. A., Roth, F. P., & Fox, N. A. (2008). A comparison of the speech and language skills of children with cochlear implants and children with normal hearing. *Communication Disorders Quarterly*, 29, 195-210.
- Schorr, E. A., Roth, F. P., & Fox, N. A. (2009). Quality of life for children with cochlear implants: perceived benefits and problems and the perception of single words and emotional sounds. *Journal of Speech, Language and Hearing Research*, 52, 141-152.
- Schvartz, K. C., Chatterjee, M., & Gordon-Salant, S. (2008). Recognition of spectrally degraded phonemes by younger, middle-aged, and older normal-hearing listeners. *Journal of the Acoustical Society of America*, 124, 3972-3988.
- Sennaroglu, L., Ziyal, Z., Atas, A., Sennaroglu, G., Yucel, E., Sevinc, S., et al. (2009). Preliminary results of auditory brainstem implantation in prelingually deaf children with inner ear malformations including severe stenosis of the cochlear aperture and aplasia of the cochlear nerve. *Otology and Neurotology*, 30, 708-715.
- Shams, L., & Seitz, A. R. (2008). Benefits of multisensory learning. *Trends in Cognitive Sciences*, 12, 411-417.
- Shannon, R. V. (2002). The relative importance of amplitude, temporal and spectral cues for cochlear implant processor design. *American Journal of Audiology*, 11, 124-127.
- Sharma, A., Gilley, P. M., Dorman, M. F., & Baldwin, R. (2007). Deprivation-induced cortical reorganization in children with cochlear implants. *International Journal of Audiology*, 46, 494-499.
- Sharma, A., Nash, A. A., & Dorman, M. F. (2009). Cortical development, plasticity and re-organization in children with cochlear implants. *Journal of Communication Disorders*, 42, 272-279.
- Shatzman, K. B., & McQueen, J. M. (2006). Prosodic knowledge affects the recognition of newly acquired words. *Psychological Science*, 17, 372-377.
- Shinn-Cunningham, B. G., & Best, V. (2008). Selective attention in normal and impaired hearing. *Trends in Amplification*, 12, 283-299.
- Simon, E., Escudero, P., & Broersma, M. (2010). *Learning minimally different words in a third language: L2 proficiency as a crucial predictor of accuracy in an L3 word learning task*. Paper presented at the Sixth international symposium on the acquisition of second language speech (New Sounds 2010).
- Skinner, M. W., Holden, L. K., Whitford, L. A., Plant, K. L., Psarros, C. E., & Holden, T. A. (2002). Speech recognition with the Nucleus 24 SPEAK, ACE,

- and CIS speech coding strategies in newly implanted adults. *Ear and Hearing*, 25, 207-223.
- Skipper, J. I., Goldin-Meadow, S., Nusbaum, H. C., & Small, S. L. (2009). Gestures orchestrate brain networks for language understanding. *Current Biology*, 19, 661-667.
- Sorkin, D. L., & Zwolan, T. A. (2008). Parental perspectives regarding early intervention and its role in cochlear implantation in children. *Otology and Neurotology*, 29, 137-142.
- Spencer, L. J., Gantz, B. J., & Knutson, J. F. (2004). Outcomes and achievement of students who grew up with access to cochlear implants. *The Laryngoscope*, 114, 1576-1581.
- Spencer, L. J., & Tomblin, J. B. (2006). Speech production and spoken language development of children using "Total Communication". In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children* (pp. 166-192). Oxford: Oxford University Press.
- Spencer, L. J., & Tomblin, J. B. (2009). Evaluating phonological processing skills in children with prelingual deafness who use cochlear implants. *Journal of Deaf Studies and Deaf Education*, 14, 1-21.
- Spencer, L. J., Tye-Murray, N., & Tomblin, J. B. (1998). The production of English inflectional morphology, speech production and listening performance in children with cochlear implants. *Ear and Hearing*, 19, 310-318.
- Stacey, P. C., Fortnum, H. M., Barton, G. R., & Summerfield, A. Q. (2006). Hearing-impaired children in the United Kingdom, I: auditory performance, communication skills, educational achievements, quality of life and cochlear implantation. *Ear and Hearing*, 27, 161-186.
- Stacey, P. C., & Summerfield, A. Q. (2008). Comparison of word-, sentence-, and phoneme-based training strategies in improving the perception of spectrally distorted speech. *Journal of Speech, Language and Hearing Research*, 51, 526-538.
- Stager, C. L., & Werker, J. F. (1997). Infants listen for more phonetic detail in speech perception than in word learning tasks. *Nature*, 388, 381-382.
- Stoel-Gammon, C. (2011). Relationships between lexical and phonological development in young children. *Journal of Child Language*, 38, 1-34.
- Storkel, H. L. (2002). Restructuring of similarity neighbourhoods in the developing mental lexicon. *Journal of Child Language*, 29, 251-274.
- Storkel, H. L. (2004). Do children acquire dense neighborhoods? An investigation of similarity neighborhoods in lexical acquisition. *Applied Psycholinguistics*, 25, 201-221.
- Storkel, H. L. (2009). Developmental differences in the effects of phonological, lexical and semantic variables on word learning by infants. *Journal of Child Language*, 36, 291-321.
- Storkel, H. L., Armbruster, J., & Hogan, T. P. (2006). Differentiating phonotactic probability and neighborhood density in adult word learning. *Journal of Speech, Language and Hearing Research*, 49, 1175-1192.
- Storkel, H. L., & Hoover, J. R. (2010a). An online calculator to compute phonotactic probability and neighborhood density on the basis of child corpora of spoken American English. *Behavior Research Methods*, 42, 497-506.

- Storkel, H. L., & Hoover, J. R. (2010b). Word learning by children with phonological delays: differentiating effects of phonotactic probability and neighborhood density. *Journal of Communication Disorders*, 43, 105-119.
- Storkel, H. L., & Morrisette, M. L. (2002). Lexicon and phonology: interactions in language development. *Language, Speech, and Hearing Services in Schools*, 33, 24-37.
- Strelnikov, K., Rouger, J., Barone, P., & Deguine, O. (2009). Role of speechreading in audiovisual interactions during the recovery of speech comprehension in deaf adults with cochlear implants. *Scandinavian Journal of Psychology*, 50, 437-444.
- Summerfield, A. Q., Nakisa, M. J., McCormick, B., Archbold, S. M., Gibbin, K. P., & O'Donoghue, G. M. (2002). Use of vocalic information in the identification of /s/ and /sh/ by children with cochlear implants. *Ear and Hearing*, 23, 58-77.
- Svirsky, M. A., Robbins, A. M., Kirk, K. I., Pisoni, D. B., & Miyamoto, R. T. (2000). Language development in profoundly deaf children with cochlear implants. *Psychological Science*, 11, 153-158.
- Svirsky, M. A., Stallings, L. M., Lento, C. L., Ying, E., & Leonard, L. B. (2002). Grammatical morphologic development in pediatric cochlear implant users may be affected by the perceptual prominence of the relevant markers *Annals of Otology, Rhinology and Laryngology*, 111, 109-112.
- Svirsky, M. A., Teoh, S.-W., & Neuburger, H. (2004). Development of language and speech perception in congenitally, profoundly deaf children as a function of age at cochlear implantation. *Audiology and Neuro-Otology*, 9, 224-233.
- Swingle, D. (2007). The roots of the early vocabulary in infants' learning from speech. *Current Directions in Psychological Science*, 17, 308-312.
- Swingle, D. (2009). Contributions of infant word learning to language development. *Philosophical Transactions of the Royal Society B*, 364, 3617-3632.
- Swingle, D., & Aslin, R. N. (2007). Lexical competition in young children's word learning. *Cognitive Psychology*, 54, 99-132.
- Szagan, G. (2000). The acquisition of grammatical and lexical structures in children with cochlear implants: a developmental psycholinguistic approach. *Audiology and Neuro-Otology*, 5, 39-47.
- Tellier, M. (2008). The effect of gestures on second language memorisation by young children. *Gesture*, 8, 219-235.
- Teoh, S. W., Pisoni, D. B., & Miyamoto, R. T. (2004a). Cochlear implantation in adults with prelingual deafness. Part I. Clinical results. *The Laryngoscope*, 114, 1536-1540.
- Teoh, S. W., Pisoni, D. B., & Miyamoto, R. T. (2004b). Cochlear implantation in adults with prelingual deafness. Part II. Underlying constraints that affect audiological outcomes. *The Laryngoscope*, 114, 1714-1719.
- Thal, D., Tobias, S., & Morrison, D. (1991). Language and gesture in late talkers: a one-year follow-up. *Journal of Speech and Hearing Research*, 34, 604-612.
- Tharpe, A. M., Ashmead, D. H., & Rothpletz, A. M. (2002). Visual attention in children with normal hearing, children with hearing aids, and children with cochlear implants. *Journal of Speech, Language and Hearing Research*, 45, 403-413.

- Thomas, M. S. C., & Johnson, M. H. (2008). New advances in understanding sensitive periods in brain development. *Current Directions in Psychological Science*, 17, 1-5.
- Thompson, R., Emmorey, K., & Gollan, T. H. (2005). "Tip of the fingers" experiences by deaf signers. *Psychological Science*, 856-860.
- Thoutenhoofd, E., Archbold, S. M., Gregory, S., Lutman, M. E., Nikolopoulos, T. P., & Sach, T. H. (2005). *Paediatric cochlear implantation: evaluating outcomes*. London: Whurr Publishers.
- Tobey, E. A., Geers, A. E., Brenner, C., Altuna, D., & Gabbert, G. (2003). Factors associated with development of speech production skills in children implanted by age five. *Ear and Hearing*, 24, S36-S45.
- Tobey, E. A., Rekart, D., Buckley, K. A., & Geers, A. E. (2004). Mode of communication and classroom placement impact on speech intelligibility. *Archives of Otolaryngology: Head and Neck Surgery*, 130, 639-643.
- Tobey, E. A., Wiessner, N., Lane, J., Sundarajan, M., Buckley, K. A., & Sullivan, J. (2007). Phoneme accuracy as a function of mode of communication in pediatric cochlear implantation. *Audiological Medicine*, 5, 283-292.
- Tomblin, J. B., Barker, B. A., & Hubbs, S. (2007). Developmental constraints on language development in children with cochlear implants. *International Journal of Audiology*, 46, 513-523.
- Turner, C. W., Reiss, L., & Gantz, B. J. (2008). Combined acoustic and electric hearing: preserving residual acoustic hearing. *Hearing Research*, 242, 164-171.
- Tyler, R. S., Fryau-Bertschy, H., Kelsay, D. M. R., Gantz, B. J., Woodworth, G. P., & Parkinson, A. (1997). Speech perception by prelingually deaf children using cochlear implants. *Archives of Otolaryngology - Head and Neck Surgery*, 40, 183-199.
- Van Alphen, P. M., & Smits, R. (2004). Acoustical and perceptual analysis of the voicing distinction in Dutch initial plosives: the role of prevoicing. *Journal of Phonetics*, 32, 455-491.
- Van de Velde, H., Van Hout, R., & Gerritsen, M. (1997). Watching Dutch change: a real time study of variation and change in standard Dutch pronunciation. *Journal of Sociolinguistics* 1, 361-391.
- Van den Bogaerde, B., & Baker, A. E. (2005). Code mixing in mother-child interaction in deaf families. *Sign Language and Linguistics*, 8, 155-178.
- Van den Bogaerde, B., & Baker, A. E. (2008). Bimodal language acquisition in Kodas. In M. Bishop & S. L. Hicks (Eds.), *Hearing, mother father deaf: hearing people in deaf families* (pp. 99-131). Washington: Gallaudet University Press.
- Van Hessen, A. J., & Schouten, M. E. H. (1992). Modeling phoneme perception II: a model of stop consonant discrimination. *Journal of the Acoustical Society of America*, 92, 1856-1868.
- Vermeulen, A. M., Van Bon, W., Schreuder, R., Knoors, H., & Snik, A. F. M. (2007). Reading comprehension of deaf children with cochlear implants. *Journal of Deaf Studies and Deaf Education*, 12, 283-302.
- Vitevitch, M. S., & Luce, P. A. (1998). When words compete: levels of processing in perception of spoken words. *Psychological Science*, 9, 325-329.

- Vitevitch, M. S., & Luce, P. A. (1999). Probabilistic phonotactics and neighborhood activation in spoken word recognition. *Journal of Memory and Language*, 40, 374-408.
- Walley, A. C. (1993). The role of vocabulary development in children's spoken word recognition and segmentation ability. *Developmental review*, 13, 286-350.
- Walley, A. C., & Flege, J. E. (1999). Effect of lexical status on children's and adults' perception of native and non-native vowels. *Journal of Phonetics*, 27, 307-332.
- Walley, A. C., Metsala, J. L., & Garlock, V. M. (2003). Spoken vocabulary growth: its role in the development of phoneme awareness and early reading ability. *Reading and Writing: An Interdisciplinary Journal*, 16, 5-20.
- Waltzman, S. B., Cohen, N. L., Green, J., & Roland Jr., J. T. (2002a). Long-term effects of cochlear implants in children. *Archives of Otolaryngology: Head and Neck Surgery*, 126, 505-511.
- Waltzman, S. B., & Roland Jr., J. T. (2005). Cochlear implantation in children younger than 12 months. *Pediatrics*, 116, 487-493.
- Waltzman, S. B., Roland, J. T., & Cohen, N. L. (2002b). Delayed implantation in congenitally deaf children and adults. *Otology and Neuro-otology*, 23, 333-340.
- Wang, N.-Y., Eisenberg, L. S., Johnson, K. C., Fink, N. E., Tobey, E. A., Quittner, A. L., et al. (2008). Tracking development of speech recognition: longitudinal data from hierarchical assessments in the Childhood Development After Cochlear Implantation Study. *Otology and Neurotology*, 29, 240-245.
- Wass, M., Ibertsson, T., Lyxell, B., Sahlen, B., Hallgren, M., Larsby, B., et al. (2008). Cognitive and linguistic skills in Swedish children with cochlear implants - measures of accuracy and latency as indicators of development. *Scandinavian Journal of Psychology*, 49.
- Wass, M., Ibertsson, T., Lyxell, B., Sahlen, B., Hallgren, M., Larsby, B., et al. (2009). Cognitive and linguistic skills in Swedish children with cochlear implants - measures of accuracy and latency as indicators of development. *Scandinavian Journal of Psychology*, 49.
- Watson, L. M., Archbold, S. M., & Nikolopoulos, T. P. (2006). Children's communication mode five years after cochlear implantation: changes over time according to age at implant. *Cochlear Implants International*, 7, 77-91.
- Watson, L. M., Hardie, T., Archbold, S. M., & Wheeler, A. (2008). Parents' views on changing communication after cochlear implantation. *Journal of Deaf Studies and Deaf Education*, 10, 104-116.
- Weber, A., & Cutler, A. (2004). Lexical competition in non-native spoken-word recognition. *Journal of Memory and Language*, 50, 1-25.
- Wechsler-Kashi, D., Schwartz, R. G., Cleary, M., & Madell, J. R. (2009). *Lexical access and organization in children with CIs*. Paper presented at the Poster presented at the 12th Symposium on Cochlear Implants in Children.
- Werker, J. F., Cohen, L. B., Lloyd, V. L., Casasola, M., & Stager, C. L. (1998). Acquisition of word-object associations by 14-month old infants. *Developmental Psychology*, 34, 1289-1309.
- Werker, J. F., & Curtin, S. (2005). PRIMIR: a developmental framework of infant speech processing. *Language Learning and Development*, 1, 197-234.

- Werker, J. F., & Fennell, C. (2004). Listening to sounds versus listening to words: early steps in word learning. In D. G. Hall & S. R. Waxman (Eds.), *Weaving a lexicon* (pp. 79-109). Cambridge: MIT Press.
- Werker, J. F., Fennell, C. T., Corcoran, K. M., & Stager, C. L. (2002). Infants' ability to learn phonetically similar words: effects of age and vocabulary size. *Infancy*, 3, 1-30.
- Werker, J. F., & Logan, J. S. (1985). Cross-language evidence for three factors in speech perception. *Perception and Psychophysics*, 37, 35-44.
- Werker, J. F., & Tees, R. C. (1983). Developmental changes across childhood in the perception of non-native speech sounds. *Canadian Journal of Psychology*, 37, 278-286.
- Werker, J. F., & Tees, R. C. (2005). Speech perception as a window for understanding plasticity and commitment in language systems of the brain. *Developmental Psychobiology*, 46, 233-251.
- Werker, J. F., & Yeung, H. H. (2005). Infant speech perception bootstraps word learning. *Trends in Cognitive Sciences*, 9, 519-527.
- Wever, C. C. (2002). Parenting deaf children in the era of cochlear implantation: a narrative ethical analysis. Radboud University.
- Wheeler, A., Archbold, S. M., Gregory, S., & Skipp, A. (2007). Cochlear implants: the young people's perspective. *Journal of Deaf Studies and Deaf Education*, 12, 303-316.
- Wheeler, A., Archbold, S. M., Hardie, T., & Watson, L. M. (2009). Children with cochlear implants: the communication journey. *Cochlear Implants International*, 10, 41-62.
- Wie, O. B., Falkenberg, E.-S., Tvette, O., & Tomblin, J. B. (2007). Children with a cochlear implant: characteristics and determinants of speech recognition, speech-recognition growth rate and speech production. *International Journal of Audiology*, 46, 232-243.
- Wiefferink, C. H., Spaai, G. W. G., Uilenburg, N., Vermeij, B. A. M., & De Raeve, L. (2008). Influence of linguistic environment on children's language development: Flemish versus Dutch children. *Deafness and Education International*, 10, 226-243.
- Willstedt-Svensson, U., Lofqvist, A., Almqvist, B., & Sahlen, B. (2004). Is age at implant the only factor that counts? The influence of working memory on lexical and grammatical development in children with cochlear implants. *International Journal of Audiology*, 43, 506-515.
- Wilson, B. S., & Dorman, M. F. (2008a). Cochlear implants: a remarkable past and a brilliant future. *Hearing Research*, 242, 3-21.
- Wilson, B. S., & Dorman, M. F. (2008b). Cochlear implants: current designs and future possibilities. *Journal of Rehabilitation Research & Development*, 45, 695-730.
- Wilson, M., Bettger, J. G., Niculae, I., & Klima, E. S. (1997). Modality of language shapes working memory: evidence from digit span and spatial span in ASL signers. *Journal of Deaf Studies and Deaf Education*, 2, 150-160.
- Wilson, M., & Emmorey, K. (1997). A visuospatial "phonological" loop in working memory: evidence from American Sign Language. *Memory and Cognition*, 25, 313-320.

- Wilson, M., & Emmorey, K. (1998). A "word length effect" for sign language: further evidence for the role of language in structuring working memory. *Memory & Cognition*, 26, 584-590.
- Wilson, M., & Emmorey, K. (2003). The effect of irrelevant visual input on working memory for sign language. *Journal of Deaf Studies and Deaf Education*, 8, 97-103.
- Wilson, M., & Emmorey, K. (2006). Comparing sign language and speech reveals a universal limit on short-term memory capacity. *Psychological Science*, 17, 682-683.
- Woodhouse, L., Hickson, L., & Dodd, B. (2009). Review of visual speech perception by hearing and hearing-impaired people: clinical implications. *International Journal of Language and Communication Disorders*, 44, 253-270.
- Xu, L., & Pfingst, B. E. (2008). Spectral and temporal cues for speech recognition: implications for auditory prostheses. *Hearing Research*, 242, 132-140.
- Xu, L., Thompson, C. S., & Pfingst, B. E. (2005). Relative contributions of spectral and temporal cues for phoneme recognition. *Journal of the Acoustical Society of America*, 117, 3255-3267.
- Xu, L., & Zheng, Y. (2007). Spectral and temporal cues for phoneme recognition in noise. *Journal of the Acoustical Society of America*, 122, 1758-1764.
- Yoshida, K. A., Fennell, C. T., Swingle, D., & Werker, J. F. (2009). Fourteen-month-old infants learn similar-sounding words. *Developmental Science*, 12, 412-418.
- Yoshinaga-Itano, C. (2003). From screening to early identification and intervention: discovering predictors to successful outcomes for children with significant hearing loss. *Journal of Deaf Studies and Deaf Education*, 8, 11-30.
- Yoshinaga-Itano, C. (2006). Early identification, communication modality, and the development of speech and spoken language skills: patterns and considerations. In P. E. Spencer & M. Marschark (Eds.), *Advances in the spoken language development of deaf and hard-of-hearing children* (pp. 298-327). Oxford: Oxford University Press.
- Ziliak, Z., & Van de Velde, H. (2007). Stop variation in Dutch. Thursday Linguistics Seminar, University of Florida, 29 November 2007.
- Zwolan, T. A., Ashbaugh, C. M., Alarfaj, A., Kileny, P. R., Arts, H. A., El-Kashlan, H. K., et al. (2004). Pediatric cochlear implant patient performance as a function of age at implantation. *Otology and Neurotology*, 25, 112-120.

SUMMARY IN ENGLISH

PEDIATRIC COCHLEAR IMPLANTATION

A cochlear implant (CI) is an electronic ear prosthesis that directly stimulates the auditory nerve and partially restores access to sound and speech for profoundly deaf children and adults. The last decade has witnessed a substantial increase in the number of implantations in deaf children. At the same time, a rapid decrease of the age at implantation to below 12 months and advances in design and speech processors have increased the benefit children can obtain from the CI. Bilateral implantation and the combination of acoustic hearing aids and CIs can even further increase the benefit, especially in noisy environments (Chapter 1).

Although the potential and success of CIs has far exceeded expectations, they do not restore normal hearing. Compared to the human ear, sound processing with a CI is characterized by poor spectral, and to a lesser extent temporal, resolution. Recent studies with large samples of children have indicated that many continue to be delayed in their spoken language development compared to their peers with normal hearing, even after several years of CI use. However, there is substantial inter-individual variation in outcomes (Chapter 1).

Standardized speech perception, speech production and expressive and receptive vocabulary and language tests are typically used for assessing spoken language outcomes in children with a CI. Relevant as these may be in the clinical setting, they tell us little about actual performance with the CI and underlying processes in speech perception that may help to explain the observed large inter-individual variation in outcomes. For this reason, the first goal of this thesis was to study the perception of sounds and words and their interrelationship (Chapter 2).

The observed delays in spoken language development further suggest that children with a CI may benefit from having access to alternative modes of communication such as sign language. However, the role of signed input in the education of children with a CI is much debated (Chapter 1). Instead of supporting spoken language development it has been suggested that any form of signed input impedes spoken language development. Typically these studies have compared two groups of children from different educational settings, usually Oral Communication settings (i.e., only spoken language) and Total Communication settings (i.e., both spoken language and some form of signed communication). By contrast, only a few studies have assessed both language modalities in the same children. Furthermore, no systematic study has yet been done on the effects of using sign-supported speech on spoken language processing in children with a CI. The second goal of this thesis was therefore to obtain further insight into the effects of signed input on spoken language abilities, in particular speech perception (Chapter 2).

STUDY DESIGN

This thesis has accomplished these goals by examining the use of acoustic cues in sound perception and the representation of sound contrasts in novel words, by interrelating similar performance measures in both language modalities, and by investigating the effects of bimodal (i.e., simultaneously spoken and signed) input on speech perception. Specifically, we assessed speech and sign perception abilities in a sample of 15 5-to 6-year-old children with a CI who varied in the extent and nature of signed input received at home and school. Half were educated a spoken language, supported with signs, and the other half were also educated in a sign language. Average age at implantation in the sample was 1;8 and average length of CI use four years. Their performance was compared to that of 20 age-matched children with normal hearing and 21 young adults with normal hearing. The administered tasks included sound and sign categorization, rapid word and sign learning and phonological short-term memory in both modalities. In addition, an extra task designed to investigate the effects of bimodal input on spoken word recognition and learning was administered to a subset of the children with a CI (Chapter 3).

THE PERCEPTION OF SOUNDS AND WORDS

Listeners discriminate and identify speech sounds on the basis of language-specific combinations of acoustic cues present in the speech input, such as spectral and temporal cues. The development of adult-like cue weighting continues until later childhood and likely presents an extra challenge for children with a CI given their limitations with sound processing. We therefore investigated the use of acoustic cues in vowel and consonant contrasts with a sound categorization task (Chapter 4). In each contrast, different acoustic cues were manipulated, such as spectrum and duration for the vowel contrasts. Results showed that the children with a CI used some acoustic cues less effectively than their peers with normal hearing, resulting in shallower discrimination functions. The place of articulation contrast /fʊ/-/sʊ/ presented them with the most difficulties. Importantly, however, both groups of children and the adults showed similar perceptual cue weighting patterns for the vowel and consonant contrasts. For instance, they all weighted the spectral cue as relatively stronger than the durational cue in categorizing the vowel contrasts. That is, despite poor spectral resolution of the implant, children with a CI appear to show typical language-specific cue weighting patterns. Finally, the children with normal hearing did not yet exhibit adult-like use of acoustic cues and categorized contrasts less consistently than the adults, consistent with previous reports in the literature on the continuing development of sound perception into childhood.

In Chapter 5, we examined the interrelationship between sounds and words by testing children and adults' ability to learn novel minimal pairs (e.g., /tat/-/tat/) in

rapid word learning tasks. Their scores in these tasks were related to their sound perception and phonological short-term memory. The latter was measured with a digit span task. The same consonant and vowel contrasts included in the sound categorization task distinguished the minimal pairs in the rapid word learning tasks. The results showed that, whereas both child groups had problems with learning novel minimal pairs in a demanding task, only the children with a CI experienced similar problems with a less demanding and more ecologically valid task. Age at implantation did not correlate with sound categorization, rapid word learning or phonological short-term memory. However, the latter correlated significantly with length of CI use, highlighting the importance of auditory experience in the development of phonological short-term memory. Phonological short-term memory further correlated significantly with sound categorization for the children with a CI. A significant correlation between sound categorization and rapid word learning was found for the children with normal hearing but not for the children with a CI, and for only one of the two rapid word learning tasks. This correlation suggests that the construction of novel lexical representations is affected by the stability of phonetic category boundaries, consistent with existing literature on the continuing development of both phonological and lexical representations into childhood.

SPEECH AND SIGN PERCEPTION: RELATIONS AND INTERACTIONS

Chapters 6 and 7 investigated the relationship and interaction between sign and speech perception in children with a CI. In Chapter 6 we showed that they obtained equal levels of performance in the spoken and signed modality on the two rapid word and sign learning tasks and on the phonological short-term memory tasks. However, on the categorization task they performed more poorly in the signed modality. Correlations between the two modalities for each task showed significant *positive* correlations for several measures, whereas negative correlations would have been expected in case of a direct negative influence of signing experience on speech perception. That is, in our sample the children with higher sign perception scores also obtained higher speech perception scores. Moreover, length of CI use correlated with scores in both language modalities, underlining the importance of language input following implantation for the development of speech and sign perception abilities. These findings suggest that spoken and sign language development are not mutually exclusive for children with a CI and that other factors such as early language stimulation, cognitive development and efficient parent-child interaction may be more important in determining language outcomes in both modalities.

In Chapter 7 we extended our investigation of the relationship between the two language modalities to real-time interaction in a sign-supported speech context. That is, we wanted to determine whether exposing children with a CI to bimodal input facilitated or hampered their speech perception. For that reason, we compared spoken word recognition and learning in speech-only and bimodal conditions. The

stimuli consisted of familiar and novel word and sign pairs, both phonologically similar (i.e., minimal pairs) and dissimilar. Crucially, although familiarization in the bimodal condition was in speech and sign, testing was only in speech, allowing us to directly investigate the effects of bimodal input on speech perception. The results revealed no negative effects of bimodal exposure on spoken word recognition and learning and in fact suggested positive effects on the recognition of phonologically similar familiar words, such as /kɔp/ and /pɔp/. These results are consistent with the positive correlations reported in Chapter 6 and further indicate that the two modalities can actually complement each other in language processing.

IMPLICATIONS

The discussion of our findings (Chapter 8) focused on the increase in lexical competition that is likely to result from less sharp boundaries between phonetic categories and a lack of phonetic detail in newly created lexical representations. Furthermore, we argued that increased competition in the mental lexicon will likely negatively impact the speed and efficacy of spoken word recognition and verbal working memory processes, and slow down vocabulary acquisition and the development of phonological awareness. Additionally, our findings from Chapters 6 and 7 showed that signed and spoken language development are not mutually exclusive for children with a CI and that bimodal input may even facilitate their spoken word recognition. Signed input therefore does not appear to have negative effects on spoken language processing. Thus, it is argued that signed input should not be withheld from children with a CI, especially given its importance in stimulating early social and cognitive development, in the case of implant malfunctioning and in facilitating interactions with deaf peers without a CI. In fact, this speaks for bilingualism in a spoken and a signed language as the ultimate goal in the rehabilitation and education of children with a CI. Evidently, to achieve this goal considerable effort and support is required from all those involved in pediatric cochlear implantation, including parents, clinicians, speech-language therapists and teachers, and last but not least, researchers, who need to provide a stronger evidence base regarding the effects of signed input on social, cognitive and language development in children with a CI.

SAMENVATTING IN HET NEDERLANDS

COCHLEAIRE IMPLANTATIE BIJ KINDEREN

Een cochleair implantaat (CI) is een elektronische binnenoorprothese die direct de gehoorzenuw stimuleert en op die manier geluidswaarneming gedeeltelijk kan herstellen voor dove kinderen en volwassenen. In het afgelopen decennium is het aantal implantaties bij kinderen fors gestegen. Tegelijkertijd is de leeftijd waarop geïmplantiseerd wordt sterk gedaald tot onder de 12 maanden. Deze ontwikkeling en technologische verbeteringen hebben het profijt dat kinderen van een CI kunnen hebben, sterk vergroot. Recente innovaties zoals bilaterale implantatie en het gecombineerd gebruik van een CI en een akoestisch gehoorapparaat kunnen dit profijt mogelijk nog verder vergroten, vooral in rumoerige luisteromgevingen (Hoofdstuk 1).

Hoewel de mogelijkheden en het succes van CI's de verwachtingen ver te boven zijn gegaan, schiet een CI nog steeds tekort in vergelijking met het normale oor. Geluidswaarneming met een CI wordt namelijk gekenmerkt door een relatief slechte spectrale, en in iets minder mate, temporele resolutie. Inderdaad laten recente studies met grote onderzoeksgroepen zien dat de gesproken taalontwikkeling van veel van deze kinderen achterblijft ten opzichte van horende leeftijdgenootjes, zelfs als het CI al enkele jaren gebruikt wordt. De onderlinge variatie in behaalde resultaten is echter erg groot (Hoofdstuk 1).

Gewoonlijk worden gestandaardiseerde spraakherkennings-, spraakproductie- en expressieve en receptieve woordenschat- en taaltesten gebruikt om de gesproken taalvaardigheid van kinderen met een CI te meten. Hoewel dit soort testen van groot belang zijn in de klinische setting, zeggen ze weinig over de effectieve werking van het CI en over onderliggende processen in de spraakwaarneming die mogelijk mede de grote variatie in resultaten kunnen verklaren. Het eerste doel van dit proefschrift was daarom om de waarneming van klanken en woorden en hun onderlinge relatie te bestuderen (Hoofdstuk 2).

De waargenomen achterstanden in de gesproken taalontwikkeling suggereren verder dat kinderen met een CI mogelijk baat hebben bij toegang tot alternatieve manieren om te communiceren zoals gebarentaal. De rol van gebarenaanbod in het onderwijs aan deze kinderen staat echter ter discussie (Hoofdstuk 1). Sommige onderzoekers beweren dat, in plaats van de gesproken taalontwikkeling te ondersteunen, elke vorm van gebarenaanbod de gesproken taalontwikkeling juist in de weg staat. In hun studies vergelijken zij meestal twee groepen kinderen uit verschillende onderwijssettings, namelijk Orale Communicatie (alleen gesproken taalaanbod) en Totale Communicatie (zowel gesproken taalaanbod als een vorm van gebarenaanbod). Er zijn slechts enkele studies beschikbaar die beide taalmodaliteiten in dezelfde kinderen hebben onderzocht. Daarnaast is er nog geen

systematisch onderzoek gedaan naar de effecten van gebarenondersteuning op de spraakwaarneming bij kinderen met een CI. Het tweede doel van dit proefschrift was daarom om meer inzicht te krijgen in de effecten van gebarenaanbod op gesproken taalvaardigheden, in het bijzonder de spraakwaarneming (Hoofdstuk 2).

OPZET VAN HET ONDERZOEK

Om bovenstaande doelen te verwezenlijken, is voor dit proefschrift onderzoek gedaan naar het gebruik van akoestische cues in klankwaarneming en naar de representatie van klankcontrasten in nieuwe woorden, zijn de uitkomsten van vergelijkbare taken in beide taalmodaliteiten aan elkaar gerelateerd, en is onderzoek gedaan naar de effecten van gebarenondersteuning op de spraakwaarneming. Hiertoe is de spraak- en gebarenwaarneming onderzocht in een groep van 15 kinderen met een CI tussen de vijf en zes jaar oud. Deze kinderen verschilden in de mate van gebarenaanbod die ze thuis en op school kregen. Ongeveer de helft ontving onderwijs in een gesproken taal, ondersteund met gebaren. De andere helft ontving daarnaast onderwijs in een gebarentaal. De gemiddelde leeftijd van implantatie was 1;8 en de kinderen hadden hun CI gemiddeld vier jaar. Hun resultaten werden vergeleken met die van 20 normaalhorende kinderen van dezelfde leeftijd en 21 normaalhorende jongvolwassenen. De taken die afgenomen zijn, waren een klanken- en gebarencategorisatietask, woord- en gebaarleertaken en een task om het fonologische korte-termijn geheugen te meten. Daarnaast werd bij een kleinere groep van kinderen met een CI een extra task afgenomen die de effecten van gebarenondersteuning op het herkennen en leren van gesproken woorden onderzocht (Hoofdstuk 3).

DE WAARNEMING VAN KLANKEN EN WOORDEN

Luisteraars onderscheiden en herkennen spraakklanken aan de hand van taalspecifieke combinaties van akoestische cues in het spraaksignaal, zoals spectrale en temporele cues. Het correct leren gebruiken van deze cues loopt door tot na het achtste levensjaar en is waarschijnlijk een extra uitdaging voor kinderen met een CI door hun beperkte geluidswaarneming. In dit proefschrift hebben we het gebruik van akoestische cues voor het onderscheiden van enkele medeklinker- en klinkercontrasten onderzocht aan de hand van een klankcategorisatietask (Hoofdstuk 4). Voor elk contrast werden verschillende akoestische cues gemanipuleerd, bijvoorbeeld spectrum en duur voor de klinkercontrasten. De resultaten van deze studie lieten zien dat de kinderen met een CI sommige akoestische cues minder effectief gebruikten dan normaalhorende kinderen, wat resulteerde in minder steile discriminatiecurven. Het medeklinkercontrast /fu/-/su/, een contrast in plaats van articulatie, was het meest moeilijk voor hen. Beide groepen kinderen en de volwassenen lieten vergelijkbare resultaten lieten zien wat betreft het relatieve

belang van de twee gemanipuleerde cues in een contrast. Zo vonden ze allemaal de spectrale cue belangrijker dan de temporele cue bij het categoriseren van de klinkercontrasten. Ondanks de beperkte spectrale resolutie van het CI vertoonden de kinderen met een CI dus de gebruikelijke taalspecifieke cue-wegingspatronen. De normaalhorende kinderen, tot slot, gebruikten verscheidene akoestische cues nog niet zo effectief als de volwassenen en categoriseerden klanken ook minder consistent dan volwassenen. Dit komt overeen met eerdere studies naar de ontwikkeling van klankwaarneming bij normaalhorende kinderen.

In Hoofdstuk 5 onderzochten we de samenhang tussen het waarnemen van klanken en woorden door de vaardigheid van kinderen en volwassenen om nieuwe minimale paren te leren (bijvoorbeeld /tat/-/tat/) te testen aan de hand van woordleertaken. Hun scores op deze taken werden gerelateerd aan hun klankwaarneming en fonologisch korte-termijn geheugen. Het laatste werd gemeten met een taak waarbij de proefpersonen reeksen van uitgesproken cijfers moesten herhalen. De minimale paren in de woordleertaken onderscheidde zich in dezelfde medeklinker- en klinkercontrasten als gebruikt waren in de klankcategorisatietaken in Hoofdstuk 4. De resultaten lieten zien dat, terwijl beide groepen kinderen moeite hadden met het leren van nieuwe minimale paren in een cognitief veeleisende taak, alleen de kinderen met een CI vergelijkbare problemen ondervonden bij een cognitief minder veeleisende en meer natuurlijke taak. Leeftijd van implantatie correleerde niet met klankcategorisatie, woordleren noch fonologisch korte-termijn geheugen. Het laatste correleerde wel met de duur van CI-gebruik, wat suggereert dat auditief aanbod erg belangrijk is voor het ontwikkelen van het fonologisch korte-termijn geheugen. Daarnaast correleerde fonologisch korte-termijn geheugen met klankcategorisatie bij de kinderen met een CI. Tot slot werd een correlatie gevonden tussen klankwaarneming en woordleren bij de normaalhorende kinderen, maar niet bij de kinderen met een CI, en voor slechts één van de twee woordleertaken. Deze correlatie suggereert dat het creëren van nieuwe lexicale representaties beïnvloed wordt door de stabiliteit van fonetische grenzen tussen klankcategorieën, wat overeen komt met de bestaande literatuur over de nog onvoltooide ontwikkeling van zowel fonologische als lexicale representaties op deze leeftijd.

SPRAAKWAARNEMING EN GEBARENWAARNEMING: RELATIES EN INTERACTIES

In Hoofdstuk 6 en Hoofdstuk 7 onderzochten we de relatie en interactie tussen gebaren- en spraakwaarneming. In Hoofdstuk 6 lieten we zien dat kinderen met een CI vergelijkbaar scoorden in beide modaliteiten op de woord- en gebaarleertaken en de fonologisch korte-termijn geheugentaak. Op de categorisatietaken scoorden ze echter slechter in de gebarenmodaliteit. Bij de kinderen met een CI vonden we positieve correlaties tussen de twee modaliteiten voor verscheidene maten, terwijl negatieve correlaties verwacht zouden worden als gebarenaanbod een directe

negatieve invloed op spraakwaarneming zou hebben. Met andere woorden, in onze onderzoeksgroep behaalden de kinderen die relatief hoog scoorden in de gebarenmodaliteit eveneens relatief hoge scores in de gesproken modaliteit. Daarnaast correleerde de duur van CI-gebruik met scores in beide modaliteiten, wat het belang onderstreept van taalaanbod na implantatie voor de ontwikkeling van spraak- en gebarenwaarnemingsvaardigheden. Deze resultaten suggereren dat de ontwikkeling van gesproken taal en gebarentaal elkaar niet uitsluit voor kinderen met een CI en dat andere factoren zoals vroege taalstimulering, cognitieve ontwikkeling en efficiënte ouder-kind interactie mogelijk vooral bepalend zijn bij het voorspellen van de taalvaardigheden in beide modaliteiten.

In Hoofdstuk 7 breidden we ons onderzoek naar de relatie tussen de twee taalmodaliteiten uit naar hun interactie in een gebarenondersteunende context. Specifieker wilden we vaststellen of gebarenondersteuning de spraakwaarneming bij kinderen met een CI zou faciliteren of juist in de weg zou staan. Om dit te onderzoeken, vergeleken we het herkennen en leren van woorden in een gesproken en gebarenondersteunende testconditie. De stimuli bestonden uit bekende en nieuwe woord- en gebarenparen die fonologisch op elkaar leken (minimale paren) of niet. Het is belangrijk om te vermelden dat, hoewel familiarisatie met de stimuli in de gebarenondersteunende conditie in zowel spraak als gebaren plaatsvond, het testen alleen in spraak gedaan werd om zo de directe effecten van gebarenondersteuning op de spraakwaarneming vast te stellen. De resultaten lieten geen negatieve effecten van gebarenondersteuning op de spraakwaarneming zien en zelfs positieve effecten op de herkenning van bekende woorden die fonologisch op elkaar leken, zoals /kɔp/ en /pɔp/. Deze bevindingen zijn in overeenstemming met de positieve correlaties tussen de twee modaliteiten in Hoofdstuk 6 en suggereren verder dat de twee modaliteiten elkaar zelfs aan kunnen vullen tijdens de taalverwerking.

IMPLICATIES

In de discussie van onze bevindingen (Hoofdstuk 8) lag de nadruk op de grotere lexicale competitie die in alle waarschijnlijkheid resulteert uit minder duidelijke grenzen tussen fonetische categorieën en een gebrek aan fonetisch detail in recent gecreëerde lexicale representaties. Daarnaast beargumenteerden we dat meer competitie in het mentale lexicon waarschijnlijk de snelheid en effectiviteit van gesproken woordherkenning en verbale werkgeheugenprocessen negatief beïnvloedt, en woordenschatverwerving en de ontwikkeling van fonologisch bewustzijn vertraagt. Daarnaast toonden de resultaten uit Hoofdstukken 6 en 7 aan dat de ontwikkeling van gesproken taal en gebarentaal elkaar niet uit hoeven te sluiten voor kinderen met een CI en dat gebarenondersteuning de gesproken woordherkenning zelfs kan faciliteren. Gebarenaanbod lijkt dus in ieder geval geen negatieve effecten op de gesproken taalverwerking te hebben. We stellen daarom dat gebarenaanbod

niet onthouden moet worden aan kinderen met een CI, zeker gezien het belang van een dergelijk aanbod voor het stimuleren van de vroege sociale en cognitieve ontwikkeling, maar ook om op terug te vallen als het CI niet goed (meer) functioneert en om de interactie met dove leeftijdgenootjes zonder CI te vergemakkelijken. Het ultieme doel in het rehabiliteren en onderwijzen van kinderen met een CI, vinden wij, moet dan ook tweetaligheid in een gesproken taal en een gebarentaal zijn. Om dit doel te bereiken is uiteraard een grote inspanning en medewerking nodig van eenieder die betrokken is bij de implantatie van dove kinderen, waaronder ouders, artsen, logopedisten, onderwijzers en, niet te vergeten, onderzoekers, die voor meer evidentie moeten zorgen ten aanzien van de effecten van gebarenaanbod op de sociale, cognitieve en taalontwikkeling bij kinderen met een CI.