

Swantje Zachau

SIGNS IN THE BRAIN:
HEARING SIGNERS' CROSS-
LINGUISTIC SEMANTIC
INTEGRATION STRATEGIES

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SWANTJE ZACHAU

**SIGNS IN THE BRAIN: HEARING
SIGNERS' CROSS-LINGUISTIC
SEMANTIC INTEGRATION
STRATEGIES**

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Abstract

Audio-oral speech and visuo-manual sign language as used by the Deaf community are two very different realizations of the human linguistic communication system. Sign language is not only used by the hearing impaired but also by different groups of hearing individuals. To date, there is a great discrepancy in scientific knowledge about signed and spoken languages. Particularly little is known about the integration of the two systems, even though the vast majority of deaf and hearing signers also have a command of some form of speech. This neurolinguistic study aimed to achieve basic knowledge about semantic integration mechanisms across speech and sign language in hearing native and non-native signers.

Basic principles of sign processing as reflected in electrocortical brain activation and behavioral decisions were examined in three groups of study participants: Hearing native signers (children of deaf adults, CODAs), hearing late learned signers (professional sign language interpreters), and hearing non-signing controls. Event-related brain potentials (ERPs) and behavioral response frequencies were recorded while the participants performed a semantic decision task for priming lexeme pairs. The lexeme pairs were presented either within speech (spoken prime-spoken target) or across speech and sign language (spoken prime-signed target). Target-related ERP responses were subjected to temporal principal component analyses (tPCA). The neurocognitive basis of semantic integration processes were assessed by analyzing different ERP components (N170, N400, late positive complex) in response to the antonymic and unrelated targets. Behavioral decision sensitivity to the target lexemes is discussed in relation to the measured brain activity.

Behaviorally, all three groups of study participants performed above chance level when making semantic decisions about the primed targets. Different result patterns, however, hinted at three different processing strategies. As the target-locked electrophysiological data was analyzed by PCA, for the first time in the context of sign language processing, objectively allocated ERP components of interest could be explored. A little surprisingly, the overall study results from the sign-naïve control group showed that they performed in a more content-guided way than expected. This suggested that even non-experts in the field of sign language were equipped with basic skills to process the cross-linguistically primed signs. Behavioral and electrophysiological study results together further brought up qualitative differences in processing between the native and late learned signers, which raised the question: can a unitary model of sign processing do justice to different groups of sign language users?

Keywords: audio-visual processing, cross-linguistic priming, cross-modal bilingualism, event-related brain potentials, late positive complex, N170, N400, semantics, sign language

Zachau, Swantje, Viittomia aivoissa: kuinka kuulevat viittomakielen käyttäjät prosessoivat puhutun ja viittomakielen merkityksiä?

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Tiivistelmä

Kuuloaistiin ja ääntöelimestön motoriikkaan perustuva puhe ja kuurojen yhteisön käyttämä, näköaistiin ja käsien liikkeisiin perustuva viittomakieli ovat kaksi varsin erilaista ihmisen kielellisen viestintäjärjestelmän toteutumismuotoa. Viittomakieltä käyttävät kuulovammaisten ohella myös monet kuulevat ihmisryhmät. Tähänastinen tutkimustiedon määrä viittomakielistä ja puhutuista kielistä eroaa huomattavasti. Erityisen vähän on tiedetty näiden kahden järjestelmän yhdistämisestä, vaikka valtaosa kuuroista ja kuulevista viittomakielen käyttäjistä hallitsee myös puheen jossain muodossa. Tämän neurolingvistisen tutkimuksen tarkoituksena oli hankkia perustietoja puheen ja viittomakielen välisistä semanttisista yhdistämissmekanismeista kuulevilla, viittomakieltä äidinkielenään tai muuna kielenä käyttävillä henkilöillä.

Viittomien prosessoinnin peruseräitä, jotka ilmenevät aivojen sähköisen toiminnan muutoksina ja valintapäätöksinä, tutkittiin kolmessa koehenkilöryhmässä: kuulevilla viittomakieltä äidinkielenään käyttävillä henkilöillä (kuurojen aikuisten kuulevilla ns. CODA-lapsilla, engl. children of deaf adults), kuulevilla viittomakielen myöhemmin oppineilla henkilöillä (viittomakielen ammattitulleilla) sekä kuulevilla viittomakieltä osaamattomilla verrokkihenkilöillä. Tapahtumasidonnaiset herätepotentiaalit (ERP:t) ja käyttäytymisvasteen frekvenssit rekisteröitiin koehenkilöiden tehdessä semanttisia valintoja viritetyistä (engl. primed) lekseemipareista. Lekseemiparit esitettiin joko puheena (puhuttu viritesana – puhuttu kohdesana) tai puheen ja viittomakielen välillä (puhuttu viritesana – viitottu kohdesana). Kohdesidonnaisille ERP-vasteille tehtiin temporaaliset pääkomponenttianalyysit (tPCA). Semanttisten yhdistämisprosessien neurokognitiivista perustaa arvioitiin analysoimalla erilaisia ERP-komponentteja (N170, N400, myöhäinen positiivinen kompleksi) vastineina antonyymisiin ja toisiinsa liittymättömiin kohteisiin. Käyttäytymispäätöksen herkkyyttä kohdelekseemeille tarkastellaan suhteessa mitattuun aivojen aktiviteettiin.

Käyttäytymisen osalta kaikki kolme koehenkilöryhmää suoriutuivat satunnaistasoa paremmin tehdessään semanttisia valintoja viritetyistä kohdelekseemeistä. Erilaiset tulokset viittaavat kuitenkin kolmeen erilaiseen prosessointistrategiaan. Kun kohdelukittua elektrofysiologista dataa analysoitiin pääkomponenttianalyysin avulla ensimmäistä kertaa viittomakielen prosessoinnin yhteydessä, voitiin tutkia tarkkaavaisuuden objektiivisesti allokoituja ERP-komponentteja. Oli jossain määrin yllättävää, että viittomakielellisesti natiivin verrokkiryhmän tulokset osoittivat sen jäsenten toimivan odotettua sisältölähtöisemmin. Tämä viittaa siihen, että viittomakieleen perehtymättömilläkin henkilöillä on perustaidot lingvistisesti ristiin viritettyjen viittomien prosessointiin. Yhdessä käyttäytymisperäiset ja elektrofysiologiset tutkimustulokset toivat esiin laadullisia eroja prosessoinnissa viittomakieltä äidinkielenään puhuvien henkilöiden ja kielen myöhemmin oppineiden henkilöiden välillä. Tämä puolestaan johtaa kysymykseen, voiko yksi viittomien prosessointimalli soveltaa erilaisille viittomakielen käyttäjryhmille?

Asiasanat: audiovisuaalinen prosessointi, kieltenvälinen virittyminen, late positive complex, monikanavien kaksikielisyys, N170, N400, semantiikka, tapahtumasidonnainen herätepotentiaali, viittomakieli

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Swantje Zachau

Abbreviations

ANOVA	Analysis of Variance
AoA	Age of Acquisition
ASL	American Sign Language
BSL	British Sign Language
CODA	Child of Deaf Adults
EEG	Electroencephalogram
ELAN	Early Left Anterior Negativity
EOG	Electrooculogram
ERP	Event-Related Brain Potential
fMRI	functional Magnetic Resonance Imaging
fNIRS	functional Near-Infrared Spectroscopy
FinSL	Finnish Sign Language
DGS	German Sign Language (Deutsche Gebärdensprache)
ISI	Interstimulus Interval
ITI	Intertrial Interval
LAN	Left Anterior Negativity
L1	first language
L2	second language
LPC	Late Positive Complex
LSE	Spanish Sign Language (Lengua de Signos Española)
LVF	Left Visual Field
MEG	Magnetoencephalography
MRI	Magnetic Resonance Imaging
PCA	Principal Component Analysis
PET	Positron Emission Tomography
rmANOVA	repeated-measures Analysis of Variance
RHM	Revised Hierarchical Model
RQ	research question
RVF	Right Visual Field
SPS	Syntactic Positive Shift
SZ	Swantje Zachau [author]
tPC	temporal Principal Component
tPCA	temporal Principal Component Analysis
VWFA	Visual Word Form Area

Original publications

This thesis is based on the following publications, which are referred throughout the text by their Roman numerals.

- I Zachau S, Leppänen PHT, Ervast L, Heinänen K, Suominen K, Lehtihalmes M & Korpilahti P (2012). Semantic representation of speech and signing in codas and interpreters: Behavioral patterns of interaction. *Multimodal Communication 1(2)*, 105-125.
- II Zachau S, Korpilahti P, Hämäläinen JA, Ervast L, Heinänen K, Suominen K, Lehtihalmes M & Leppänen PHT (2014). Electrophysiological correlates of cross-linguistic semantic integration in hearing signers: N400 and LPC. *Neuropsychologia, 59*, 57-73.
- III Zachau S, Lehtihalmes M, Korpilahti P, Ervast L, Heinänen K, Suominen K, Hämäläinen J & Leppänen P (unpublished manuscript). Reading signs right: N170 is connected to cross-linguistic semantic integration in hearing signers.

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1 Introduction

Ferdinand de Saussure (*1857, †1913), the founding father of modern structural linguistics and semiotics, recognized that human language is remarkably multidimensional. In his classical trichotomy, he distinguished *langage*, the human capability to use language, from *langue*, language in the sense of abstract systems of rules (like English, Finnish etc.), and *parole*, the actual act of language usage (e.g., Matthews 1997). It took decades, though, before the scientific community began to recognize that the primary code of *langue* must not always be vocal (a spoken language). The acknowledgement of signed language as a linguistically full-fledged visual language code was initiated primarily due to the work of William C. Stokoe (*1919, †2000) in 1960 (Stokoe 1960). Other than de Saussure's *code écrit*, the literary language, signed languages are not based on speech but coexist as self-contained linguistic codes besides spoken languages. They are the primary code of a social minority and are probably therefore often commonly perceived as inferior and secondary. Signed languages are the naturally evolved form of *langue*, which is used when a *code vocal* is physically unfeasible due to defective hearing.

Sign language is furthermore not only used by the hearing impaired themselves but also by their relatives, friends, and different supporters of the *Deaf* (= biologically deaf and associate of the signing community) life and culture who are often not hearing impaired. Even though heredity is the main risk factor for severe hearing impairments and deafness, about 90-95% of children born to deaf parents are hearing (e.g., Shield 2005). Vice versa, more than 90% of deaf children are born into hearing families (e.g., Marschark 1997). Consequently, the Deaf community is socially highly challenging for its associates in terms of within-community enculturation and global identity. Sign language is passed on to all members of the Deaf community and represents the most integrative constituent of the community's identity.

Biologically hearing and primarily acculturated in the Deaf community, hearing children of deaf parents face severe challenges of socio-cultural integration and identity. Living within and between two worlds, the vast majority of these subjects grow up biculturally as well as bilingually (Singleton & Tittle 2000). They acquire sign language from their parents and speech from other hearing family members or at daycare/school. Such a balanced acquisition of at least one spoken and at least one signed language from the earliest stages of life is referred to as *cross-modal* (or *bimodal*) *bilingualism*. Because they are adjusted to the hearing

and to the Deaf culture, cross-modal bilinguals do not strike one as deviating at first glance. However, they often report a deep sense of being different. In 1983, this self-conception led to the founding of a nowadays internationally operating organization representing the public and social interests of these *children of deaf adults* (CODA International, Inc.) in the United States of America. The acronym *CODA* stands for the organization's associates. Further, it was intentionally aligned with music theory terminology by the organization's founder, CODA herself, for reasons of self-definition:

I recall practicing classical music pieces for symphony orchestra concerts and having conductors explain the term coda. In a musical composition, it was the concluding segment dependent upon the preceding musical development; yet, it was an altered version of the original. In my eyes, I was the human analogy to this musical form.

(Brother 1983, p. 1)

The data for this dissertation was collected in the city of Oulu in northern Finland between 2005 and 2008. Ten years prior to this study, in 1995, Finland had been the third country worldwide to legally recognize sign language as minority language in its constitution. Two signed languages exist in Finland: The widely used *Finnish Sign Language* (FinSL, suomalainen viittomakieli), and the regionally restricted *Finnish-Swedish Sign Language* (FinSSL, suomenruotsalainen viittomakieli). About 4000-5000 hearing impaired signers and 6000-9000 hearing signers live in Finland among its roughly 5.5 million residents, and more than 500 persons had registered a signed language as their mother tongue at the population register by the end of 2014 (Finnish Association of the Deaf 2015).

Therefore, the majority of signers, in Finland and elsewhere, are hearing. Having had the opportunity to see the immense beauty of signed language and to experience the difficulty of learning it myself, it was this study's intention to advance the scientific knowledge about different aspects of cross-modal bilingualism. Such informed insights could help to leverage a more positive self-image of hearing sign language users: Being special is not only a burden – it can be such a treasure, too.

In search of more detailed insights into the cognitive status of cross-modal bilinguals, this dissertation compiles data from (neuro-)cognitive studies of sign language processing in hearing signers. The overall goal is a more general understanding of how the brain handles two physically very different languages

and what happens when they collide. This dissertation studies the outcome of different modes of sign language acquisition in two groups of signers: CODAs on the one hand, who acquired sign language naturally and untutored from birth on (L1), in parallel to or slightly preceding the acquisition of speech, and professional sign language interpreters on the other hand, who learned sign language during (early) adulthood as a foreign language (L2) in highly structured classroom- and schoolbook-settings long after their first language. The comparison of the two groups' processing profiles thus offers a retrospective perspective on the two modes of sign language acquisition. A group of sign-naïve individuals served as controls. For the ability of separating different processes on a timely scale, the EEG method was chosen to register the brain's activity when it is challenged across spoken and signed language. The integration of *event-related brain potential* (ERP) data from different processing stages of a semantic decision task with the corresponding behavioral results yielded fairly circumstantial considerations.

In the following, the literature on relevant aspects of sign language representation, processing, and acquisition will be reviewed. Because data for all studies (I-III) were based on one single experiment, the chapters on the study results and the discussion related to them are composed accordingly. All results are first presented (chapter 5) and only thereafter discussed (chapter 6) in line with the research questions (RQs), as introduced in chapter 3.

2 Literature review

2.1 The cognitive neuroscience of signed language

Speech and sign language are two physically very different manifestations of rule-governed human communication. However, sign language is without doubt a full-fledged linguistic system (e.g., Emmorey 2002, Pfau et al. 2012, Sandler & Lillo-Martin 2006). It is therefore commonly presumed that the two systems are processed in a functionally similar way. Previous studies on the neurocognitive basis of signed language often reasoned that similarities in representation and processing of speech and signing reflect the core functions of human language. In contrast, differences in representation and processing were considered to result from differences in sensory modalities of transmission. Fairly consentaneous to date, this view has been questioned by recent reviews (Corina et al. 2013, MacSweeney et al. 2008) highlighting the possibility of specific neural systems mediating at least some aspects of signed language in deaf signers. Corina and colleagues (Corina et al. 2013) see the reason for the traditional search for cross-linguistic similarities historically founded in the urge of sign language researchers to correct the common misconception of the visual language system as inferior to speech, by proving that it is a true human language. Sign language linguists Sandler and Lillo-Martin wrote about bias in sign language research:

No serious approach to the study of sign language can be entirely atheoretical. One might adopt the hypothesis that sign language must be very much like spoken language, as it is the same human brain that is responsible for them both. An opposing hypothesis is that sign language is likely to be very different structurally from spoken language because of the different modality, despite the identity of species and function. Any number of variations on those two themes are imaginable. In order to investigate and categorize the system and its components, some kind of tool must be applied, and investigators will choose the tools that best fit their initial theory [...].

(Sandler & Lillo-Martin 2006, p. 4)

The study of sign language, thus, is inevitably multifaceted. This dissertation approaches a number of research questions with neurocognitive methodology. It attempts a universal description of the neurofunctional system underlying

circumscribed linguistic processes. The actual sign language used to stimulate the brain in a controlled manner would be expected to be interchangeable (e.g., German Sign Language DGS instead of FinSL), if it were understood by the participants (e.g., when studying signers of DGS instead of FinSL). But what is not interchangeable is the specific characteristics of the groups of study participants. Even if the most prototypical signer is often described as a congenitally and profoundly deaf person, who had ideally acquired sign language naturally from his or her deaf parents during early childhood, this study was designed for studying hearing signers. Deafness, like any other sensory deprivation, usually entails neuroplastic adaptations in the central nervous system (for a review see Bavelier & Neville 2002). Neural processes related to sign language processing may therefore differ between hearing and deaf signers. Further, factors like the age of hearing loss or the age and manner of sign language acquisition (naturally acquired vs. structurally taught) may also cause neuroplastic changes in the underlying system. This dissertation studies sign processing in a group of natively bilingual CODAs with naturally acquired sign language knowledge, and a group of sign language interpreters with systematically acquired foreign language knowledge in signing. The comparison of this study's results with other groups of signers must always take hearing status, age, and manner of language acquisition into account. Results from studies with deaf signers in particular must be considered with care when transferred to hearing signers. Furthermore, this study aims at a functional description of successive processes on a time scale and possible cross-linguistic interrelations of them, rather than on the precise identification of activated anatomical brain structures. All of this will be mirrored in the emphasis of selected topics in the literature review. After briefly reviewing localization studies, electrophysiological studies form the focus of this dissertation.

2.1.1 Lesion studies

Long before modern neuroscientific technology allowed precise examinations of brain functioning, neurologist and co-founder of the *Brain* journal John Hughlings-Jackson (*1835, †1911) wrote in the journal's first volume in 1878:

no doubt, by disease of some part of the brain, the deaf-mute might lose his neural system of signs which are of some speech value to him.

(Hughlings-Jackson 1878, p. 304)

Since then, a number of lesion studies of deaf ASL signers took up this discussion and predominantly aimed at the determination of which hemisphere of the brain is responsible for processing signed languages: Is signed language processed more "visuo-spatially" (i.e., with a right-hemispheric dominance) or more "linguistically" (i.e., with a left-hemispheric dominance)? Convincing evidence mounted for the assumption that it is the left hemisphere that is dominant for the comprehension and production of signed language (e.g., Bellugi et al. 1989, Hickok et al. 1996, Hickok et al. 2002, Marshall et al. 2004, Poizner et al. 1987; for reviews see Campbell et al. 2008, Corina 1998, Hickok et al. 1998a). As for speech, lesions in circumscribed brain areas of the left hemisphere, but not of the right hemisphere, lead to circumscribed losses of linguistic function in sign language users (*sign language aphasia*). The gross anatomic architecture for both language systems, thus, seems to rely crucially on left-hemispheric perisylvian brain areas, whereas lesions in the right hemisphere of the deaf cause impairment of non-linguistic visuospatial abilities. Some studies of persons with sign language aphasia further revealed functional dissociations between sign language and conventional gestures (Corina et al. 1992, Marshall et al. 2004; for reviews see, e.g., Emmorey 2002, Hickok et al. 1998a, MacSweeney et al. 2008).

2.1.2 Brain imaging studies

Around the turn of the millennium, neurocognitive research methodology advanced significantly, and respective research facilities were increasing in numbers. This enabled sign language researchers to proceed from behavioral observations as an outcome of brain damage to the observation of stimulus processing in the undamaged brain. These studies aim at the mapping of stimulus-related processes to specific brain structures with different methods such as functional imaging magnetic resonance (fMRI), positron emission tomography (PET), functional near-infrared spectroscopy (fNIRS) and others (see Capek & Neville 2015). They clearly support the assumption based on lesion studies that sign language shares a considerable number of brain structures for production and perception with speech (for recent reviews see Campbell et al. 2008, Corina et al. 2013, Emmorey & Özyürek 2014, MacSweeney et al. 2008). In spite of convincing data on the overlapping left-hemispheric competency for spoken and signed language, the role and importance of repeatedly reported right-hemispheric contribution to sign language processing in deaf signers in particular remains an unsolved and controversially discussed issue to date (for reviews see Corina et al. 2013, Hickok

et al. 1998b). The discussion extends to new interpretations of the functional roles of the two hemispheres in human language processing in general (e.g., McGettigan & Scott 2012) and to the "linguisticisation" or "grammaticalization" of gesture (see MacSweeney et al. 2008), noting the overlap in function and neural substance between speech, co-speech gesture, and sign (for a review see Emmorey & Özyürek 2014). This somewhat challenges the classical definitions of human communication and language *per se*. The exploration of domain general vs. domain specific properties of speech and sign language – and the extent of overlap with other domains – situates right at the core of these progressive approaches (see Poeppel et al. 2012).

One research line clearly illustrates the extent of this discussion. In 1999, Nishimura and colleagues reported PET case data, suggesting that viewing sign language could activate the supertemporal gyri bilaterally (hosting the auditory cortices) in a congenitally deaf subject (Nishimura et al. 1999). Petitto and colleagues suggested that our species might be hardwired to detect modality-independent aspects of the patterning of language *per se* (in other words: analyzing phonologically structured material, MacSweeney et al. 2004) rather than to process modality-dependent aspects of the language input in the dominant hemisphere (Petitto et al. 2000). This hypothesis on the neuroplasticity of auditory brain areas initiated a series of further investigations striving to determine how far neuroplastic alterations in the auditory cortices reflect linguistic or more basic, non-linguistic, processing strategies. Finney and colleagues (Finney et al. 2001) reported activation of the right auditory cortex (confirmed by MEG data by Finney et al. 2003), including the primary auditory cortex, to non-linguistic visual stimulation (a moving dot pattern) in early-deafened subjects. Intending to explore whether the activation of auditory brain areas to visual stimuli is attributable to sensory deprivation or to the exposure to sign language, the group extended their research to bimodal bilinguals (Fine et al. 2005). The authors described no differences in the size or responsiveness of early visual areas to the non-linguistic peripheral visual motion stimulus between deaf signers, bimodal bilinguals, and hearing non-signers. The largest effect of auditory deprivation was found in the (right-hemispheric) auditory cortex. Visual responses in the auditory cortex were absent in the bimodal bilinguals. MacSweeney and colleagues (2004) attempted to dissociate the brain reflections of visual linguistic (sign language) versus non-linguistic (a manual-brachial gesture code) communication in deaf native signers, hearing native signers, and hearing non-signers. Due to a (right-hemispheric) activation enhancement in the superior temporal cortex – which is traditionally associated with auditory

processing – to both types of stimuli in deaf subjects only, the authors suggested that auditory deprivation rather than the knowledge of sign language causes right-hemispheric brain areas to take over a certain degree of visual processing functions. The knowledge of sign language seemed to determine the activation of left-hemispheric classical language areas to linguistic stimulation. A recent study of sign processing in congenitally deaf signers by Leonard and colleagues (Leonard et al. 2012) challenged the assumption that auditory brain areas can generally restructure for the processing of visual stimulation in the auditory deprived. They combined structural MRI scans with functional data acquired using the MEG (magnetoencephalography) method. This approach allows a precise localization of stimulus-related activation with a high time resolution. When judging picture-sign pairs for congruity, deaf native signers did not show activity in the auditory cortex at around 100 ms. Later processing stages of this group (300-350 ms) highly overlapped with hearing subjects processing speech. The authors concluded:

that visual afferents are not directed to auditory cortex for initial sensory processing to a greater extent in deafness.

(Leonard et al. 2012, p. 9703)

However, the activation overlap was due to semantic encoding regardless of input modality.

2.1.3 Electrophysiological studies

While brain imaging studies allow us to localize brain activation to stimulation (such as sign language) with a high spatial resolution, the determination of sub-processes and their timely progression are not straightforwardly accessible due to the hemodynamic nature of the measured signal (e.g., Capek & Neville 2015). Unlike imaging studies, the measurement of *event-related brain potentials* (ERPs) provides neurocognitive measures which allow task-related processes to be followed on a millisecond time scale as they unfold. The ERP method is thus an apt approach to depicting multileveled cognitive processes such as language processing from a functional perspective (e.g., Swaab et al. 2012).

Studies reporting ERP correlates of sign language processing are relatively scarce. In a seminal publication, Kutas and colleagues (1987) compared ERP responses to the processing of semantic anomalies when the stimulation was written (English) or spoken (English) in native English speakers with those

occurring in signed stimulation (*American Sign Language*, ASL) in congenitally deaf persons. Even though the shape of the evoked brain responses to congruous and incongruous sentence endings differed between the three groups and conditions, the difference waves revealed remarkable similarities. By subtracting the brain responses to congruous lexemes from those to incongruous lexemes, their difference mirrored the figurative display of the N400 response (for reviews see Federmeier & Laszlo 2009, Kutas & Federmeier 2011) and was assumed to reflect the extra process involved in dealing with semantically unexpected presentations. The authors concluded that this cognitive process may be independent of the surface structure and sensory modality of presentation. This assumption associates strikingly with the hypothesis of a common mental lexicon for speech and sign language as evident on the basis of brain imaging studies (e.g., Klann et al. 2002, MacSweeney et al. 2006).

Since the ERP study by Kutas and colleagues (1987), few attempts have been undertaken to broaden our understanding of the electrophysiological basis of sign language perception, while a few more focused on the effects of auditory deprivation on non-linguistic visual processing (e.g., Armstrong et al. 2002, Bottari et al. 2014, Hauthal et al. 2015, Neville et al. 1983, Neville & Lawson 1987a, Neville & Lawson 1987b) and on speech reading in signers (Skotara et al. 2011, Skotara et al. 2012), while others studied sign production (Baus & Costa 2015).

Aiming at a detailed examination of linguistic – i.e., semantic and syntactic – processing subsystems, Neville and colleagues (1992) compared ERP responses initially to reading English sentences in normally hearing and congenitally deaf adults. The words forming the sentences were assigned to two linguistic groups: *Open-class words* (e.g., nouns, verbs, and adjectives), assumed to provide mainly semantic information, and *closed-class words* (e.g., conjunctions, auxiliaries, and articles), which carry much of the syntactic structure in a sentence. For the open-class words, the authors stated that they did not find any group differences in occipital areas. Anterior N100 appeared earlier in the deaf than in the hearing subjects, and brain responses tended to be more positive in the deaf than in the hearing subjects after around 250 ms. Likewise, occipital ERPs to closed-class words were similar in morphology and timing and differed only in their degree of hemispheric asymmetry between the groups (asymmetrical in the hearing and symmetrical in the deaf subjects). However, the N280 component found to closed-class words in the hearing was absent in the deaf subjects. Furthermore, a separately calculated N400-effect in response to semantic anomalies was reported for hearing and deaf participants. These responses differed only in terms of peak latency being

slightly later in the deaf participants. The authors concluded in favor of fairly robust aspects of semantic processing, despite divergent early language experience between the groups (auditory or visual mother tongue), whereas processes central to grammatical processing were interpreted to be highly vulnerable to early language experience. This implies that speech and sign language can be assumed to share a considerable set of semantically related processing features, while syntactic structures might differ remarkably. Neville (1991b, 1991a) transmitted the 1992 study to examine sign language processing. The English sentences were translated into ASL and the individual signs were classified as open- and closed-class. In contrast to the absent N280 response to written English closed-class words in the deaf group, signed closed-class items did elicit a negative potential in them. Further, signed semantic anomalies did elicit the N400 response over parietal regions bilaterally, which was similar to responses to written English in non-signers. ERP responses of a CODA group and a group of late learned sign language interpreters were examined in addition to the groups of hearing non-signers and congenitally deaf in a hemifield sign processing task on all words of the sentences. The ASL items were projected either to the left (LVF) or right (RVF) visual field, i.e., to the right or the left hemisphere respectively. In summary, deaf signers and CODAs showed a left-hemispheric specialization for ASL. The pattern of results was similar to non-signing controls reading English, but it was not observed for ASL processing in them or in the group of interpreters. The authors concluded that the left-hemispheric specialization for sign language only occurs when the signs are acquired with grammatical competence within a time-limited maturational window (by the age of about 10 years).

Following this line of investigation, Neville and colleagues (1997) expanded the study of sign processing by ERPs in deaf native signers, hearing native signers (CODAs), hearing late learned signers (interpreters), and hearing non-signers. In summary, the ERP pattern of open- and closed-class signs was fairly equally characterized in all four groups. Among others, but probably most strikingly, the signs did not evoke a posterior N280 but an N250 response to both sign classes, with several differences from the N280 in the group of hearing persons. The authors concluded that N250 and N280 might be functionally distinct, and the characteristics of the N250 component were the only ones found to distinguish hearing late-learners from hearing native signers in the open- and closed-class comparison. Neither N250 nor any earlier component reflected any effects of sign class in the hearing non-signers. The overall activation patterns of the deaf subjects resembled those of the hearing subjects reading English words, and group

differences between the deaf subjects and the CODAs seemed to be independent of sign class and were therefore interpreted as dependent on hearing status. The N400 evoked by semantically anomalous signs in the sentential context was present in all signing groups, but not in the hearing non-signers. Only the deafs' N250 showed a significant increase in amplitude to semantically anomalous sentence endings. In summary, even though the overall morphology of the ERPs elicited by signs differed from those reported in written or spoken English, a detailed analysis of qualitative aspects between groups and conditions suggested a large degree of similarity between native users of a language, independent of the presented modality, especially in terms of brain topography. Both hearing status and age of language acquisition (AoA) influenced different processing aspects. To the best of my knowledge, the above reviewed studies by Helen Neville and colleagues are the only studies to date that provide a sound comparison of ERP responses to signed language in hearing non-signers, hearing native signers and hearing late learned signers.

After a decade of research focusing on the localization of brain activation, a number of recent sign language studies resumed the task of describing the neurocognitive basis of sign processing with the more functionally-timely oriented ERP method. Uncoupling from the circumstantial series of studies by Neville and colleagues, most of the newer studies addressed sign processing exclusively in deaf individuals. Capek and colleagues (2009) examined brain processes associated with semantic and syntactic incongruities in a deaf group watching ASL sentences. Just as expected on the basis of previous language studies, they found N400 over central and posterior sites in response to the semantic violations and an anterior negativity (ELAN), followed by a widely distributed P600 in response to the syntactic violations.

In 2012, three studies further probed the time-course of lexical access in sign language. Grosvald and colleagues (2012) studied the processing of linguistic and non-linguistic manual actions (ASL signs and grooming gestures) in deaf signers passively watching sentences. Results from time-windows after 400 ms revealed N400-like responses to signed and pseudo-signed sentence endings, while the non-linguistic gestures elicited a large positivity. The N400-effect on phonologically legal pseudo-sign sentence endings was somewhat larger than those on semantically incongruent signs. No significant effects related to semantic status were found prior to 400 ms. In a similar experiment, Gutierrez and colleagues (2012b) varied ASL sentence endings for semantic expectancy and phonological form (with a special interest in the location parameter, i.e., place-of-articulation).

Deaf signers watched the signs for comprehension. Besides N400-effects, the authors found, unlike Grosvald and colleagues (2012), an early activation (150-250 ms time range) related to semantic properties of the signs, which they suggested were similar to what has been described for written speech. In sum, the authors reported indications for an early stage of lexical selection (around 350 ms) and a later stage of semantic integration (around 450 ms). Difficulties in semantic integration were proposed to be reflected in late N400 effects (450-600 ms window). Finally, Gutierrez and colleagues (2012a) studied phonological priming in deaf native and non-native signers in a delayed lexical decision task on Spanish Sign Language (LSE) sign pairs. Their data showed that the location parameter led to modulations of N400 (300-500 ms window), while handshape modulated a negative-going wave in the 600-800 ms window. The effects connected to phonological overlap were stronger in the native signers than in the group of non-native signers, which was suggested to mirror less efficient form-based processing of the latter group.

These differences [SZ: behaviorally supported by Carreiras et al. 2008, Corina & Hildebrandt 2002, Dye & Shih 2006, Emmorey et al. 1995, Mayberry & Eichen 1991, Newman et al. 2002, Newport 1990] seem to suggest that although decodification of phonological forms in late signers is accurate, it requires more effort and is less automatic.

(Gutierrez et al. 2012a, p. 1344).

The closer determination in how far processing differences between native and late signers are quantitative or qualitative was left open for further investigation.

Hosemann and colleagues (2013) tested the prediction of upcoming linguistic input in deaf signers judging German Sign Language (DGS) sentences for correctness. The authors analyzed ERPs time-locked to trigger points connected to different parameters of the transition phase between two signs in a sentence (handshape change, target change, and sign onset). Semantically unexpected signs evoked a biphasic N400-late positivity pattern. N400 effects (expected vs. unexpected signs) were reported to be time-locked to (co-articulatory) events prior to sign onset and interpreted to support forward models of language comprehension (see Hosemann et al. 2013). Martin and colleagues (2013) reported N400 data of unimodal bilingual readers indicating different lexical prediction mechanisms between L1 and L2 readers. The inclusion of cross-modal bilingualism into these examinations remains a task for future studies.

In 2014, Hänel-Faulhaber and colleagues (Hänel-Faulhaber et al. 2014) reported ERP correlates of semantically and morphosyntactically incorrect DGS sentences in deaf signers. In accordance with earlier studies, the authors reported an N400-effect elicited by signed semantic violations. Morphosyntactic violations elicited a left anterior negativity (LAN) response and a syntactic positive shift (SPS, or P600).

In sum, electrophysiological studies of sign language processing find ERP correlates of linguistic aspects, which are very similar (though not entirely identical) to what is known from the study of oral and written language. This supports the suggestion that spoken and signed human languages are functionally similarly organized, despite their different surface structure.

2.2 Semantic priming

In this project, *semantic priming* was used as a tool to measure organization and processing mechanisms in the conjunction of the hearing bilinguals' two mental lexica. The term refers to the improved speed or accuracy of response to a stimulus (*target*) following a preceding stimulus (*prime*) when the pair of stimuli are semantically related compared with when they are unrelated (Meyer & Schvaneveldt 1971; see also McNamara 2005). Semantic priming is assumed to relate to the principle of *spreading activation* (Collins & Loftus 1975). Semantic content is organized in neural networks, in which internal representations of concepts are linked to each other. An activated representation – e.g., the prime in the study design used here – spreads a certain level of activation to its proximal neighbors and more distal neighbors (e.g., to the targets), which is decreasing with increasing distance from the prime. The patterns of behavioral responses to the different targets give initial insight if priming is possible between speech and signing, which would suggest that the mental lexica were cross-linguistically interconnected in bimodal bilinguals. Current models of the bilingual mental lexicon in general suggest the existence of two distinct but strongly interconnected mental lexica for separate languages (Kroll & Stewart 1994; cf. Brysbaert & Duyck 2010, Kroll et al. 2010). It is mostly assumed that phonological and morphosyntactic forms differ across languages whereas concepts (i.e., non-linguistic world knowledge) and meanings (i.e., the specific semantic content connected to a specific lexical unit) are shared (see Pavlenko 2009). Both languages are simultaneously active, while the continuous phonemic input stream is mapped onto both lexica (e.g., according to principles formulated in the Cohort Model by

Marslen-Wilson (1987)) until an unambiguous lexical decision can be made (see Marian 2009).

The co-activation of (visual) speech and signed language has also been demonstrated in deaf (Morford et al. 2011, Ormel et al. 2012) and hearing (Emmorey et al. 2008, Shook & Marian 2012) bimodal bilinguals.

The phonological and lexical systems of languages that do not share modality appear to be activated in parallel, even when featural information from one of the two languages is largely absent from the input.

(Shook & Marian 2012, p. 320)

2.3 Sign language acquisition

The study of sign language acquisition – often searching for supramodal learning processes underlying language acquisition in general – must consider factors that are as heterogeneous as is the group of sign users and its surrounding during acquisition (see Lieberman & Mayberry 2015). Because no circumstantial model of sign language processing exists to date, the study of sign acquisition is largely aligned with speech acquisition studies.

2.3.1 Deaf children

To attract and hold deaf babies' attention in a communicational situation, adults signing to infants use modifications in their expressions (infant-directed signing, or "motherese"). These include slower and larger movements and more repetitions than expressions in adult-directed signing (Masataka 1996).

Infant babbling is the maturational departure point for speech production. In 1991, Petitto and Marentette published their finding of a manual form of babbling in deaf infants acquiring sign language from birth:

The similarities between manual and vocal babbling suggest that babbling is a product of an amodal, brain-based language capacity under maturational control, in which phonetic and syllabic units are produced by the infant as a first step toward building a mature linguistic system.

(Petitto & Marentette 1991, p. 1493)

Around the age of 10 months, manual babbling then gives way to the emergence of the first words, which are often claimed to appear earlier in sign acquisition than in speech acquisition (e.g., Lillo-Martin 2008). But this difference, if any, does not persist for long as many other milestones concerning the acquisition of grammatical structures (for an overview see Baker et al. 2008, Mayberry & Squires 2006) are achieved at a comparable maturational course to speech.

Like children acquiring spoken languages, children acquiring sign languages are highly analytic and acquire grammatical structure one piece at a time through communicative interactions with the people who care for them.

(Mayberry & Squires 2006, p. 295)

Certain visuospatial aspects of sign language are challenging for the acquiring child, and there may be other modality-dependent factors influencing language acquisition (see Lillo-Martin 2008), but in general it seems that language modality is no major imperative for how children acquire language (also see Emmorey 2002, chapter 5).

2.3.2 Hearing children as L1 learners of sign language

One question dominating the study of bilingualism in general is the degree of storage and processing overlap between the two involved languages. Truly bilingual persons perform as well in one language as in the other, but it must be kept in mind that:

[t]he bilingual is not the sum of two complete or incomplete monolinguals; rather, he or she has a unique and specific linguistic configuration.

(Grosjean 2008, p. 13)

Even though some circumscribed inefficiencies or developmental delays have been reported, bimodal bilingual children's spoken language performance is considered normal, i.e., rarely affected by the parents' deafness, if they received normal language input early on (see Schiff-Myers 1993). Concluding her review of bimodal bilingual language acquisition studies, Schiff-Myers suggested that those *kids of deaf adults* who realize early in development that that they are learning two languages may be those learning standard speech without any problems. Indications further suggest that the attitude of the children's input providers plays

a decisive role in their language selection (Kanto et al. 2013, Lillo-Martin et al. 2014, Van den Bogaerde et al. 2009).

Comparing unimodal and bimodal bilingual language development, studies suggest that bilingual children accomplish all early language milestones in each language with equal timing (Holowka et al. 2002, Petitto et al. 2001, Petitto & Kovelman 2003). Further, this time course seems no different from monolingual language acquisition. This similarity in development, together with the ability for lexical differentiation from the earliest age, is interpreted to indicate the development of a differentiated language system, for which the children are well set (Petitto & Kovelman 2003). The statement that the human brain is prepared to learn more than one language from the earliest ages, and that bilingualism as such is no detriment to the bilingual's development, stands in remarkable contrast to the opinion that bilingual babies initially develop a unitary language system and consequently struggle with confusion until both languages are separated with the aid of meaning and grammar (see Petitto & Holowka 2002 for a more detailed discussion). Furthermore, these contrastive studies of uni- and bimodal bilingual children demonstrate that sign language does not seem to load specific demands on the linguistic capacity of a developing child, but blends in naturally with spoken forms of language.

However, the nature of conjunction between a bilingual's two languages, unimodal or bimodal, still remains to be explored to its full extent. The bilingual's two languages are not entirely separable but interfere on numerous levels. Code-switching is the most prominent form of bilingual language mixing. A code-switch is the rule-governed change from one language to another for a word, phrase, or sentence (e.g., Grosjean 2008, Poplack 1980, Poplack 2002). Code-switching has been assumed to be a universal phenomenon amongst bilinguals. However, a number of studies on bimodal bilingual patterns of language mixing reported that bimodal bilinguals rarely code-switch. Instead, they intermix both their languages simultaneously (*code-blending*; e.g., Baker & Van den Bogaerde 2008, Bishop 2010, Casey & Emmorey 2009, Emmorey et al. 2008, Pyers & Emmorey 2008, Van den Bogaerde & Baker 2005). This prominent difference between unimodal and bimodal bilingualism is explained by the involvement of distinct articulators. It is physically impossible to utter two spoken languages at the same time, whereas simultaneous signing and speaking is feasible (see Emmorey et al. (2008) for a model proposal of code-blend production in bimodal bilinguals).

In a neuroimaging study, Neville and colleagues (1998) observed that hearing native signers processed both speech and sign language within left-hemispheric,

classical language areas of the brain. The authors summarized that the CODA group's activation patterns were similar but not identical to those of hearing non-signers reading speech or to a deaf group viewing ASL. Additionally, both the Neville et al. (1998) study (fMRI) and an earlier study by Neville and colleagues (1997) (ERPs) pointed to

extensive right hemisphere activation in early learners of ASL and support[] the proposal that activation within parietooccipital and anterior frontal areas of the right hemisphere may be specifically linked to the linguistic use of space.

(Neville et al. 1998, p. 927)

The cortical activation patterns underlying the expression of spatial relationships in English (prepositions) and ASL (locative classifier constructions) in bimodal bilinguals were then studied by Emmorey and colleagues (2005; see Damasio et al. 2001 for the same task conditions in monolingual English speakers and Emmorey et al. 2002 for deaf ASL signers). The CODAs displayed bilateral parietal cortex activation regardless of the language's modality, however, with ASL engaging the right-hemispheric parietal cortex more strongly than English. The authors concluded that this activation pattern might be associated with the knowledge of sign language and result from the subject's lifelong experience with a spatial language, which requires a visual-motoric transformation.

Brain activation related to processing pictures of grammatical (linguistic) and emotional (non-linguistic) facial expressions in bimodal bilinguals (Emmorey & McCullough 2009) were studied in contrast to deaf signers (McCullough et al. 2005) and revealed (along with MacSweeney et al. 2002) that:

bimodal bilinguals (hearing signers) recruit more posterior regions within left superior temporal cortex than deaf signers when comprehending sign language.

(Emmorey & McCullough 2009, p. 131)

The authors further concluded that neural activation patterns of language processing in bimodal bilinguals appear to be unique, and that, therefore:

hearing signers should not be viewed simply as a language control group for deaf signers.

(Emmorey & McCullough 2009, p. 131)

Rudner and colleagues (2007) examined the neural representation of cross-modal binding of speech and sign language into unitary representations in bimodal bilinguals as linked to the *episodic buffer*. The episodic buffer is a component of a model of working memory (Baddeley 1986, Baddeley & Hitch 1974), which is responsible for the formation and maintenance of bound information (Baddeley 2000, Repovš & Baddeley 2006) and is represented in a range of anterior and posterior regions (Rudner et al. 2007). The authors presented evidence for separate sign and speech loops in bilinguals in a previous study (Rönnberg et al. 2004) and focused on binding mechanisms in their 2007 study in a 2-back task across speech and signing. Cross-linguistic binding led to slower and less accurate behavioral responses compared to "speech only" and "sign only" conditions, which suggested that the cognitive load was enhanced during this condition. Executive function, though, could not be tied to binding processes. The episodic buffer for speech-sign binding was shown to include a posterior network.

[...] we suggest that the right middle temporal activation found in the present study relates to binding in the episodic buffer of phonological representations in the speech and sign loops of working memory to semantic memory representations in long-term memory.

(Rudner et al. 2007, p. 2272)

Growing up bimodal bilingual, thus, entails very specific neuroplastic adaptations in the developing brain, which are still measureable during adulthood.

2.3.3 Hearing adults as L2 learners of sign language

Even though ASL has become a commonly taught language in North America (Woll 2012) and most other Western countries, very little is known about the acquisition mechanisms and the cognitive foundation of L2 signers to date. The most common form of L2 sign acquisition is found in hearing adults with a spoken language as L1, who may learn sign languages for professional reasons (e.g., teachers, interpreters, therapists, researchers; Mayberry 2006, Woll 2012).

Woll (2012) reviews that, in contrast to infants acquiring sign language as L1, iconicity plays an important role in adult beginning learners of sign language as L2. She interprets this difference to stem from previous experience with interpreting gestural representations, which facilitates recall and learnability of iconic signs.

Numerous cases of linguistic transfer from previous knowledge to the newly acquiring L2 were reviewed and deemed to be an important topic in the study of L2 acquisition.

Adult L2 learners of sign language who experienced a spoken language in early life were shown to outperform deaf L1 sign language learners with no language experience in early life in ASL performance (Mayberry et al. 2002). Hearing late learned signers' brains, however, were reported to not show right hemispheric angular gyrus activation (inferior parietal region) during ASL processing, which was found in hearing native signers (Newman et al. 2002). The time window for the recruitment of this region seemed to have closed before they started to learn sign language, and late learned signers

seemed to rely most heavily on the network of LH [SZ: left-hemispheric] regions already established for the processing of English.

(Newman et al. 2002, p. 78)

Leonard and colleagues (2013) conducted a combined MEG/MRI study with beginning adult L2 signers, who had to judge picture-sign/written word pairs for congruency. The data showed modality-specific word encoding processes at early processing stages (~100 ms for spoken words and ~150 ms for written words and ASL). After about 200 ms, spoken, written and signed words were processed in very similar left-lateralized networks supporting lexico-semantic encoding. This finding was interpreted in the way that a small amount of sign instruction is required to elicit automatic lexico-semantic processing in beginning L2 signers.

For a review of the only electrophysiological study conducted in hearing L2 signers to date (Neville et al. 1997), see chapter 2.1.3 of this thesis.

In sum, the literature suggests that late learned hearing signers use specific mechanisms to acquire sign language, amongst other things by employing previous linguistic knowledge. They can reach high levels of performance, but their processing mechanisms may differ in some respects from those of native signers.

3 Aims of the study

The purpose of this study was to explore the principles of language representation and processing in hearing sign language users of different ages and with different manners of language acquisition. The multimodal convergence of speech and sign language was examined using behavioral and cognitive neuroscientific measures in native bilingual CODAs and late learned but highly proficient sign language interpreters. It was the study's specific aim to investigate whether signed and spoken language semantic systems are interwoven and can interfere with each other in these groups. Cortical responses (ERPs) to cross-linguistically primed signs in adult hearing sign language users were explored (specifically, N400 and late positive complex in Study II and N170 in Study III) and the electrophysiological measures were tied to behavioral lexical decisions in the targets (Study I). A group of non-signing adults served as controls. Research question 2 introduces the overall outcome of target-locked ERP responses as uncovered by the PCA method. Research question 3 focuses on sign processing abilities in the control group, and in research question 4 the overall results concerning the native and late learned signers are contrastively discussed.

The specific aims (research questions, RQs) were as follows:

- [RQ1]: to explore whether the mental lexica of hearing signers converge to the degree that preceding spoken input can influence lexical decisions on signed lexemes (Study I)

- [RQ2]: to evaluate electrophysiological correlates of sign language processing in the multimodal context (Studies II and III)

- [RQ3]: to characterize neurocognitive features of the processing of cross-linguistically primed signs in hearing non-signers (Studies II and III)

- [RQ4]: to differentially characterize neurocognitive features of the processing of cross-linguistically primed signs in early and late learned hearing signers (Studies II and III)

4 Materials and methods

4.1 Participants

The hearing adult volunteers were recruited by word-of-mouth advertising and gave written informed consent for their participation. They were offered a small representation allowance for participating in a single examination session at Oulu University Hospital, Finland. In accordance with the university's regulations at the time of data acquisition, ethics approval was not required for the study of healthy volunteers.

A total of 17 non-signing individuals (hereafter *controls*), 16 natively bilingual signers (hereafter *CODAs*), and 15 sign language interpreters with late learned knowledge in signing (hereafter *interpreters*) participated in this study. Normal hearing was assured by audiogram screening before the actual test session. Due to enhanced hearing thresholds and technical or other artifacts, data from five participants were excluded and only the responses from 15 controls (5 males; average age 42, $SD = 10.08$), 15 CODAs (5 males; average age 45, $SD = 12.91$), and 13 interpreters (1 male; average age 31, $SD = 7.31$) entered the final analyses ($N = 43$). All participants were native speakers of Finnish, had normal or corrected-to-normal vision and no diagnosed neurological diseases. They had not taken any interfering medication prior to the examination.

The CODAs had acquired sign language during early childhood and were bilingual in FinSL and Finnish. The interpreters were systematically educated in FinSL starting at a mean age of 22 years ($SD = 6.04$), on average 10 years ($SD = 4.52$) before the examination and were therefore to be considered second language learners of FinSL. Only one interpreter communicated with Deaf friends by signing at the age of 15. The interpreters had completed a vocational sign language interpreting program in Finland and worked in their profession or otherwise signed on a nearly daily basis. Thus, both the signing groups knew sign language at a very elaborate or fluent level. The CODAs were selected for participation in the study based on their bimodal bilingualism. None of the interpreters were CODAs, and only two of the CODAs were educated as sign language interpreters. It should be noted that Finnish and Swedish are official national languages in Finland, and Finns are generally very acquainted with a number of foreign languages, such as English. For this reason the controls were not to be considered strictly monoglots.

The CODAs and the interpreters completed a language assessment questionnaire. On a self-rating language dominance scale between 0 (= spoken Finnish) and 10 (= FinSL), the CODAs ranked a mean of 3.80 ($SD = 2.10$) and the interpreters ranked significantly more towards speech at a mean of 1.18 ($SD = 1.06$). Independent sample t-tests based on questions asked in the questionnaire (see Appendix 1) further showed that the CODAs signed privately more often than the interpreters ($p < .05$) and the interpreters signed more often in official contexts than the CODAs ($p < .05$). The interpreters reported to use less sign language in communication with other hearing sign language users than the CODAs ($p < .01$). The language generally used to communicate with friends, the preference for either one of the two languages, the importance of the hand in communication, and the amount of deliberate and unintended code-switches in communication did not differ between the two groups ($ps > .05$).

4.2 Material

The task demanded an active semantic judgment on lexeme pairs of varying semantic relationships from the participants. The paired lexemes were presented one after another. The first of the two lexemes was always presented in the auditory modality. The second lexeme was either another auditory word (*context-coherent*) or its translate in visual FinSL (*context-incoherent*). The participants' electroencephalogram (EEG) and behavioral decisions were digitally registered. It was the experiment's goal to uncover the basis of semantic integration. The degree of semantic relationship between the lexeme pairs therefore ranged from very closely related to unrelated. A close semantic relationship was assured by choosing antonymic word pairs. Antonymic word pairs were selected because the basis of antonymic relations is common knowledge-intensive. The first lexemes acted as priming words (primes) for the second lexemes (targets) in the sense of *semantic priming* (for a more detailed discussion of the concept see section 2.2 of this thesis). Because accurate contextualization is essential for antonyms to be perceived as such, the participants were asked for their explicit semantic decisions: "was the second lexeme the opposite [antonym] of the first one?"

4.2.1 Experimental design

Paired lexemes of different semantic relationships were gathered for the task (see Appendix 2). All of these lexemes were common nouns, which mostly belonged to

everyday language (e.g., *aamu/morning* – *ilta/evening*). Some of the nouns also represented more abstract concepts (e.g., *hyväksyminen/approval* – *hylkääminen/rejection*). The pairs' relationships were threefold: First, antonyms (e.g., *kaupunki/city* – *maaseutu/countryside*) represented pairs of strong semantic relations (*Antonymy*). Second, the antonymic target was substituted by an associative partner (e.g., *metsä/forest* replacing *maaseutu/countryside*), which resulted in a weaker semantic relation within the pair (via the antonymic target, *Indirectness*). Third, unrelated pairs (e.g., *kaupunki/city* - *vauva/baby*) shared no systematic semantic relation (*Unrelatedness*). Taken the within- and cross-linguistic variants of each trial into account, this resulted in a total of six experimental conditions:

1. context-coherent Antonymy
2. context-coherent Indirectness
3. context-coherent Unrelatedness
4. context-incoherent Antonymy
5. context-incoherent Indirectness
6. context-incoherent Unrelatedness

Within this design, Antonymy and semantic Unrelatedness stood for clearly opposing decisions ("yes" and "no"), whereas the correct rejection ("no") of the Indirectness condition may have been more ambiguous to achieve. Targets of the Indirectness condition were incorporated in the calculation of the behavioral decision sensitivity index (Study I), and in the data matrix for the calculation of the temporal component structure (Studies II and III). But it is reasonable to assume that antonymic and unrelated targets produce the clearest interpretable semantically primed effects with regard to the research questions of this thesis. The results related to them are therefore the focus of discussion here.

4.2.2 Stimuli

The paired lexemes consisted of gradable, complementary, and reciprocal antonymic pairs (see, e.g., Jones 2002) of concrete (~54%) and abstract (~46%) nouns, which were equally divided between antonymic and indirectly related/unrelated targets (two-tailed t-test: $p > .17$). Because these linguistic sub-categories were irrelevant for the task, they were not separately analyzed. Comparing the lexical frequency of the antonymic targets and the indirectly

related/unrelated targets (Parole corpus), an independent samples t-test showed that the two groups of targets did not differ from each other ($p > .671$).

A total of 144 Finnish words (mean length 864 ms, $SD = 175.95$) were spoken by a female native Finnish speaker in a sound-shielded recording studio and digitally recorded. The 98 FinSL translates of the antonymic and indirectly related/unrelated targets (mean length 2,824 ms, $SD = 526.20$) were signed by a female, native Finnish, sign language interpreter standing in front of a dark blue background, and were digitally videotaped in one uninterrupted session. Independent-sample t-tests showed no significant length difference between auditory antonymic (874 ms, $SD=159.52$) and indirectly related/unrelated (834 ms, $SD=175.59$) and no length difference between visual antonymic (2806 ms, $SD=498.66$) and indirectly related/unrelated (2791 ms, $SD=566.22$) targets. Thus, all physical parameters as well as the signer's position were reliably stable between the individual signs. The signer started and ended each sign in a resting position (Figure 1), and a still image of that posture was used to create a smooth changeover between the individual signs. On- and offset of the individual signs were the picture frame, in which the signer's hands began to move from the resting position and in which they returned to motionlessness respectively. In linguistic theory, the onset of a sign is controversial. Because sign language is very much simultaneously organized with many linguistic parameters executing at the same time, the timing of the onset of a sign, particularly those in sentential contexts, is a challenge. The Move-Hold-Model by Liddell and Johnson (1989) established the assumption that two signs are intersected by a semantically empty transition phase, the fluent changeover of phonological parameters between the offset of the preceding sign to the onset of the succeeding sign. The onset of a sign is, therefore, often defined as the moment when the handshape is completed and the hand is in hold in its correct first location. The signed stimuli in this project, however, stood alone and not in a sentential context. The transition phase, here the period from when the signer's hands began to move from the resting position until reaching the linguistically defined stimulus onset, was not subjected to co-articulation. There is no doubt that all phonological parameters succeeding the neutral hold position belonged to the forthcoming signed lexeme. Following the same principle for both the signed and the spoken lexemes, attempts were made to keep the stimuli as natural as possible. The transition phase was therefore included in the stimulus material. Piloting data analyses at the case and small group level clearly revealed all the expected ERP responses and bore no indication of the time-point for triggering being misplaced.

To further ensure that processing differences between conditions were truly task-related, some lexemes were presented more than once. Samples from the set of indirectly related items were also presented as unrelated targets of word pairs within the same block, and 19 lexemes were repeated in different conditions (e.g., *night* as associative partner for the target of the pair *brightness-darkness* and as prime for *day*). On two occasions, two different signs were used for one spoken lexeme, which was presented in two different trials. Independent sample t-tests indicated that the mean length of neither the auditory nor the visual antonymic or indirectly related targets differed from each other. The complete list of stimuli is displayed in Appendix 2.



Fig. 1. The still image of the signer visible throughout the experiment.

4.3 Procedure

The volunteering participants were invited to the examination session at Oulu University Hospital, where two to three examiners welcomed them individually. They were informed about the general procedure and techniques used during the experiment and gave written consent for participation. The hearing level at the moment of the testing was examined by audiogram screening. Participants from the two signing groups completed a questionnaire about their language acquisition and use of sign language. The examiners gave detailed verbal explanations of the task with the aid of a visual computer demonstration while an electrode cap was mounted at the participants' heads. The test session started when the participants had a clear understanding of their assignment and the technical setup was completed.

One test session consisted of three blocks of stimuli. Each block contained stimulus pairs of all six conditions but only one kind of antonymic relationship (gradable, complementary, reciprocal). Each of the six experimental conditions was presented 55 times in total (19, 18 and 18 trials per block, respectively). The conditions' order was randomized but identical for all participants. The three blocks were presented in a pseudorandom manner to the different participants. Short breaks were held between the individual blocks.

The participants were instructed to always look at the screen, where an image of the signers' resting position or the dynamic signs was constantly visible. This procedure was intended to keep both the signers' language channels activated and to thereby facilitate the processing of the actual semantic content of the randomly intermixed auditory and visual targets. Participants of all three groups had the same task: To determine or guess whether the lexemes of each presented pair were "opposites of each other" (antonymic) or not. They were told to indicate their responses ("yes, opposite" or "no, not opposite") by pressing buttons on a computer mouse, but only after an acoustic signal. The participants were not informed about the Indirectness condition. A new trial cycle did not begin until a response was registered.

The interstimulus interval (ISI) between prime and target was 400 ms, the ISI between the target and the go-signal (500 Hz sine tone lasting 200 ms) was 700 ms, and the intertrial interval (ITI) between the behavioral response and the presentation of the new trial cycle's prime was 1,500 ms. Due to flexible ITIs, the length of the actual experiment somewhat varied. The entire examination session typically lasted about two to three hours.

4.3.1 EEG data acquisition

An electrically shielded room was prepared for EEG data acquisition. The participants were fitted with an electrode cap (EasyCap, Falk Minow Services) with equidistant electrode positions and insert earphones. They were seated on a bench with a computer mouse in the hand of their choice. Stimulus presentation was performed by an unpublished and noncommercial software (ErpStim by K. Suominen). The auditory stimuli were presented at 74 dB SPL. The visual stimuli were projected onto a screen on the wall at a distance of ~270 cm from where the participants were sitting (picture frame: 86 cm height x 93.5 cm width; \approx vertical visual angle: 18° , horizontal visual angle: 20°). The signer did not, however, take up the entire picture frame (see Fig. 1). The signs were easily perceivable without the systematic need of eye movements.

The EEG was digitally recorded with a Neuroscan SynAmps amplifier and Acquire software (AC recording) at a sampling rate of 1000 Hz, with a data accuracy of $0.168\mu\text{V}$ and an online band-pass filter of 0.05 Hz - 70 Hz. The data was acquired from 30 Ag/AgCl surface electrodes (gray electrodes in Figure 2). Further, AFz served as ground electrode, FCz as online-reference and a bipolar electrooculogram (EOG) was recorded from above the right and below the left eye (white electrodes in Figure 2). The impedances of the electrodes were kept below 5 k Ω . Behavioral decision responses were recorded along with the electrophysiological data.

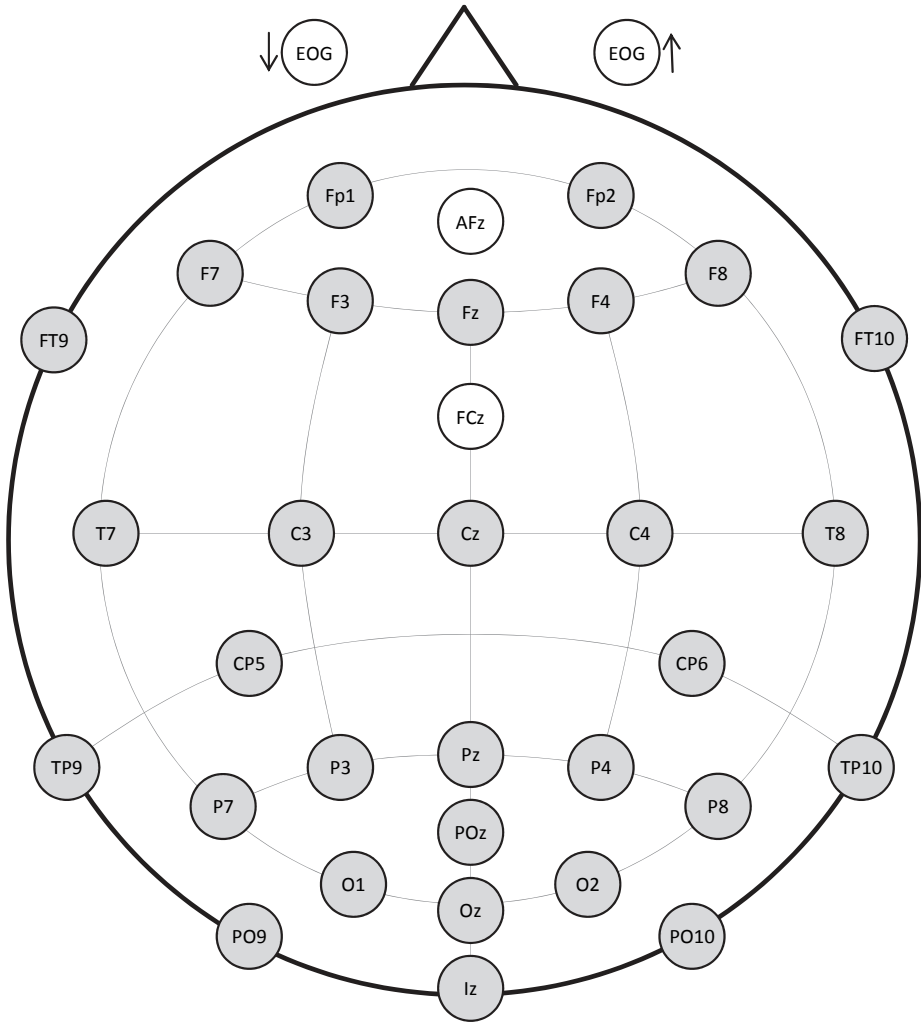


Fig. 2. The experimental electrode setup (FCz online reference, AFz ground).

4.3.2 EEG data post-processing

The acquired EEG data were post-processed online with Brain Vision Analyzer (Brain Products GmbH) software. They were re-referenced to the average reference, and FCz was reused for the analysis of the results. A notch filter (50 Hz, +/- 2.5 Hz at 24 db/oct) and an offline band-pass filter (0.5 Hz – 25 Hz at 12 dB/oct) were

applied. Electroocular artifacts in the segmented EEG epochs (-100 ms to 870 ms in relation to stimulus onset) were corrected (Gratton et al. 1983). Segments exceeding an absolute amplitude of $\pm 150 \mu\text{V}$, a voltage difference of $50 \mu\text{V}$ between two sampling points, or a voltage difference of $200 \mu\text{V}$ within the segment as well as segments not reaching a voltage difference of $0.5 \mu\text{V}$ within 100 ms intervals were not further analyzed. All remaining segments were baseline corrected to -100 ms. The stimulus-locked ERPs were constructed by averaging responses to the prime and each of the targets without considering the accuracy of the related behavioral decision. Low trial numbers after artifact rejection in any one of the four auditory or three visual target conditions led to the participant's exclusion from further analysis of all stimuli from the respective modality. The final electrophysiological data set therefore included 13 controls, 14 CODAs, and 12 interpreters for the auditory conditions, whereas all the 15 controls, 15 CODAs, and 13 interpreters were included in the visual conditions. The remaining datasets yielded a very good return of target segments (on average 54 – 55 out of a maximum of 55 responses per stimulus) to be included into the final analysis.

4.4 Analysis

4.4.1 Behavioral data (Study I)

D-prime transformation

Behavioral decisions ("yes" and "no") to the target lexemes were counted for each of the 43 participants. To diminish the potential bias towards a certain answer, which may not necessarily reflect the actual detection of the signal, the individual raw values were transformed into d' (d-prime) scores for auditory and visual conditions respectively. This procedure from the standards of signal detection theory (see Macmillan & Creelman 2005) determines the measured difference between signal and signal-plus-noise by calculating the difference between the z-score of the hit rate (H) and the z-score of the false-alarm rate (F ; $d' = z(H) - z(F)$). A d' score of 0 mirrors a random response pattern (no signal detected) and a d' score of 4.65 represents the effective ceiling. Because the different target categories were merged into one omnibus value for auditory conditions and one for visual conditions respectively, both d' scores and raw responses were used to interpret the participants' processing strategies.

Statistics

The d' scores of each of the two modality conditions (auditory and visual) for each of the three groups (controls, CODAs and interpreters) were tested against the null hypothesis (H_0) in six separate two-tailed one-sample t-tests. Paired-samples t-tests were applied to test group-wise for differences between auditory and visual conditions. One-way analysis of variance (ANOVA) across all three groups was used to test for differences between them, and post-hoc analyses were performed by the Scheffé test.

In an attempt to learn more about the relationship between auditory and visual conditions, correlation coefficients of d' scores between sensory modalities were calculated across all groups and separately for each of the three groups. The examination of correlations between the rate of untransformed correct responses across modalities was used to unfold more detailed insights into the functional patterning of task performance.

The data sets' normal distributions were assured by one-sample Kolmogorov-Smirnov tests (two-tailed), and Pearson correlations were addressed. An alpha level of .05 was used for all statistics unless stated otherwise.

4.4.2 EEG data (Studies II and III)

Principal component analysis (PCA)

Factor-analytical temporal principal component analysis (tPCA) was chosen as the data-driven analysis method. It provides an objective approach to separating ERP components, even if they are latent or overlapping (e.g., Kayser & Tenke 2005). Temporal PCA generates one model (signified in factor loadings for each component) from all subjects, conditions, and electrodes included in the data matrix, and assigns a numeral contribution factor (factor score) to each data point in the data matrix.

Temporal PCA was executed with SPSS software using a covariance matrix. Both Varimax and Promax rotation were circumstantially explored. Varimax rotation with Kaiser's normalization (Kaiser 1958) reliably separated individual components and was therefore selected for the final analysis (Kayser & Tenke 2003; cf. Dien et al. 2005). Components cumulatively explaining 99% of the variance within the dataset were rotated (Kayser & Tenke 2003).

Individual averages of the segmented and post-processed EEG responses to the auditory antonymic, indirectly related and unrelated targets on one hand and averaged responses to the visual targets on the other hand were analyzed separately. The EEG sampling rate was reduced from 1000 Hz to 250 Hz before being subjected to PCA. The matrix for responses to the auditory targets was based on 39 individuals, and the matrix for responses to the visual targets included all 43 individuals. Curve progression and spatial distribution of the tPC and ERP datasets were visually inspected and compared. Under the consideration of temporo-spatial characteristics usually reported for ERP components at certain time points, the tPCs of interest were named (component number + latency in ms) and assigned to ERPs. The temporal PC factor scores were used as dependent variables for further statistics. Detailed statistical analyses were chosen for each component individually based on literature review and character of the actual data.

The components of interest were auditory tPC3-512 and tPC1-772 (Figure 3, upper picture) and visual tPC4-188, tPC7-520 and tPC1-752 (Figure 3, lower picture). Note that only the responses to the antonymic and unrelated targets are discussed in this dissertation. Data were corrected for violations of sphericity using the Greenhouse-Geisser correction (Greenhouse & Geisser 1959) where applicable.

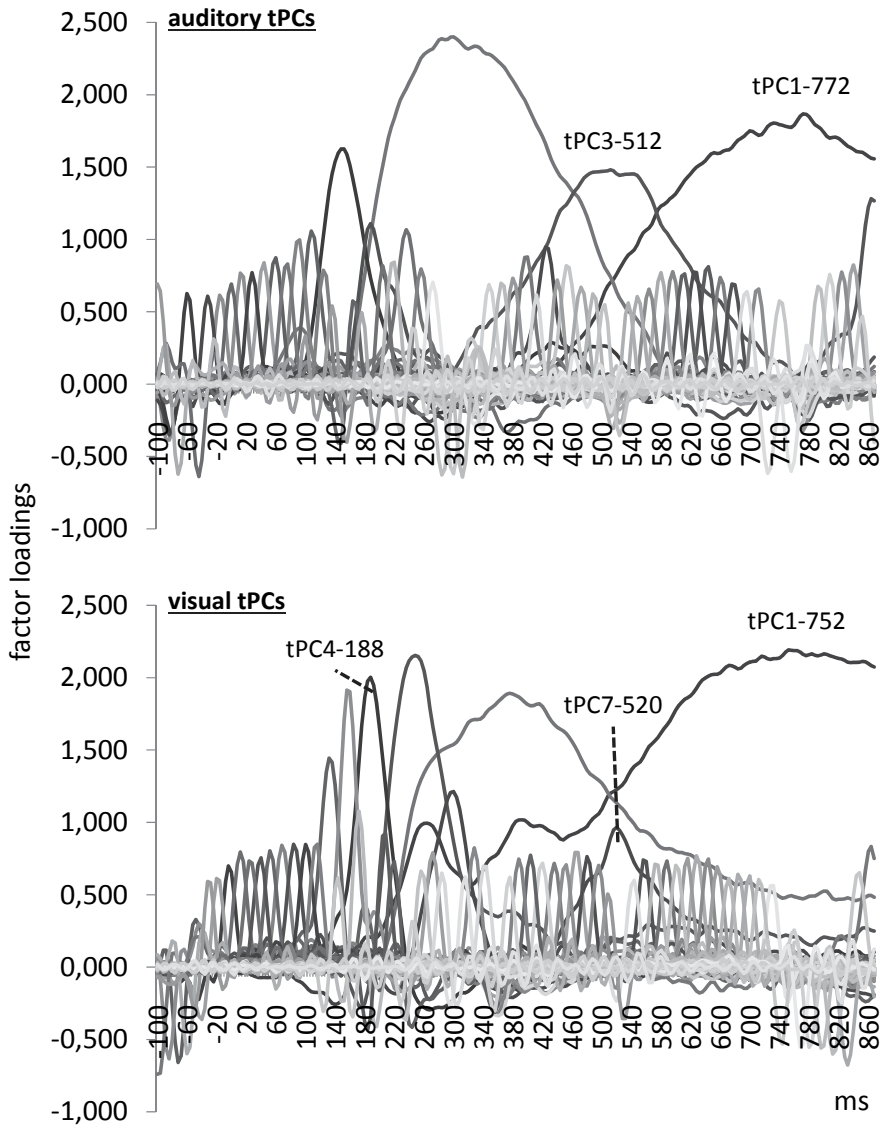


Fig. 3. Temporal principal component (tPC) factors of responses to auditory (upper picture) and visual (lower picture) antonymic, distantly related and unrelated targets. PCA was conducted separately for auditory condition ($N = 39$) and visual conditions ($N = 43$). The results are plotted against the 970 ms (-100 ms to 870 ms) sampling epoch.

Statistics for the auditory components

Auditory tPC3-512 explained 6.46% of the variance in the auditory dataset and corresponded to the auditory N400 component. Auditory tPC1-772 explained 40.27% of the variance in the auditory dataset and corresponded to the auditory LPC component. The statistical analysis for these components all followed the same model and procedure.

The tPC factor scores were subjected to repeated-measures (rm)ANOVA including four within-subject factors:

1. *condition* (antonymic/unrelated)
2. *hemisphere* (left/right)
3. *medial*
 - medial (F3/F4, C3/C4, CP5/CP6, P3/P4, O1/O2)
 - lateral (F7/F8, T7/T8, TP9/TP10, P7/P8, PO9/PO10)
4. *anterior-posterior*
 - frontal (F3/F4, F7/F8)
 - central (C3/C4, T7/T8)
 - centro-parietal (CP5/CP6, TP9/TP10)
 - parietal (P3/P4, P7/P8)
 - occipital (O1/O2, PO9/PO10)

The group served as a between-subject factor (controls, CODAs and interpreters). When group-related interactions returned statistically positive results, the same rmANOVA model was used to follow the results up by paired comparisons and within-group analyses. Paired-sample t-tests were employed to further uncover significant interactions and main effects, and for this, mean values were calculated for cross-level effects whenever necessary.

Statistics for the visual components

Visual tPC4-188 explained 4.79% of the variance in the visual dataset and corresponded to the visual N170 component. The tPC factor scores of the occipito-temporal electrodes were subjected to rmANOVA including three within-subject factors:

1. *condition* (antonymic/unrelated)
2. *hemisphere* (left/right)
3. *anterior-posterior* (P7/P8, PO9/PO10, O1/O2)

The effects were examined for paired groups (controls and CODAs, controls and interpreters, CODAs and interpreters) with the group as a between-subject factor. Statistically significant group-related interactions were followed up by within-group comparisons using the same model as above. Condition-related interactions were followed up by an rmANOVA run for each stimulus condition separately.

Visual tPC7-520 explained 1.37% of the variance in the visual dataset and corresponded to the visual N400 component. Visual tPC1-752 explained 59.31% of the variance in the visual dataset and corresponded to the visual LPC component. The analyzing procedure for these components was identical to the one used for their auditory equivalents (see above).

4.4.3 Correlations between the EEG data (tPC scores) and the behavioral index of decision sensitivity (d' scores) (Studies II and III)

By attempting to explore the functional significance of individual ERP components for the task of this study, selected tPC component scores of all electrodes included in the respective component's statistical analysis were correlated with the d' scores of the corresponding sensory modality by Pearson Correlation analyses. All d' scores are of positive value whereas the tPC score values vary in polarity along with the respective ERP component. A positive correlation between the d' scores and a negative tPC/ERP component therefore reflects an increase in positivity and thus a reduction in amplitude size and vice versa.

5 Results

5.1 Behavioral data (Study I)

The responses to the antonymic targets were correct (*hits*) when they were "yes, opposite", and the correct responses to the distantly-related and unrelated targets were "no, not opposite" (*correct rejections*). The rate of correct responses to the auditory target conditions (upper picture) and the visual target conditions (lower picture) are displayed in Figure 4.

Figure 5 shows the group-clustered d' scores representing the bias-corrected decision sensitivity to the auditory and visual targets. The null hypothesis (H_0) was rejected for each of the d' scores (all $ps = .000$) reflecting some kind of decision sensitivity to all the target conditions in each of the three groups. Paired-sample t -tests showed that all the groups exhibited higher d' scores for the responses to the auditory than to the visual target conditions ($ps < .002$). ANOVA examinations yielded significant group differences in both, the bias-corrected responses to the auditory ($F(2, 40) = 5.158, p = .010$) and to the visual ($F(2, 40) = 69.460, p < .001$) targets. Post hoc analyses revealed that the d' scores to the auditory targets were significantly higher in the interpreters than in the controls ($p = .042$) and the CODAs ($p = .019$) whereas the controls and the CODAs scored equally. The interpreters' d' scores to the visual targets were again higher than in both the other groups ($ps < .001$), but the CODAs scored higher than the controls ($p < .001$) in these conditions.

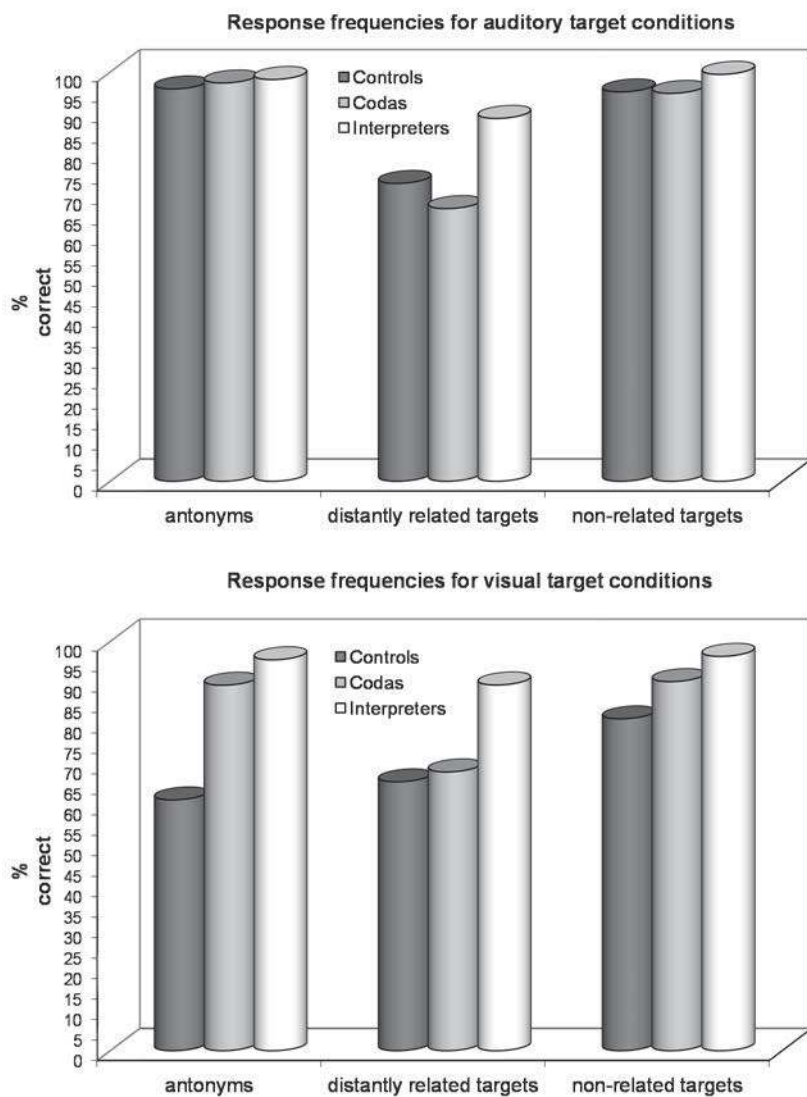


Fig. 4. Response frequencies to auditory targets (upper picture) and visual targets (lower picture) for the 15 controls, the 15 CODAs and the 13 interpreters. Percentage of correct responses displayed. Reprinted with permission from the Multimodal Research Centre, Auckland, New Zealand from Zachau et al. (2012).

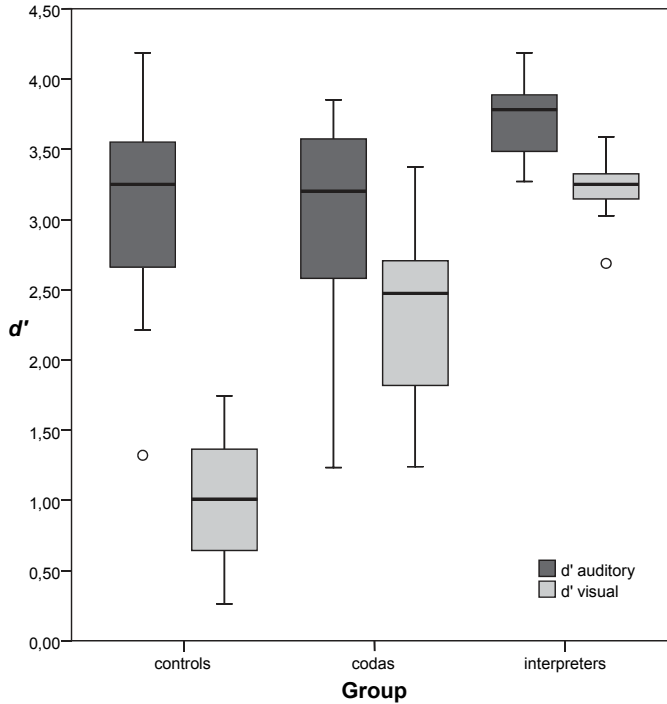


Fig. 5. D-prime (d') scores of auditory (dark bars) and visual (light bars) targets for the 15 controls, the 15 CODAs, and the 13 interpreters. Reprinted with permission from the Multimodal Research Centre, Auckland, New Zealand from Zachau et al. (2012).

Correlation analyses revealed that the auditory and visual d' scores (Figure 5) correlated positively with each other across all participants ($r = .534, N = 43, p < .001$). Group-wise calculations, however, showed that only the CODAs' d' scores correlated significantly ($r = .740, n = 15, p = .002$), whereas both the controls' ($r = .419, n = 15, p = .120$) and the interpreters' ($r = .529, n = 13, p < .063$) correlations did not reach significance. Accordingly, correlation analyses based on the untransformed response frequencies (Figure 4) yielded significance for the responses to all the three target conditions across all participants ($ps < .010$) and no significance in the control group alone ($ps > .124$). In the CODAs, the responses to the distantly related and the unrelated (but not antonymic, $p < .196$) targets highly correlated across modalities ($ps = .000$). In the interpreters, the responses to the antonymic and the distantly related (but not unrelated, $p < .175$) targets correlated across modalities ($ps < .010$). The different correlation patterns in the CODAs and

the interpreters indicated different processing strategies with a different emphasis on different linguistic categories between the two groups of signers. All correlations were positive, and therefore, the higher the score was in one modality, the higher it was also in the other modality.

5.2 EEG data (Studies II and III)

The ERP data (Figure 6 for auditory data and Figure 7 for visual data) was visually inspected. Several components were obvious at earlier latencies while no clear peaks were detectable at later latencies. Temporal PCA was able to capture the variance in the data and to ascribe it to different underlying factors. The factors of interest for this study were matched with the corresponding ERP components.

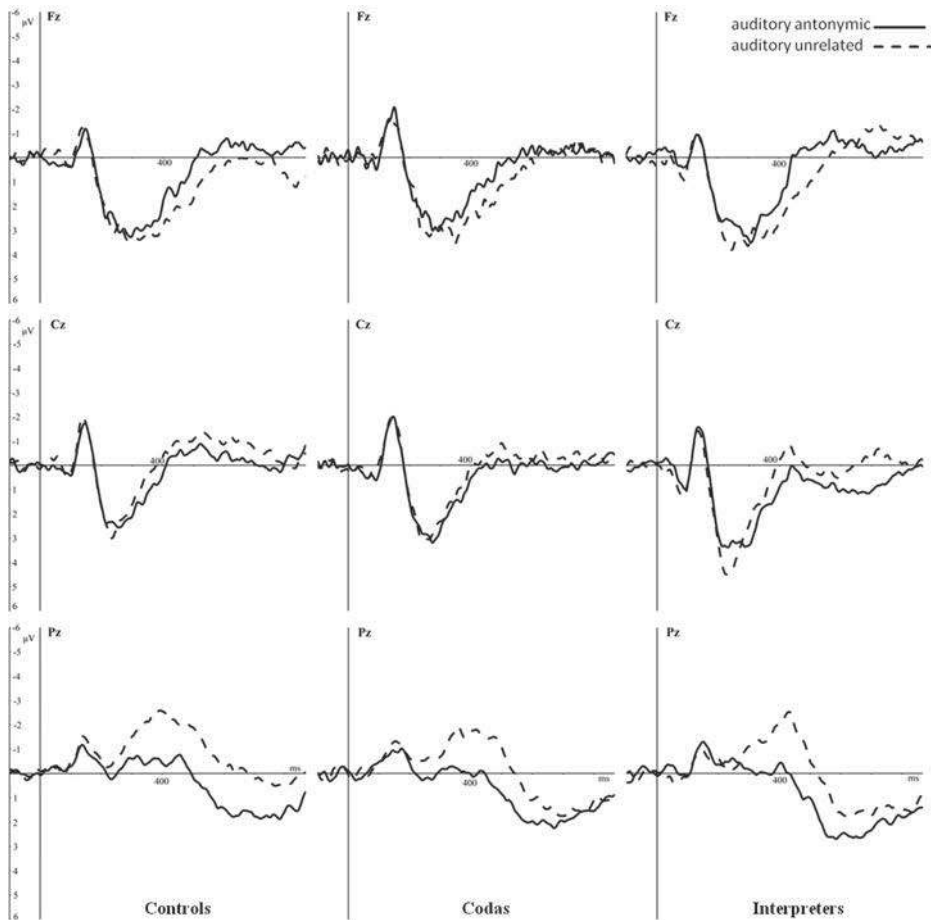


Fig. 6. Averaged EEG segments of responses to the auditory antonymic and unrelated targets of a semantic priming task across speech and sign language. Grand averages of the auditory targets for 13 controls (left column), 14 CODAs (middle column), and 12 interpreters (right column) are displayed for electrodes Fz (upper row), Cz, (middle row), and Pz (lower row). Intervals are shown from -100 ms to 870 ms (x-axis) and from -6 to 6 μV (y-axis, tick marks every 100 ms) at a sampling rate of 1000 Hz. Negativity is plotted upwards. Reprinted with permission from Elsevier Ltd.

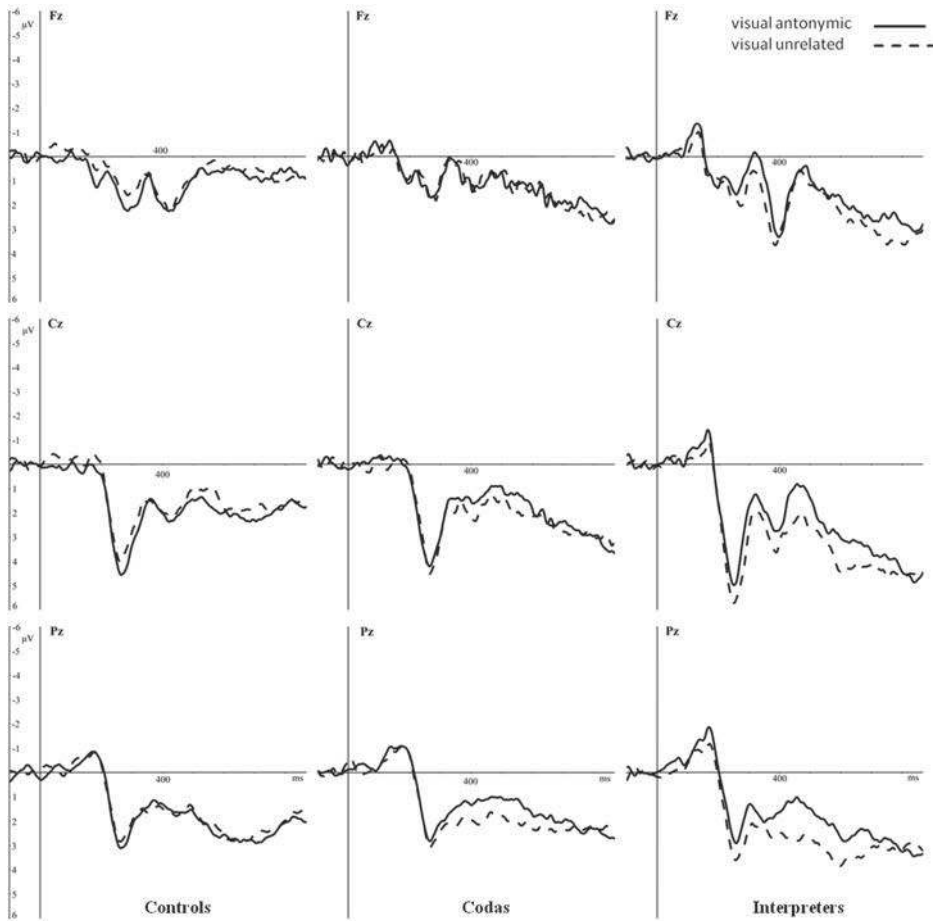


Fig. 7. Averaged EEG segments of responses to the visual antonymic and unrelated targets of a semantic priming task across speech and sign language. Grand averages of the visual targets for 15 controls (left column), 15 CODAs (middle column), and 13 interpreters (right column) are displayed for electrodes Fz (upper row), Cz (middle row), and Pz (lower row). Intervals are shown from -100 ms to 870 ms (x-axis) and from -6 to 6 μ V (y-axis, tick marks every 100 ms) at a sampling rate of 1000 Hz. Negativity is plotted upwards. Reprinted with permission from Elsevier Ltd.

5.2.1 Auditory tPC3-512 (N400) (Study II)

The latent auditory N400 was reflected in a latent component showing larger negative scores over frontal and positive scores over parietal sites in response to the antonymic than the unrelated targets (Figure 8).

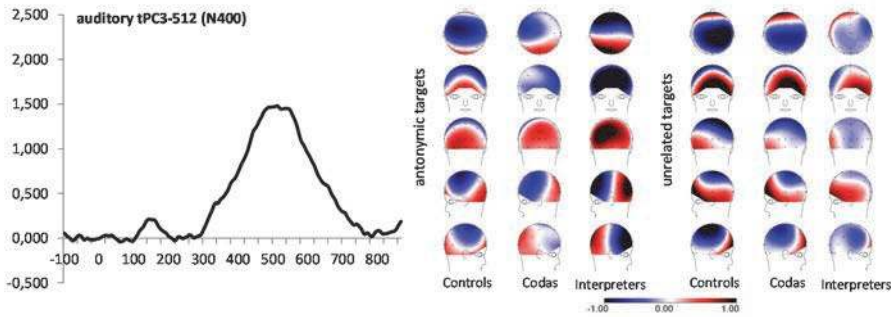


Fig. 8. Temporal PC factor loadings of the auditory tPC3-512 (N400) are displayed on the left. The column on the right shows factor score topographies of each group for the corresponding component within antonymic and unrelated targets. Reprinted with permission from Elsevier Ltd.

For detailed statistical results concerning this component, see Zachau and colleagues (2014). In summary, (rm)ANOVA showed a significant interaction between medial levels, anterior-posterior levels, and group ($F(5.3, 94.9) = 2.53, p = .032$), which derived from the interpreters processing these dimensions differently compared with the controls ($F(2.3, 53.5) = 3.36, p = .036$) and the CODAs ($F(2.5, 60.6) = 3.00, p = .045$). The results indicated that the topography of the responses to the auditory stimuli was similarly specific in controls and CODAs, while interpreters differed from both groups in that their responses were large at all recording sites (Figure 8).

Further, significant interactions between stimulus, hemisphere, and anterior-posterior factors ($F(1.6, 57) = 12.39, p = .000$) and between stimulus, medial factors, and anterior-posterior factors ($F(2.5, 90.9) = 4.14, p = .012$) were revealed across groups. Auditory antonyms generated a pronounced negative response at medial fronto-central sites and a positive, left-lateralized response at parieto-occipital sites. Auditory unrelated targets were topographically different with a focus on medial centro-parietal areas (Figure 8).

5.2.2 Auditory tPC1-772 (LPC) (Study II)

The auditory LPC was a late component with no clear peak, which exhibited positive tPC scores over parieto-occipital sites and negative scores over bilateral fronto-temporal sites (Figure 9).

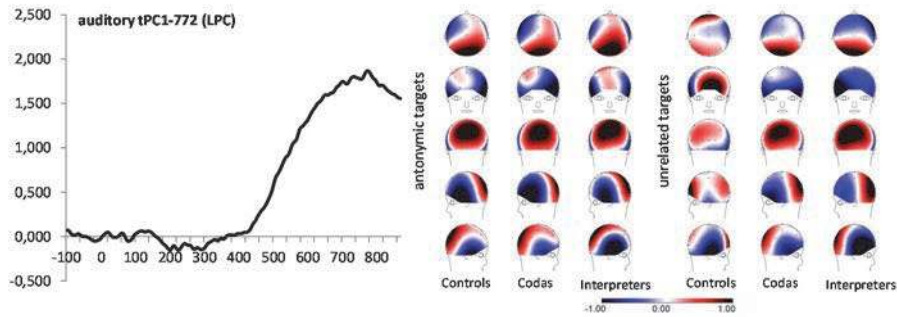


Fig. 9. Temporal PC factor loadings of the auditory tPC1-772 (LPC) are displayed on the left. The column on the right shows factor score topographies of each group for the corresponding component within antonymic and unrelated targets. Reprinted with permission from Elsevier Ltd.

For detailed statistical results concerning this component see Zachau et al. (2014). In summary, (rm)ANOVA showed a significant interaction between stimulus, anterior-posterior levels, and the group ($F(2.8, 51) = 3.32, p = .029$), which derived from a group difference between the controls and the interpreters ($F(1.5, 33.7) = 7.31, p = .005$). In the controls, a frontal positivity appeared in response to the auditory unrelated targets, while positive activity at parieto-occipital sites was reduced (Figure 9). The group of interpreters exhibited a stimulus main effect ($F(1, 11) = 5.18, p = .004$) over left-hemispheric centro-parietal and right-hemispheric fronto-central brain areas, indicating that the intensity of responses was different between the targets at these locations.

5.2.3 Visual tPC4-188 (N170) (Study III)

The N170 response (Figure 10) was evident at around 190 ms at all groups' occipital channels (Figure 11).

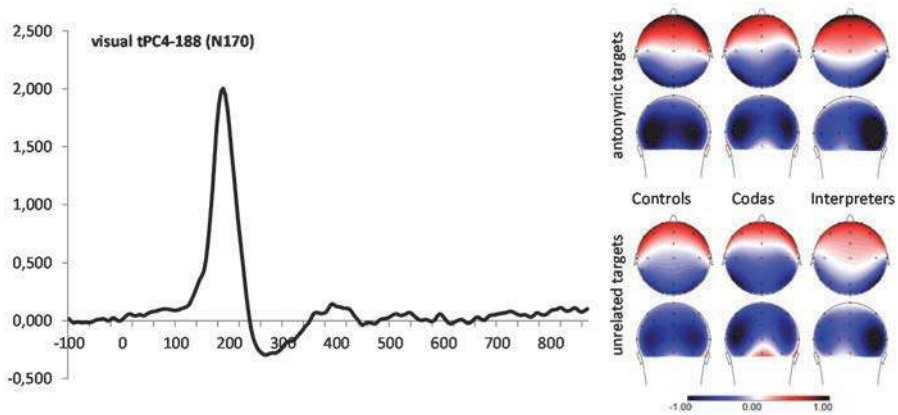


Fig. 10. Temporal PC factor loadings of the visual tPC4-188 (N170) are displayed on the left. The column on the right shows factor score topographies of each group for the corresponding component within antonymic and unrelated targets.

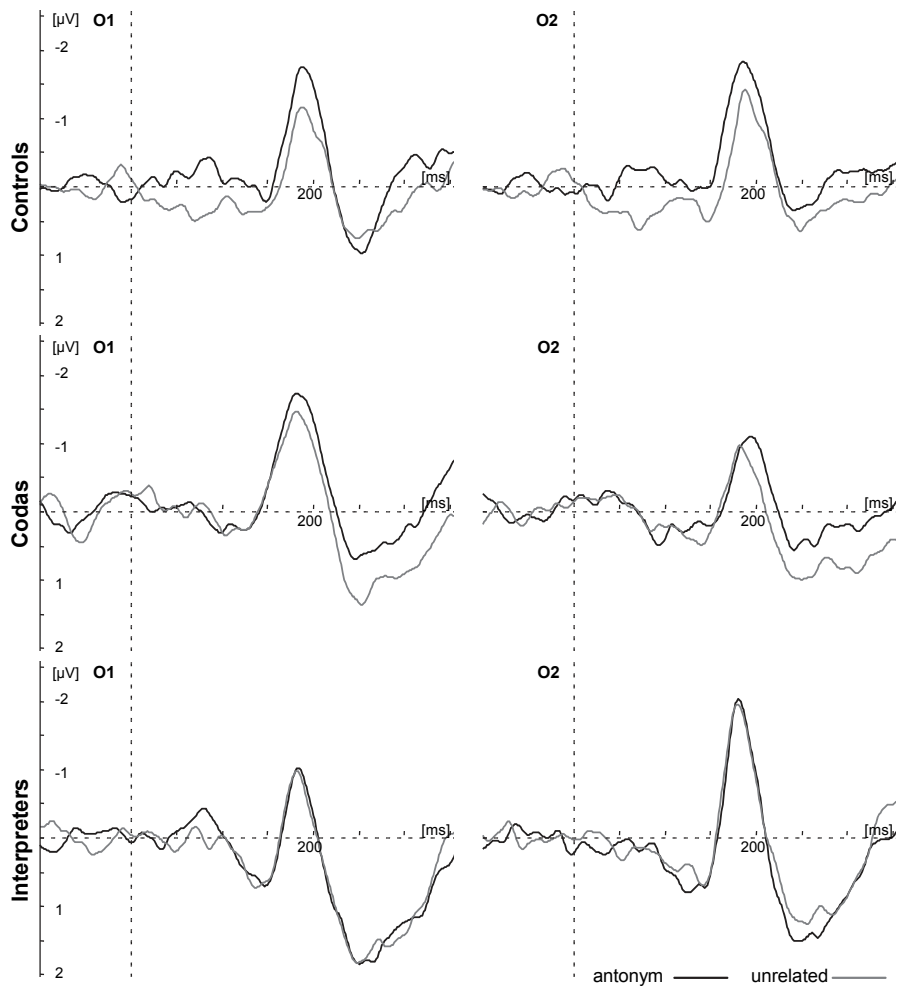


Fig. 11. Averaged EEG segments of the time-locked occipital responses to the signed antonymic and unrelated targets showing the N170 response peaking at about 190 ms. Grand averages of the visual targets for 15 controls (upper row), 15 CODAs (middle row), and 13 interpreters (lower row) are displayed for electrodes O1 (left column) and O2 (right column). Intervals are shown from -100 ms to 350 ms (x-axis, tick marks every 50 ms) and from -2.5 to 2 μ V (y-axis) at a sampling rate of 1000 Hz. Negativity is plotted upwards.

Repeated-measures ANOVA on the occipito-temporal electrodes showed nothing but stimulus main effects in the group comparisons between the controls and the CODAs ($F(1, 28) = 6.97, p = .013$) and between the controls and the interpreters ($F(1, 26) = 7.60, p = .011$). The comparison between the two signing groups, however, revealed a significant interaction between stimulus condition, hemisphere and anterior-posterior electrode sites ($F(1.51, 39.16) = 4.13, p = .034$). In signers, hemispheric and anterior-posterior electrode sites interacted significantly for the visual antonyms ($F(1.44, 37.34) = 5.30, p = .017$) but not for the unrelated targets ($p = .57$). This reflected an anterior processing focus, which was more prominent over the right hemisphere (tPC scores T6: -1.18, PO10: -.75, O2: -.69) than over the left hemisphere (tPC scores T5: -.79, PO9: -.52, O1: -.65). Further, the comparison of the CODAs with the interpreters showed an interaction between hemisphere and group ($F(1, 26) = 4.78, p = .038$). This group difference resulted from a right-hemispheric dominance of the N170 response in the interpreters only (see Figure 10) as confirmed by a hemispheric main effect ($F(1, 12) = 6.37, p = .027$) in the group-wise follow-up analysis.

5.2.4 Visual tPC7-520 (N400) (Study II)

The latent visual N400 was reflected in a component with negative scores at frontal and central sites and positive scores at posterior regions (Figure 12).

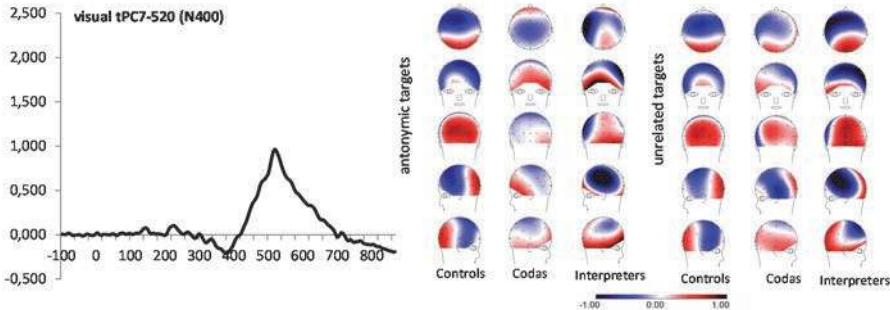


Fig. 12. Temporal PC factor loadings of the visual tPC7-520 (N400) are displayed on the left. The column on the right shows factor score topographies of each group for the corresponding component within antonymic and unrelated targets. Reprinted with permission from Elsevier Ltd.

Statistical analyses revealed a significant four-way interaction between stimulus, hemisphere, anterior-posterior levels, and group ($F(4.6, 91.7) = 2.40, p = .047$). The CODAs differed from the controls ($F(2.2, 62.5) = 4.02, p = .019$) and the interpreters ($F(2.6, 68) = 3.25, p = .033$). The controls and the interpreters did not differ from each other ($p > .05$).

Follow-up analyses showed that the interaction of stimulus, hemisphere, and anterior-posterior levels was significant in CODAs only ($F(4, 56) = 7.03, p = .001$). The CODAs responded with a left-hemispheric centro-parietal negativity to the visual unrelated targets but not to the antonymic targets. The controls and the interpreters showed more central negativities bilaterally, which were equal in response to the different stimuli (Figure 12).

5.2.5 Visual tPC1-752 (LPC) (Study II)

The relatively latent visual LPC scored positively over central sites and negatively over occipital and parietal sites bilaterally (Figure 13).

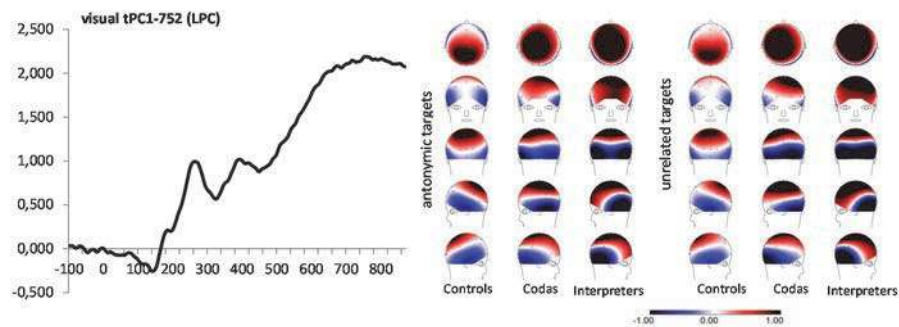


Fig. 13. Temporal PC factor loadings of the visual tPC1-752 (LPC) are displayed on the left. The column on the right shows factor score topographies of each group for the corresponding component within antonymic and unrelated targets. Reprinted with permission from Elsevier Ltd.

Statistical analyses showed a significant interaction between medial levels, anterior-posterior levels, and group ($F(8, 160) = 4.70, p = .000$), which derived from the interpreters processing medial by anterior-posterior dimensions differently from the two other groups ($ps < .003$). Interactions of medial and anterior-posterior levels were significant in all three groups ($ps = .000$). Medial electrodes (averaged across stimuli and hemispheres) were more positive than

lateral sites in all three groups ($ts > 2.67$, $ps < .021$), which reflected the positive responses over fronto-central midline and medial regions and the negative responses over lateral and parieto-occipital areas across all groups (Figure 13). The fronto-central medial positivity was more frontally and laterally distributed in the CODAs and the interpreters than in the controls (Figure 13).

Further, an interaction of stimulus, hemisphere and group ($F(2, 40) = 5.27$, $p = .009$) uncovered a stimulus by hemisphere interaction, which was exclusively found in the CODA group ($F(1, 14) = 11.55$, $p = .004$). Paired-sample t-tests (averaged data across medial-lateral and anterior-posterior levels) showed a laterality effect for the unrelated target responses ($t = 3.04$, $p = .009$) only, which reflected a leftward shift of the fronto-central positivity (Figure 13).

5.3 Correlations between tPC scores and d' scores (Studies II and III)

5.3.1 Auditory tPC3-512 (N400) (Study II)

Correlation analysis revealed a significant correlation of the auditory d' scores with the tPC scores reflecting the N400 responses to the auditory antonymic targets in the controls only ($r = -.645$, $p = .017$ at O1; $r = -.572$, $p = .041$ at O2). The less negative (smaller) the N400 was over the occipital areas bilaterally, the higher the task performance in them.

Correlations with the responses to the unrelated targets were found in the controls ($r = .653$, $p = .016$ at F4; $r = -.711$, $p = .006$ at O1; $r = -.594$, $p = .032$ at O2) and in the CODAs ($r = .672$, $p = .016$ at F8; $r = -.544$, $p = .044$ at P3; $r = -.541$, $p = .046$ at P4). The more negative (larger) the N400 over right frontal areas and the less negative (smaller) the N400 over bilateral parietal (CODAs) or occipital (controls) areas, the better the decision sensitivity.

5.3.2 Auditory tPC1-772 (LPC) (Study II)

Correlation analysis revealed a significant correlation between the auditory d' scores and the tPC scores reflecting the LPC responses to the auditory antonymic targets in the controls ($r = .553$, $p = .050$ at C3; $r = -.678$, $p = .011$ at O1) and in the CODAs ($r = -.540$, $p = .046$ at P7). The more positive (larger) the response over left central areas and the less positive (smaller) over left occipital areas, the higher

the task performance in the controls. In the CODAs, a less positive (smaller) response over left parietal areas was correlated with a higher task performance.

Correlations with the responses to the unrelated targets were found in the interpreters only ($r = -.592, p = .043$ at F8; $r = -.631, p = .028$ at T8; $r = .598, p = .040$ at P3; $r = .708, p = .010$ at P7; $r = .643, p = .027$ at O1). The less positive (smaller) the LPC at right fronto-central areas and the more positive (larger) at left parieto-occipital areas, the more sensitive their decisions.

5.3.3 Visual tPC4-188 (N170) (Study III)

Correlation analysis revealed that only the CODAs' N170 in response to the unrelated targets at the right occipital electrode (O2) correlated positively with the d' scores ($r = .699, p = .004$; all other $ps > .097$), indicating that the more positive (smaller) the N170, the better the behavioral detection sensitivity on the antonymic and unrelated targets.

5.3.4 Visual tPC7-520 (N400) (Study II)

Correlation analysis revealed a significant correlation between the visual d' scores and the tPC scores reflecting the N400 responses to the visual antonymic targets in the interpreters only ($r = -.675, p = .011$ at P4). A more negative (larger) N400 over right parietal areas correlated with a higher task performance.

Correlations with the responses to the unrelated targets were found in the controls ($r = .551, p = .033$ at F7; $r = -.582, p = .023$ at PO10; $r = -.640, p = .010$ at O2) and in the interpreters ($r = -.622, p = .023$ at F8; $r = .594, p = .032$ at P7). The more positive (smaller) the N400 over left frontal areas and the more negative (larger) over right parieto-occipital areas, the higher the task performance in the controls. In the interpreters, a higher task performance correlated with a more negative (larger) N400 over right frontal areas and more positive (smaller) response over left parietal areas.

5.3.5 Visual tPC1-752 (LPC) (Study II)

Correlation analysis revealed a significant correlation between the visual d' scores with the tPC scores, reflecting the LPC responses to the visual antonymic targets in the CODAs ($r = .573, p = .039$ at O1) and in the interpreters ($r = .569, p = .042$

at TP10). The more positive (larger) the LPC over the CODAs' left occipital areas and over the interpreters' right mastoid, the higher their task performance.

Correlations with the responses to the unrelated targets were found in the CODAs only ($r = -.549$, $p = .034$ at C4; $r = -.582$, $p = .023$ at CP6; $r = .515$, $p = .049$ at PO9). The more negative (smaller) the LPC response over right centro-parietal areas and the more positive (larger) over right parieto-occipital areas, the higher the task performance.

6 Discussion

6.1 Summary and discussion of the results

The aim of this project was to explore the impact of differently acquired sign language knowledge on linguistic – particularly semantic – representation and processing in native and non-native hearing adult signers. Results from the original publications are discussed below. The structure of the discussion adheres to the order of the project's initial research questions (RQs, see chapter 3 of this thesis).

6.1.1 [RQ1] Convergence of mental lexica in hearing signers (Study I)

Even after bias-correction (d' transformation), all three groups of the present study revealed a significant level of decision sensitivity to each of the six target conditions (Figure 5). All groups scored higher when making semantic decisions on the auditory targets than when deciding on the visual targets. The controls and the CODAs responded equally well to the auditory targets, while the interpreters displayed an even higher sensitivity than either one of the other two groups. The interpreters, thus, seemed to execute the task with enhanced *metalinguistic awareness* (i.e., the ability to reflect consciously on the nature and properties of language, Van Kleeck 1982). This assumption is fairly reasonable considering the interpreters' professional background and it is in line with previous literature on interpreters' state of mind when they are ready to translate (e.g., Napier & Barker 2004, Peterson 2000). Concerning the nonverbal domain, enhanced executive control was found in unimodal bilinguals (e.g., Bialystok 2001, Bialystok et al. 2004) and was suggested to result from the constant management of two competing languages (Bialystok et al. 2004), but more recent findings including bimodal bilinguals reveal that this is not the case when those two languages do not compete for the same channel of articulation (Emmorey et al. 2008). Similarly, it can be hypothesized that the interpreters in this study were in a metacognitive state of mind, which allowed them to process the input analytically in a holistic way. Both speech and signs are phonemically structured, i.e., they consist of a closed set of meaningless elements, which form meaning by combination (e.g., Brentari 1998, Sandler & Lillo-Martin 2006). However, since there is no phonemic conformance whatsoever between the two languages, native bimodal bilinguals may not face this

competition. The CODAs, on one hand, have implicit knowledge of both languages and thus could make lexical decisions without considering all aspects available from the entire system. The interpreters, on the other hand, were in a metacognitive state of mind, which allowed them to process the input holistically. This may have resulted in linguistic competition due to a general activation level, despite the two input languages' different input modalities, i.e., more cognitive effort. This strategy still seemed very functional, as it led to them outperforming even the controls in auditory semantic decision sensitivity.

The bias-corrected decision sensitivity to the visual targets was evident in all three groups, albeit at three different levels with the interpreters scoring the highest, followed by the CODAs and finally the controls. Since language (i.e., also speech) processing is cross-modally organized (see, e.g., Marian 2009), sign-naïve participants were also equipped with a certain skill to decode (or guess the meaning of) the signed targets, possibly along sign-inherent iconic clues or mouthing, which were not controlled for in the study design (see section 6.1.3 of this dissertation). The discrepancy between auditory and visual decision sensitivity in the CODA group may reflect the fact that Finnish was the self-rated dominant language at the time of the examination (section 4.1 of this dissertation), and not all of the CODAs were frequently using signing for a variety of reasons. This, combined with the fact that the presented stimuli consisted of rather modern school book vocabulary, which some of the CODAs had never before been confronted with, might have led to a decrease in automation during task performance. In addition, less structured acquisition circumstances than in the interpreter group and/or slight conceptual differences of the translational equivalent signed targets (based on speech) may have contributed to the significantly less precise and much more heterogeneous behavioral outcome in the CODA group. Only the CODA group's d' scores were correlated across modalities, which further supports the assumption that the lower visual score was input-guided rather than being an indicator for poor test performance per se.

Overall, the study design clearly mirrors strategies of cross-linguistic semantic interaction, which may be based on linguistic but unequal principles in the CODA and interpreter groups, while the non-signers seemed to employ some kind of compensatory strategy to execute the task. According to the developmental Revised Hierarchical Model (RHM) of word recognition by Kroll & Stewart (1994), L2 words are learned by accessing the conceptual level via lexical representations of L1. The more fluent a second language learner becomes, the stronger the direct connection becomes to the conceptual level. The behavioral outcome of this study

is in line with this suggestion and previous studies (for a discussion see Morford et al. 2011), even if the interpreter group was highly proficient. Their learning history may account for a strategic persistence, just as Morford and colleagues formulated in their discussion:

For less proficient L2 readers, the translation may function to mediate access and provide a critical link to meaning, [...]. For more proficient L2 readers, that link may be unnecessary, but under conditions that permit or encourage access to the translation, it may enhance the nuances of meaning available to the L2.

(Morford et al. 2011, p. 290)

Shook and Marian (2012) proposed that cross-modal co-activation during speech comprehension results from top-down feedback connections between the semantic and lexical levels and/or lateral associative links between lexical items within the bimodal bilingual's language system. The actual nature of these interconnections and their differences between signers with different acquisition backgrounds remain as subjects for future studies.

All studies in this thesis were based on one identical set of data. The cognitive electrophysiological processes underlying the behavioral task performance discussed in this chapter – and their correlations – are discussed below. The combined multimodal consideration of behavioral and neurocognitive measures is one efficient way of broadening our understanding about the organization of the bimodal bilingual lexicon.

6.1.2 [RQ2] Electrophysiological correlates of sign language processing (Studies II and III)

Auditory and visual targets clearly evoked stimulus-locked response patterns in the averaged EEG signal. The responses to the auditory targets (Figure 6) showed a negativity peaking at around 150 ms and a fronto-central positivity peaking after 200 ms. This was succeeded by a long-lasting late response after approximately 300 ms, with a shift from frontal positivity into negativity with an opposite polarity pattern at the parietal areas displaying a negative peak at about 400 ms and positivity starting at around 500 - 600 ms. The visual targets (Figure 7) peaked roughly at 100 – 200 ms with negative voltage and shifted to positive voltage thereafter with two positive peaks at about 250 ms and 350 - 400 ms and a long-

lasting positive shift after approximately 300 ms. Later on (after 300 ms), all groups' posterior responses to the auditory unrelated targets were more negative than those to the auditory antonyms, but the two signing groups' visual antonym responses were more negative than the unrelated target responses.

One of the greatest challenges of this project was the adequate determination of individual ERP components for statistical evaluation. The sparse background literature on ERP correlates of sign processing allowed only vague expectations about the components involved in the context of the cross-linguistic task at hand. The visual inspection of the individual data sets revealed that manual peak detection, particularly of the visual target responses, was hardly possible due to multiple nearby peaks in the early time window (about 100 - 200 ms) and the appearance of an unknown amount of later (after 300 ms), seemingly long-lasting, components without clear peaks. A considerable amount of overlap between single components appeared very likely. This – and missing conventions between different studies – ruled out the option to analyze the data based on objectively pre-defined time windows. Therefore, the data was subjected to tPCA as a data-guided approach of component determination. This procedure proved successful. While the electrophysiological responses to the auditory and visual targets appeared differently (Figures 6 and 7), PCA-extracted component structures resembled each other remarkably in parts (Figure 3). Earlier more dissimilar components were likely to reflect modality-specific processes of stimulus extraction and processing, while later, more similar, components might mirror analog processes across modalities.

With a focus on the responses to the signed targets, the visual N170 response, a negative ERP component peaking at 150-200 ms over occipito-temporal electrodes was expected to appear. It is suggested that the N170 mirrors general perceptual expertise for different visual object domains and has been linked to face-processing (Bentin et al. 1996, Bötzel et al. 1995; cf. Thierry et al. 2007), visual word recognition (see Maurer & McCandliss 2008), and other different fields of visual expertise (for a review see Eimer 2011). Further, based on previous studies of word recognition memory (see, e.g., Rugg & Curran 2007), sign language semantics (Capek et al. 2009, Grosvald et al. 2012, Gutierrez et al. 2012a, Gutierrez et al. 2012b, Hosemann et al. 2013, Hänel-Faulhaber et al. 2014, Kutas et al. 1987, Neville et al. 1997), cognitive electrophysiological correlates of cross-linguistic semantic priming in bilinguals (for a review, see Altarriba & Basnight-Brown 2009, pp. 80-84), and ERP correlates of bilingual code-switching (Moreno et al. 2002, Proverbio et al. 2004, Van Der Meij et al. 2011), the present study design was

expected to evoke N400. The N400 is a centro-parietal negativity peaking 200-600 ms after stimulus onset, which is linked to highly automatic processes of recognition and familiarity. Because task execution required decision making, the late positive complex (LPC), reflecting more controlled recollection processes, was also expected to appear. The analyses of these components' characteristics within and between the three groups of study participants (see sections 6.1.3 and 6.1.4 of this thesis) provide encompassing insights into hearing signers' sign processing strategies in the cross-linguistic context at different time points and thus from varying perspectives.

The visual N170 response was evident at around 190 ms at all groups' occipital channels (Figure 11). Although clearly visible at the grand average level, peak detection proved to be highly challenging at the individual level due to multiple nearby peaks (see Figure 3). By allocating tPC4-188 to visual N170 (Figure 10), the influence of subjective misjudgment was eliminated.

Unlike N170, the visual N400 was latent and not straightforwardly visible. Based on its timing and in comparison to the auditory N400 (auditory tPC3-512; Figure 3), visual tPC7-520 was matched with the visual N400 response (Figure 12). Temporal PCA revealed that it was entirely superimposed by two components with significantly larger variability, the later LPC (tPC1-752, Figure 13) and an earlier component (Figure 3). To date, most previous studies on the electrophysiology of lexical processing in sign language selected N400 time windows for data analyses based on the visual inspection of the data (one or two phases ranging between 300 and 900 ms; Capek et al. 2009, Grosvald et al. 2012, Gutierrez et al. 2012a, Gutierrez et al. 2012b, Hänel-Faulhaber et al. 2014, Neville et al. 1997). Overlapping responses, such as those revealed by the tPCA approach, could explain the rather extended time windows used in some N400 studies (e.g., Capek et al. 2009), and may also have led to suggestions of a biphasic morphology of the N400 in response to signed stimulation (Gutierrez et al. 2012a, Neville et al. 1997). In this project, for the first time, visual N400 in response to signed stimulation was decontaminated from timely overlapping processes and analyzed based on objectively allocated component-relevant processes. In line with Gutierrez et al. (2012b), the visual N400 in Study II showed an atypical effect direction. This peculiarity remains an issue of interpretation for future studies.

Thus, as expected, both the N400 and the LPC were elicited by the study design in response to not only auditory but also to cross-modally primed, signed targets. The signed targets further elicited the N170 response and a number of additional components, which remain to be analyzed in detail during later stages of this project.

6.1.3 [RQ3] Cross-linguistic priming in hearing non-signers (Studies II and III)

Throughout this study, hearing sign-naïve adults served as a control group for the two groups of hearing signers. The non-signing controls conducted the same tasks as the signers. This was meant to control for general effects of sign language knowledge versus no knowledge. Surprisingly, even though uninformed, the controls scored behaviorally well above chance level when judging the visual targets' semantic relation to the auditory primes (Figure 4). This effect did not disappear after bias correction (Figure 5), which indicated that it was more than a random result. Instead of assuming a flaw of the used stimuli, this result provided valuable insight into the pronounced human signal decoding competency of unknown but potentially meaningful communicational targets. It has to be kept in mind that the task was not presented entirely in sign language, but it was cross-linguistic to the extent that the signs were always embedded in spoken language. The general context (i.e., the auditory primes) was equally well understood by the signers and non-signers. Given the task instruction, the presented primes raised conceptual expectations of a possible antonymic target (or a small range of targets because some lexemes can have more than one antonym) in a top-down manner. When questioned after the testing session ("how was it?"), many control participants reported that they were looking at the signer's mouth when trying to guess the meaning of the signs. Mouthing was not controlled for in this study, and a number of signs did include mouthed elements. The interpretation of the mouth and the face is an integral constituent of both sign language (e.g., Emmorey et al. 2009, Muir & Richardson 2005, Siple 1978) and speech (*speechreading*, see Campbell 2011). Therefore, also the non-signing controls were equipped with a certain skill to decode (or: guess the meaning of) the signed targets, especially because strong expectations about possible targets were already raised prior to their actual appearance. Even if a person is unaware of actual signing, iconicity eases the guessed matching of signed targets with an expected concept. The pre-existing expectations about possible targets also seemed to boost this effect when the targets were not intrinsically iconic. For example, if the prime was *mies/man*, the non-signers just had to evaluate whether the target could be its antonym, i.e., *nainen/woman*. Because it is well documented that beginning learners of sign language as L2 – but not infants acquiring a sign language as L1 – profit greatly from iconicity of the signs (see Woll 2013), this finding is an impressive demonstration of the human communicative capability. It appears very likely that

the controls used their audio-visual speechreading ability in the attempt to decode the signed targets. Still, beyond doubt, they could only guess the signs' meaning but they could not be certain if their decision was correct. Therefore, the control group's behavioral decision index for the signs (d' visual, Figure 5) was significantly below the two groups of highly proficient signers.

Cognitive mechanisms underlying speechreading are much more than an auxiliary construct in the deaf attempting to decode speech and in the hearing attempting to decode signing. They are central elements of the human communication system. Processes merging in audio-visual speechreading skills may very well represent the key competence linking auditory and visual linguistic systems. The finding of a statistically significant condition effect in the N170 responses of this study's controls conclusively demonstrates that these skills were distinct enough to evoke different activation levels for the different visual target conditions at this early processing level in them. This effect did endure in the sense that the later N400 brain responses to the unrelated visual targets correlated with the behavioral decision sensitivity index. However, no condition-related amplitude differences in the visual N400 or LPC responses, i.e., no reflections of semantic analyses, were found in the controls.

The differences between signers and non-signers in the electrophysiological brain responses to sign language processing in the cross-linguistic context analyzed here were purely qualitative in nature. This fits with ideas formulated in the *neuronal recycling hypothesis* (Dehaene 2005, Dehaene & Cohen 2007), which presumes that certain human skills (like reading and arithmetic) are evolutionarily recent, and it is therefore unlikely that they rely on brain mechanisms exclusively dedicated to them. Instead, changes to prior functions may lead to new skills, which in that sense recycle pre-existing brain circuitry. This can be mirrored in interferences between the respective skills. Considering the "gesture-first" theory of language evolution, stating that verbal languages once evolved from gestural origin and grew out of an asymmetrical motor control system for the hand (see, e.g., Corballis 2002, Toga & Thompson 2003), the controls' result pattern may not be such a surprise after all. All signed target stimuli in this study were presented in a muted modus. For this reason, the inherent features having led to their results are inevitably to be searched for at the visual level. The degree to which iconicity of the signs, mouthed elements and/or other features contributed to this result remains an open field for future studies.

6.1.4 [RQ4] Cross-linguistic priming in early and late learned hearing signers (Studies II and III)

Behaviorally, this study's sign language interpreters outperformed both the controls and the CODAs in semantic decisions about both spoken and signed targets, which was interpreted to mirror enhanced metalinguistic control (see section 6.1.1 of this thesis). It was of central interest for this study to explore neurocognitive correlates of the interpreters' processing strategy and to compare them to the native cross-linguistic processing strategy at the different levels of the N170 (representing visual structural feature encoding), the N400 (reflecting automatic recognition), and the LPC (mirroring controlled recollection).

At the early level of visual feature encoding, the occipito-temporal N170 has been linked to face-processing (Bentin et al. 1996, Bötzel et al. 1995), to visual word recognition (see Maurer & McCandliss 2008) and to other different fields of visual perceptive expertise (for a review see Eimer 2011). The N170 is suggested to mirror general perceptual expertise with different particularities for different visual object domains and their specific perceptual demands (*expertise framework*, Bukach et al. 2006). While visual word processing, e.g., results in left-lateralized N170 responses, face-related N170 is commonly reported to be right-lateralized. The *phonological mapping hypothesis* (McCandliss & Noble 2003) argues that the left-lateralization of N170 in response to words derives from the left-hemispheric property to process phonological aspects of (auditory) language, and that grapheme-to-phoneme mapping processes involved in reading make use of this property, and therefore become left-lateralized. The present study, for the first time, linked the N170 brain response to the perception of sign language. Different particularities, however, were observed between the different groups of study participants representing three different expertise levels of sign knowledge (naïve, highly proficient but late learned, and highly proficient native). Most strikingly, only the interpreters' N170 responses were generally processed with a right-hemispheric dominance whereas the CODAs' right-hemispheric N170 responses to the unrelated (but not antonymic) signed targets decreased in amplitude with increasing behavioral decision sensitivity. In line with the phonological mapping hypothesis, this is likely to indicate that the interpreters' processing strategy at this early stage of feature encoding was not so phonologically guided. Instead, they relied more on the analysis of facial features – or features very closely related to structural facial analysis – for both target conditions equally. The CODAs, however, were able to process signed targets at a different depth of perceptual analysis (see

the multimode theory of attention, Johnston & Heinz 1978) at the level of N170, and therefore were also able to process the different target conditions distinctively. The auditorily raised expectation of the antonym seemed to induce the mapping of the (unexpected) unrelated targets with phonological representations. The more they did so, the better their behavioral rejection. Processes underlying the N170 in the hearing native signers may thus fulfill a filtering gating function, which is modifiable by auditory information. This structural filter would be involved in gating the two target types to be processed with different amplitudes at the level of N400. The N400-effect on the signed targets was evident in the CODAs only.

Neither the interpreters' N170 response to the unrelated targets, nor their N170 response to the antonyms correlated with the behavioral decision sensitivity index. However, their N400 responses to both targets – despite exhibiting no amplitude difference – did. This suggests that attentional processes as reflected in ERP responses subsequent to the N170 but prior to the N400 may play a key role in the interpreters' processing strategy. The very frontal distribution of the later LPC (Figure 13), a component which is a member of the attention-related brain responses, gives further support to this assumption. The interpreters' processing strategy therefore relied less on automatic sensory assignment and more on controlled analyzing and recognition efforts, which was also reflected in a different LPC response pattern in comparison to both the other groups. According to the multimode theory of attention (Johnston & Heinz 1978), later and more semantic assignments of attention enhance the demand for processing capacity. But even though the resource costs may have been higher than in the CODAs, the interpreters' processing strategy proved highly functional. The flexibility of a less sensory guided and therefore less automated processing system may very well contribute to explaining how the interpreters could behaviorally outperform even the natively signing CODAs.

Once again, one has to bring to mind that the processing mechanisms described here underpinned the execution of a cross-modal task including auditory stimuli, which were of equal value to all participant groups, and visual targets, which represented an unknown but potentially meaningful code to the controls, a native linguistic code to the CODAs and a late learned linguistic code to the interpreters. At the level of visual feature detection, a certain degree of correct visual target assignment in the sense of the task ("was the visual target the antonym of the auditory prime?") was mirrored in a condition effect of amplitude difference in N170, which was present in all three groups and hence did not reflect actual sign language expertise. Safely assuming that all developmental windows of natural

language development had closed prior to the age of sign acquisition of the interpreter group (a mean age of 22 years), the interpreters practically started off from where the controls stood at the time of data acquisition. The late acquired sign language knowledge, therefore, was signified by a right-hemispheric shift of the N170 response. Because native sign language expertise was more connected to a reduction in right-hemispheric N170 activation (to the unrelated targets), it became apparent that the interpreters developed audio-visual integration mechanisms that did not resemble the native system of the CODAs. The interpreters' overall activation pattern on the one hand was very much suggestive of confirming the cross-modal co-activation of both language systems. The CODAs, on the other hand, possess a naturally integrated system for manual language, which followed very similar processing principles to speech, including a tight connection to phonological analysis at early processing stages. It remains the task of future studies to elaborate whether or not the L2-signers' processing strategy observed here was a transitional state and, if at all, under which conditions, they could switch to a different strategy.

6.2 Validity and recommendations for further research

In 2005, when the stimulus material for the studies of this thesis was developed and produced, no previous study had used real-time video stimulation for examining sign language processing in an ERP-design. Back then – and due to the very limited amount of published studies in this field still today – the scientific community was far from having developed common research standards. As a consequence, studies from different research groups lack methodological coherence; they are all somewhat explorative and pioneering. The triggering of the stimulus onset, which is viable for a reliable ERP outcome, is one matter, which is handled differently in the different publications. Most of the recent studies looked at sign language in a sentential context (with the exception of Gutierrez et al. 2012a) and excluded the transition phase when triggering the onset of the target signs. Hosemann and colleagues (2013), however, challenged the assumption of the "semantically empty transition phase" in sign language theory by systematically studying ERPs - in particular the N400 component - evoked by signs, which were triggered at different time points along the transition phase. They found that:

N400 onset preceded critical sign [SZ: in terms of the first correct hold position] onset and was thus clearly elicited by properties of the transition phase.

(Hosemann et al. 2013, p. 2224)

As shown by the Hosemann study, the results presented here can be interpreted with confidence, despite the majority of ERP studies thus far having chosen to use a different timing of sign stimulus onset. The possible introduction of jitter due to the slightly varying speed until the entity of articulators (hands, face, upper body) had formed a clearly recognizable formation of sign-related parameters may have led, if at all, to a slight delay (+/- 10 ms) in the visual ERPs. This can be considered a minor measuring inaccuracy and is the price for using natural stimuli.

The complexity of the stimulus material as well as the inclusion of three participant groups were a great asset to this study. Instead of conducting a series of studies, all the acquired data was intrinsically and straightforwardly based on identical terms. This left no room for even subtle methodological, individual, or tangible differences to tamper with the study outcome; instead it allowed for reliable cross-comparisons between various parameters. As a flip-side of this complexity, however, countless aspects such as the third target category (Indirectness condition) and a number of potentially meaningful ERP components were left unanalyzed. The analyses started off from the behavioral outcome as the end-product of the semantic decision process, and can be narrowed down to increasingly detailed aspects of the process itself, depending on the specific questions to answer. Due to the choice of tPCA as a data-guided analyzing approach, and the inclusion of all stimulus conditions in the data model used for tPC analyses, further investigations can be performed, and may and straightforwardly be integrated to the results achieved to date. This of course does not imply completeness. This study aimed at the uncovering of basic knowledge on sign language processing in the cross-linguistic context, and it provides a valuable starting point for further studies, but much more has to be done before we can start to formulate well-grounded neurolinguistic models about sign language processing. One difficulty, which became obvious in this study, may be that different groups of sign language users may occupy rather different mechanisms, which leaves doubt, as to whether a unitary model of sign language processing would be justified at all. Future research, besides the replication of the findings reported here, including larger samples and stricter statistical criteria (such as corrections for type I errors), should also extent to sign-sign priming conditions and deaf signers. This requires a

separate study, however, due to the audio-visual nature of the task used here, and it should tackle the challenge of how to fully focus non-signers' attention on the signed primes and targets. Future research is also invited to systematically study different parameters, that were uncontrolled for in this study. This includes inherent linguistic parameters of the signs, such as mouthing, iconicity, and standardized measures of sign fluency in the signing groups, if available, as well as eye movements (eye-tracking). Interference studies (see section 6.1.3 of this thesis) between different areas of visual expertise (such as signing, reading, faces, and gestures) are potentially highly informative for our basic understanding of the human (visual) linguistic processing capacity. The inclusion of respective non-experts as a control group is inevitable (see section 6.1.3 of this thesis).

The data-guided analysis approach in the form of tPCA invaluablely highlighted different aspects of this study's data, which were not accessible with conventional analysis methods such as peak detection or analysis based on fixed time windows. Temporal PCA is still a conversion of the measured biophysical signal into theoretical values, and aspects like the timing of the ERP components fell victim to this methodological choice. It should be the task of future ERP studies of sign language processing to develop common research standards ensuring a better comparability of data from different research groups. Additional studies using methods with a higher resolution (more EEG channels, MEG) and combined brain imaging methods would significantly advance the study of sign language processing.

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Appendices

Appendix 1(1)

Excerpt from the Language Assessment Questionnaire (visual analogue scale)

- Questions asked all signers -

Please answer the following questions.

- How do you communicate with your friends? *Kuinka kommunikoit ystäväiesi kanssa?*
- How do you communicate with other hearing signing persons? *Kuinka kommunikoit muiden kuulevien viittomakielisten henkilöiden kanssa?*
- How often do you use sign language in private situations? *Kuinka usein käytät viittomakieltä henkilökohtaisissa tilanteissa?*
- How often do you use sign language in official situations? *Kuinka usein käytät viittomakieltä virallisissa tilanteissa?*
- Do you sometimes happen to completely switch from one language to the other one within a sentence/utterance? *Vaihdatko joskus kielestä toiseen saman lauseen/ilmauksen sisällä?*
- Do you sometimes on purpose switch from one language to the other one, e.g. when you are looking for the most precise term/way to express a certain thought? *Vaihdatko joskus tarkoituksellisesti kielestä toiseen, esim. kun etsit tarkinta termiä/tapaa ilmaista tiettyä ajatusta?*
- How important is the use of hands in communication to you? *Kuinka tärkeää sinulle on käsien käyttö kommunikaatiossa?*
- How would you rate your language balance (do you feel that one language is more dominant)? *Kuinka arvioisit oman puhutun kieleesi ja viittomakielesi tasapainon (tuntuuko sinusta, että toinen kieleesi on hallitsevampi kuin toinen)?*
- Do you prefer one language compared to the other? *Suositko toista kieltäsi verrattuna toiseen?*

Appendix 1(2)

Place a cross (x) on the vertical lines below to indicate, in which relation you see your answer to the two extremes:



spoken/
never/
not important

signed/
always/
very important

Appendix 2(1)

Experimental stimuli

primes		antonymic targets		indirectly related targets	
<i>yö</i>	(night)	<i>päivä</i>	(day)	<i>auringonpaiste</i>	(sunshine)
<i>aamu</i>	(morning)	<i>ilta</i>	(evening)	<i>päivällinen</i>	(dinner)
<i>ystävä</i>	(friend)	<i>vihollinen</i>	(enemy)	<i>sota</i>	(war)
<i>vähemmistö</i>	(minority)	<i>enemmistö</i>	(majority)	<i>voittaja</i>	(winner)
<i>aikuinen</i>	(adult)	<i>lapsi</i>	(child)	<i>lelu</i>	(toy)
<i>epäjärjestys</i>	(chaos)	<i>järjestys</i>	(order)	<i>poliisi</i>	(police)
<i>maksimi</i>	(maximum)	<i>minimi</i>	(minimum)	<i>häviö</i>	(loser)
<i>vahvuus</i>	(strength)	<i>heikkous</i>	(weakness)	<i>sairaus</i>	(sickness)
<i>puhtaus</i>	(tidiness)	<i>likaisuus</i>	(dirt)	<i>jätteet</i>	(garbage)
<i>surullisuus</i>	(sadness)	<i>iloisuus</i>	(happiness)	<i>vitsi</i>	(joke)
<i>epäonnistuminen</i>	(adversity)	<i>onnistuminen</i>	(prosperity)	<i>raha</i>	(money)
<i>hyöty</i>	(advantage)	<i>haitta</i>	(disadvantage)	<i>vajaus</i>	(deficit)
<i>harrastelija</i>	(amateur)	<i>ammattilainen</i>	(professional)	<i>kyky</i>	(competence)
<i>alku</i>	(beginning)	<i>loppu</i>	(end)	<i>päämäärä</i>	(aim)
<i>viha</i>	(hate)	<i>rakkaus</i>	(love)	<i>sydän</i>	(heart)
<i>valoisuus</i>	(brightness)	<i>pimeys</i>	(darkness)	<i>yö</i>	(night)
<i>raittius</i>	(soberness)	<i>juoppous</i>	(drunkenness)	<i>olut</i>	(beer)
<i>luottamus</i>	(confidence)	<i>epäluottamus</i>	(distrust)	<i>valhe</i>	(lie)
<i>tyhmyys</i>	(stupidity)	<i>viisaus</i>	(wisdom)	<i>tietosanakirja</i>	(encyclopedia)
<i>mies</i>	(man)	<i>nainen</i>	(woman)	<i>tyttö</i>	(girl)
<i>rauha</i>	(peace)	<i>sota</i>	(war)	<i>ase</i>	(weapon)
<i>sisällä</i>	(indoor)	<i>ulkona</i>	(outdoor)	<i>sää</i>	(weather)
<i>vapaus</i>	(freedom)	<i>vankeus</i>	(captivity)	<i>vankila</i>	(prison)
<i>yksilö</i>	(individual)	<i>ryhmä</i>	(group)	<i>yhtye</i>	(band)
<i>kaupunki</i>	(city)	<i>maaseutu</i>	(countryside)	<i>metsä</i>	(forest)
<i>valhe</i>	(lie)	<i>totuus</i>	(truth)	<i>luottamus</i>	(confidence)
<i>lupa</i>	(permission)	<i>kielto</i>	(prohibition)	<i>rajoitus</i>	(restriction)
<i>tunnottomuus</i>	(numbness)	<i>tunto</i>	(sensation)	<i>rakkaus</i>	(love)
<i>hyväksyminen</i>	(approval)	<i>hylkääminen</i>	(rejection)	<i>surullisuus</i>	(sadness)
<i>erottaminen</i>	(division)	<i>yhdistäminen</i>	(unification)	<i>häät</i>	(marriage)
<i>laillisuus</i>	(legality)	<i>rikollisuus</i>	(delinquency)	<i>vankila</i>	(prison)
<i>poissaolo</i>	(absence)	<i>läsnäolo</i>	(presence)	<i>vieras</i>	(guest)
<i>siviili</i>	(civilian)	<i>sotilas</i>	(soldier)	<i>ase</i>	(weapon)

primes		antonymic targets		indirectly related targets	
<i>valveillaolo</i>	(vigilance)	<i>nukkuminen</i>	(sleep)	<i>uni</i>	(dream)
<i>terveys</i>	(health)	<i>sairaus</i>	(sickness)	<i>sairaala</i>	(hospital)
<i>tuttava</i>	(acquaintance)	<i>vieras</i>	(stranger)	<i>ulkomaa</i>	(foreign country)
<i>kuolema</i>	(death)	<i>syntymä</i>	birth	<i>vauva</i>	(baby)
<i>vuokralainen</i>	(tenant)	<i>vuokranantaja</i>	(landlord)	<i>omistaja</i>	(owner)
<i>lääkäri</i>	(doctor)	<i>potilas</i>	(patient)	<i>kipsi</i>	(cast)
<i>mies</i>	(husband)	<i>vaimo</i>	(wife)	<i>raskaus</i>	(pregnancy)
<i>vanhempi</i>	(parent)	<i>lapsi</i>	(child)	<i>lelu</i>	(toy)
<i>isovanhempi</i>	(grandparent)	<i>lapsenlapsi</i>	(grandchild)	<i>lelu</i>	(toy)
<i>veli</i>	(brother)	<i>sisko</i>	(sister)	<i>tyttö</i>	(girl)
<i>opettaja</i>	(teacher)	<i>oppilas</i>	(pupil)	<i>tutkinto</i>	(graduation)
<i>professori</i>	(professor)	<i>opiskelija</i>	(student)	<i>tutkinto</i>	(graduation)
<i>ostaja</i>	(buyer)	<i>myyjä</i>	(seller)	<i>kauppias</i>	(shop owner)
<i>työntekijä</i>	(employee)	<i>esimies</i>	(boss)	<i>valta</i>	(force)
<i>ohjattava</i>	(PhD student)	<i>ohjaaja</i>	(supervisor)	<i>työnantaja</i>	(employer)
<i>isäntä</i>	(master)	<i>palvelija</i>	(servant)	<i>työntekijä</i>	(employee)
<i>kapteeni</i>	(skipper)	<i>miehistö</i>	(crew)	<i>ryhmä</i>	(group)
<i>hyökkääjä</i>	(aggressor)	<i>puolustaja</i>	(defender)	<i>suoja</i>	(protection)
<i>vastaanottaja</i>	(recipient)	<i>lähettäjä</i>	(sender)	<i>kuuluttaja</i>	(speaker)
<i>velallinen</i>	(debtor)	<i>velkoja</i>	(creditor)	<i>onnistuminen</i>	(prosperity)
<i>työnantaja</i>	(employer)	<i>työntekijä</i>	(employee)	<i>veroilmoitus</i>	(tax return)
<i>puhuja</i>	(speaker)	<i>kuulija</i>	(listener)	<i>hyssytys</i>	(hush)

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Original publications

- I Zachau S, Leppänen PHT, Ervast L, Heinänen K, Suominen K, Lehtihalmes M & Korpilahti P (2012). Semantic representation of speech and signing in codas and interpreters: Behavioral patterns of interaction. *Multimodal Communication* 1(2), 105-125.
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