Dealing with Digits

Arithmetic, Memory and Phonology in Deaf Signers

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Linköping Studies in Arts and Science No. 632
Studies from the Swedish Institute for Disability Research No. 67
Linköping University,
Department of Behavioural Sciences and Learning
Linköping 2014

Linköping Studies in Arts and Science • No. 632
Studies from the Swedish Institute for Disability Research • No. 67

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Distributed by:
Department of Behavioural Science and Learning
Linköping University
SE-581 83 Linköping

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Edition 1:1
ISBN 978-91-7519-235-2
ISSN 0282-9800
ISSN 1650-1128

Cover image: A conjunction of multiplication and subtraction activation across deaf signers and hearing non-signers. Designed by Marie-Louise Lund-Mattsson, Per Lagman and the author.

Printed by LiU-Tryck, Linköping 2014

To Helmer and Valter

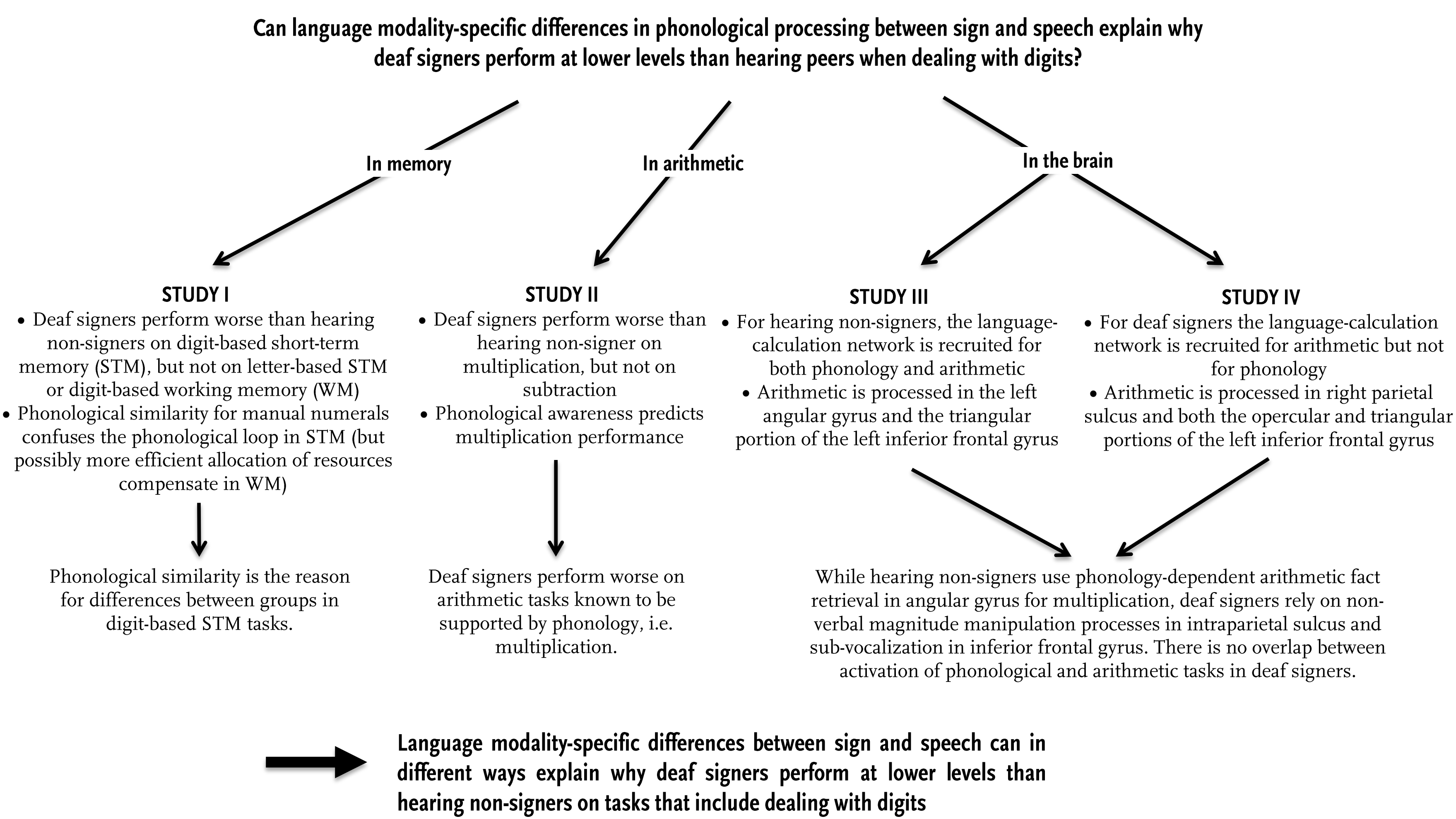
Abstract

Deafness has been associated with poor abilities to deal with digits in the context of arithmetic and memory, and language modality-specific differences in the phonological similarity of digits have been shown to influence short-term memory (STM). Therefore, the overall aim of the present thesis was to find out whether language modality-specific differences in phonological processing between sign and speech can explain why deaf signers perform at lower levels than hearing peers when dealing with digits. To explore this aim, the role of phonological processing in digit-based arithmetic and memory tasks was investigated, using both behavioural and neuroimaging methods, in adult deaf signers and hearing non-signers, carefully matched on age, sex, education and non-verbal intelligence. To make task demands as equal as possible for both groups, and to control for material effects, arithmetic, phonological processing, STM and working memory (WM) were all assessed using the same presentation and response mode for both groups. The results suggested that in digit-based STM, phonological similarity of manual numerals causes deaf signers to perform more poorly than hearing non-signers. However, for digit-based WM there was no difference between the groups, possibly due to differences in allocation of resources during WM. This indicates that similar WM for the two groups can be generalized from lexical items to digits. Further, we found that in the present work deaf signers performed better than expected and on a par with hearing peers on all arithmetic tasks, except for multiplication, possibly because the groups studied here were very carefully matched. However, the neural networks recruited for arithmetic and phonology differed between groups. During multiplication tasks, deaf signers showed an increased reliance on cortex of the right parietal lobe complemented by the left inferior frontal gyrus. In contrast, hearing non-signers relied on cortex of the left frontal and parietal lobe during multiplication. This suggests that while hearing non-signers recruit phonology-dependent arithmetic fact retrieval processes for multiplication, deaf signers recruit non-verbal magnitude manipulation processes. For phonology, the hearing non-signers engaged left lateralized frontal and parietal areas within the classical perisylvian language network. In deaf signers, however, phonological processing was limited to cortex of the left occipital lobe, suggesting that sign-based phonological processing does not necessarily activate the classical language network. In conclusion, the findings of the present thesis suggest that language modality-specific differences between sign and speech in different ways can explain why deaf signers perform at lower levels than hearing non-signers on tasks that include dealing with digits.

Sammanfattning

Dövhet har kopplats till bristande förmåga att hantera siffror inom områdena aritmetik och minne. Särskilt har språkmodalitetsspecifika skillnader i fonologisk likhet för siffror visat sig påverka korttidsminnet. Det övergripande syftet med den här avhandlingen var därför att undersöka om språkmodalitetsspecifika skillnader i fonologisk bearbetning mellan tecken- och talspråk kan förklara varför döva presterar sämre än hörande på sifferuppgifter. För att utforska det området undersöktes fonologisk bearbetning i sifferbaserade minnesuppgifter och aritmetik med hjälp av både beteendevetenskapliga metoder och hjärnavbildning hos grupper av teckenspråkiga döva och talspråkiga hörande som matchats noggrant på ålder, kön, utbildning och icke-verbal intelligens. För att testförhållandena skulle bli så likartade som möjligt för de båda grupperna, och för att förebygga materialeffekter, användes samma presentations- och svarssätt för båda grupperna. Resultaten visade att vid sifferbaserat korttidsminne påverkas de dövas prestation av de tecknade siffrornas fonologiska likhet. Däremot fanns det ingen skillnad mellan grupperna gällande sifferbaserat arbetsminne, vilket kan bero på att de båda grupperna fördelar sina kognitiva resurser på olika sätt. Dessutom fann vi att den grupp teckenspråkiga döva som deltog i studien presterade bättre på aritmetik än vad tidigare forskning visat och de skiljde sig bara från hörande på multiplikationsuppgifter, vilket kan bero på att grupperna var så noggrant matchade. Däremot fanns det skillnader mellan grupperna i vilka neurobiologiska nätverk som aktiverades vid aritmetik och fonologi. Vid multiplikationsuppgifter aktiverades cortex i höger parietallob och vänster frontallob för de teckenspråkiga döva, medan cortex i vänster frontal- och parietallob aktiverades för de talspråkiga hörande. Detta indikerar att de talspråkiga hörande förlitar sig på fonologiberoende minnesstrategier medan de teckenspråkiga döva förlitar sig på ickeverbal magnitudmanipulering och artikulatoriska processer. Under den fonologiska uppgiften aktiverade de talspråkiga hörande vänster-lateraliserade frontala och parietala områden inom det klassiska språknätverket. För de teckenspråkiga döva var fonologibearbetningen begränsad till cortex i vänster occipitallob, vilket tyder på att teckenspråksbaserad fonologi inte behöver aktivera det klassiska språknätverket. Sammanfattningsvis visar fynden i den här avhandlingen att språkmodalitetsspecifika skillnader mellan tecken- och talspråk på olika sätt kan förklara varför döva presterar sämre än hörande på vissa sifferbaserade uppgifter.

Graphical abstract



Grafisk sammanfattning

Kan språkberoende modalitetsspecifika skillnader i fonologisk bearbetning mellan teckenspråk och talspråk förklara varför teckenspråkiga döva presterar sämre än talspråkiga hörande på sifferuppgifter?

I minne

STUDIE I

- Teckenspråkiga döva presterar sämre än talspråkiga hörande på sifferbaserat korttidsminne (KTM), men inte på bokstavsbaserat KTM eller sifferbaserat arbetsminne (AM)
- Tecknade siffrors fonologiska likhet förvirrar den fonologiska loopen i STM (men mer effektiv fördelning av resurser kan kompensera i AM)

→ Skillnaderna i sifferbaserat KTM mellan de båda grupperna beror på tecknade siffrors fonologiska likhet

I aritmetik

STUDIE II

- Teckenspråkiga döva presterar sämre än talspråkiga hörande på multiplikation, men inte på subtraktion
- Fonologisk medvetenhet predicerar multiplikationsprestation

→ Teckenspråkiga döva presterar sämre än talspråkiga hörande på aritmetiska uppgifter som understödjs av fonologi, d.v.s. multiplikation.

I hjärnan

STUDIE III

- Talspråkiga hörande engagerar språk- och räkningsnätverket för både fonologi och aritmetik
- Aritmetik bearbetas i vänster gyrus angularis och gyrus triangularis

STUDIE IV

- Teckenspråkiga döva engagerar språk- och räkningsnätverket för aritmetik, men inte för fonologi
- Aritmetik bearbetas i höger parietalsulcus och i både den triangulära och operculära delen av vänster inferiora frontalgyrus

→ Medan talspråkiga hörande använder fonologiberoende minnesstrategier i gyrus angularis för multiplikation förlitar sig teckenspråkiga döva på ickeverbala magnitudmanipulationer i intrapartietalsulcus samt subvokalisering i inferiora frontalgyrus. Det finns inget överlapp mellan aktivering för fonologi och aritmetik i den döva gruppen.

→ **Språkberoende modalitetsspecifika skillnader mellan tecken- och talspråk kan på olika sätt förklara varför teckenspråkiga döva presterar sämre än talspråkiga hörande på uppgifter som innehåller siffror**

List of papers

This thesis is based on the following papers, referred to in the text by their Roman numerals:

I. Andin, J., Orfanidou, E., Cardin, V., Holmer, E., Capek, C. M., Woll, B., Rönnberg, J. & Rudner, M. (2013). Similar digit-based working memory in deaf signers and hearing non-signers despite digit span differences. *Frontiers in Psychology*, 4:942. Doi: 10.3389/fpsyg.2013.00942

II. Andin, J., Rönnberg, J. & Rudner, M. (2014). Deaf signers use phonology to do arithmetic. *Learning and individual differences*, 32:246-253. Doi: 10.1016/j.lindig.2012.03.015

III. Andin, J., Fransson, P., Rönnberg, J. & Rudner, M. Phonological but not arithmetic processing engages left posterior inferior frontal gyrus. Under revision.

IV. Andin, J., Fransson, P., Dahlström, Ö., Rönnberg, J. & Rudner, M. Deaf signers use magnitude manipulations for multiplication: fMRI evidence. Under review.

Contents

Abbreviations

AG	angular gyrus
ANS	approximate number system
ASL	American Sign Language
BA	Brodmann area
BOLD	blood-oxygen-level dependent
BSL	British Sign Language
CI	cochlear implant
CSP	complex symbol processing
GLM	general linear model
fMRI	functional magnetic resonance imaging
FWE	family wise error
FWHM	full width at half maximum
HIPS	horizontal portion of the intraparietal sulcus
HL	hearing level
IE	inverse efficiency score
IFG	inferior frontal gyrus
MNI	Montreal Neurological Institute
MR	magnetic resonance
MTG	middle temporal gyrus
PGa	anterior portion of parietal area G corresponding to angular gyrus
PGp	posterior portion of parietal area G corresponding to angular gyrus
POPE	pars opercularis of the inferior frontal gyrus
PTRI	pars triangularis of the inferior frontal gyrus
ROI	region of interest
SPL	superior parietal lobule
SPM	statistical parametric mapping
SSL	Swedish Sign Language
SSP	simple symbol processing
STG	superior temporal gyrus

STM	short-term memory
SVC	small volume correction
TCM	triple code model
WASI	Wechsler Abbreviated Scale of Intelligence
WM	working memory

Introduction

Dealing with digits is inevitable in a modern society. Digits are present in everyday life, for example, when the alarm clock awakes us, on traffic signs while driving to work or when remembering a phone number. Arithmetic processing of digits is also required in situations such as deciding how long it will take to drive to work at a certain speed, grocery shopping or when baking a cake. The ability to process and manipulate digits is also closely connected to academic success and efficient processing of digits is important for the individual as it influences and facilitates participation in society.

For profoundly deaf individuals, poor skills in digit processing have been identified within several different domains. For example, they have poorer skills than hearing individuals on arithmetic operations such as multiplication (Nunes et al., 2009) and fractions (Titus, 1995), relational statements (Kelly, Lang, Mousley, & Davis, 2003) and digit-based short-term memory (STM; Bavelier, Newport, Hall, Supalla, & Boutla, 2008; M. Wilson, Bettger, Niculae, & Klima, 1997). Many profoundly deaf individuals use signed language to communicate. There is evidence that the phonological characteristics of signed language influence STM capacity. This may contribute to arithmetic difficulties in deaf signers. The focus of this thesis is on the role of phonology in memory and arithmetic.

Deafness and signed languages

The World Health Organization estimates that the prevalence of all hearing losses is 5.3 % (WHO, 2012). Profound deafness constitutes only a small portion of this population and is usually estimated to have a worldwide prevalence of around 0.1 %. In Sweden, where the main part of the studies in the present thesis was conducted, the proportion of profoundly deaf individuals who use Swedish Sign Language (SSL) as their main mode of communication has been estimated to 0.07 % (Werngren-Elgström, Dehlin, & Iwarsson, 2003). The majority of these individuals have congenital (from birth) or early onset deafness. However, there is no universal definition of deafness. From a medical point of view a person has a profound hearing loss, and is therefore audiologically deaf, when she/he has a pure tone average (PTA) of 81 dB HL or above (WHO, 2014). From a cultural point of view, being Deaf means belonging to the deaf community (Keating, Edwards, & Mirus, 2008). This often includes using signed language as the main mode of communication (Werngren-Elgström et al., 2003). In the cultural view the degree of hearing loss is not important. To distinguish between the medical and the cultural definition "deaf" is usually used to refer to an audiological condition and "Deaf" to deaf people who use signed languages.

The aetiology of deafness can be congenital or acquired. In both types the hair cells that detect sound pressure alterations and convey information to the cochlear nerve are damaged (Arlinger, 2007; Carlson, 2010). Abnormal hair cells at birth can be a result of either an infection affecting the unborn child during pregnancy or a congenital condition that give rise to a hereditary kind of deafness (Arlinger, 2007). Acquired deafness can be caused by trauma, infections, medications or tumours. An important distinction between different types of deafness is made based on age of onset of deafness. Early onset of deafness is usually referred to as prelingual since no, or only very limited, auditory input is available during language acquisition. If, on the contrary, deafness occurs after language production has begun, it is referred to as postlingual deafness. Signed languages are used by individuals with both pre- and postlingual deafness as well as hearing individuals. However, most individuals with postlingual deafness continue to rely on spoken language, sometimes with the support of signs or signed language (Werngren-Elgström et al., 2003). Just as for spoken language, the age of acquisition of signed language influences language performance (Mayberry & Eichen, 1991). Therefore, it is important to distinguish between different signed language backgrounds. Deaf or hearing individuals who are exposed to full and complex signed language from birth, normally from deaf family members, are referred to as native signers. Individuals who encounter signed language during infancy, from birth to 3 years, can be defined as very early signers that normally have a native or native-like skill in signed language. Individuals who started acquiring signed language between 4 and 7 years of age are defined as early signers and between 8 and 14 as late signers (Mayberry, Chen, Witcher, & Klein, 2011; Mayberry & Lock, 2003).

Persons with profound deafness may benefit from hearing aids, but normally other types of strategies, such as lip-reading or signed language, are necessary. For approximately thirty years, cochlear implants (CI) have been used to enable profoundly deaf individuals to perceive sound. A CI is a device that conveys electrical stimulation based on sound into the cochlear nerve. Today, more than

90 % of children born with profound deafness in Sweden are provided with CIs (SOU 2007:87).

The deaf individuals that participate in the studies presented in the present thesis have a congenital deafness of infectious or hereditary origin. Thus, they are all prelingually deaf and have a native or native-like knowledge of SSL or British Sign Language (BSL). They define themselves as Deaf, using SSL or BSL as their primary language of communication. In the present thesis they are referred to as deaf signers.

Signed languages

Signed languages are visual, natural and complete languages with their own vocabulary and grammar, that can be described using the same terminology as spoken languages (Emmorey, 2002). This means that signed languages possess phonology, morphology, syntax and prosody (Emmorey, 2002; Klima & Bellugi, 1976; Sandler & Lillo-Martin, 2006). In contrast to spoken languages, which are produced vocally and perceived auditorily, signed languages are produced manually and perceived visually (Emmorey, 2002). In the case of spoken languages both production and perception are highly sequential, while for signed languages they are mostly simultaneous (Ahlgren & Bergman, 2006). This means that, in signed languages, meaning can be conveyed simultaneously by the use of space, two manual articulators and non-manual markers (Emmorey, 2002). Non-manual markers of signed languages include mouthing, facial expressions and head and shoulder movements that contribute with grammatical information not present in spoken languages. Thus, simultaneous decoding of hands and face is required. Signed language is a perfectly adequate means for language development and deaf children immersed in a signing environment achieve language development milestones in the same order as hearing children acquiring speech (Mayberry & Lock, 2003).

Signed languages develop independently of spoken languages to meet the communication needs of deaf people (Aronoff, Meir, Padden, & Sandler, 2008; Senghas & Coppola, 2001). Thus, they are culturally specific and unrelated to spoken languages (Emmorey, 2002). This means that despite being surrounded by the same spoken language, the signed languages in for example Great Britain and USA are as mutually unintelligible as are for example SSL and BSL. Signed languages do not have an official written form, although there are different writing systems for denoting signed languages (Hopkins, 2008). Therefore, deaf children attending school learn to read in a speech-based language which is often a second language (Musselman, 2000).

Sign language in Sweden

In Sweden, the language used in the deaf community is SSL. Signed languages have always been present in society, but have not always been acknowledged as languages in their own right. During the early 18th century Pär Aron Borg initiated sign-based education for deaf children in Sweden (Eriksson, 1999), but during the second half of the 19th century oralism, with emphasis on lip reading and speech instead of signed language, gained acceptance. During the International Congress on Education of the Deaf in Milan in 1880, it was decided that oralism was the preferred mode of communication for deaf individuals. Hence, SSL was banned from Swedish schools and oralism became the reigning model in Swedish deaf education for one hundred years. In the second half of the 20th century signed language research established the importance of signed language. As the first signed language in the world, SSL was officially recognised as a language in its own right, by the government in 1981 (Prop. 1980/81:100). Two years later a new curriculum for deaf education was introduced and since then all deaf children and their families in Sweden are offered the opportunity to learn SSL (LGr 80, 1983).

During the 1980s, 1990s and the beginning of the 21th century, almost every deaf child in Sweden attended a deaf school during their formal schooling from preschool to high school. This means that they have followed a bilingual curriculum where SSL has been the main mode of communication and written Swedish has been thought of as a second language (e.g. Bagga-Gupta, 2004). At the same time hearing parents of deaf children were offered extensive SSL courses which led to SSL being the communication language in most families with a deaf child during this period (Meristo et al., 2007). This led to a favourable linguistic development for Swedish deaf children of both deaf and hearing parents born in the last three decades of the 20th century (Roos, 2006). This means that these Swedish deaf signers constitute a unique population for whom sign language learning has been optimized (Bagga-Gupta, 2004). This is in contrast to many other deaf signing populations in countries where oral education of deaf children is still common and where there is a larger variability in preferred language in the deaf population.

The introduction of CIs has changed the view of deaf and hard-of-hearing education (SOU 2007:87) because they allow for sound processing in the deaf individual which leads to an increased ability to develop spoken language (Arlinger, 2007). Before the introduction of CIs, all deaf children attended deaf schools, but the access to spoken language offered by the CI has led to deaf children being able to attend mainstream schools (Ibertsson, 2009). This has led to fewer children who use SSL as the main mode of communication. The participants who took part in the studies included in the present thesis were born during the 1970s and 1980s and had SSL-based schooling, making this a unique sample reflecting the relative homogeneity of the Swedish deaf population in terms of language experience.

Swedish Sign Language and fingerspelling

Signed languages, SSL included, have the same principal structure as spoken languages: They have a vocabulary (lexical items) and a system of rules for how items from the vocabulary may be combined, i.e. grammar (Ahlgren & Bergman, 2006). SSL signs are listed in the SSL online lexicon which contains over 15 000 individual signs and is under constant revision (www.ling.su.se/teckenspråks resurser/teckenspråkslexikon, Svenskt teckenspråkslexikon, 2009). Every lexical sign has three manual aspects and sometimes additional mouthing aspects (Ahlgren & Bergman, 2006). The first manual aspect is handshape, which makes up the articulator of the sign (Ahlgren & Bergman, 2006). In SSL there are 37 handshapes (Svenskt teckenspråkslexikon, 2009). The second manual aspect is movement and the third is the location at which the sign is produced (Ahlgren & Bergman, 2006). The mouthing aspects are either specific to signed language or borrowed from the surrounding spoken language.

Although signed languages are not representations of either spoken or written languages, many signed languages make use of manual alphabets to represent letters (Brentari, 1998). The use of these manual alphabets is called fingerspelling and is used productively to fill lexical gaps, e.g. place and proper names, for foreign words or to describe how words are spelled (Bergman & Wikström, 1981; Sutton-Spence & Woll, 1999). The extent to which fingerspelling is used differs considerably between different signed languages (Morere & Roberts, 2012; Padden & Gunsauls, 2003). In American Sign Language (ASL), fingerspelling is used extensively and fingerspelled words constitute up to 35% of the signed discourse, whereas it is used very sparsely in Italian Sign Language (Padden & Gunsauls, 2003). BSL and SSL, on which the studies in this thesis are based, both resemble ASL in their extensive use of fingerspelling, even though there are no studies quantifying precisely the extent to which it is used.

The importance of studying signed languages

Studying linguistic and cognitive mechanisms of signed languages is of importance for extending both applied and basic knowledge. Within basic research we can capitalize on the nature of signed languages to address language modality-specific as well as language modality-general cognitive issues that cannot be addressed in any other way (Rudner, Andin, & Rönnberg, 2009; Rönnberg, Söderfeldt, & Risberg, 2000). For example, comparing functions in the sign-based visual domain and the speech-based auditory domain makes it possible to investigate the extent to which mechanisms are dependent on the modality of the language used. In the field of applied research, the findings from investigation of the mechanisms of language and cognition for signed languages may lead to the development of new methods for teaching profoundly deaf children and adults.

Phonology

Phonological representations are abstract representations of sublexical units that are stored in long term memory (LTM) and can be retrieved in response to written, signed or spoken languages as well as pictures (Cutler, 2008). Phonological processing abilities support articulation, speech perception, phonological awareness (including the ability to recognize, identify and/or manipulate sublexical units) and phonological memory (Anthony et al., 2010).

Signed language phonology

In this thesis, phonology is defined according to Sandler and Lillo-Martin (2006): "as the level of linguistic structure that organizes the medium through which language is transmitted". Thus, while spoken language phonology is concerned with the combination of sounds to form utterances, signed language phonology is concerned with how the components of the signs are put together with respect to the three manual aspects of the sign, i.e. handshape, location and movement (Liddell, 2003). Hence, these three aspects form the phonological components of the sign, and signs that share at least one of these features are considered to be phonologically similar (Klima & Bellugi, 1976; Sandler & Lillo-Martin, 2006). On a meta-linguistic level this may be comparable with phonologically similar onset and rime of spoken words. In SSL, phonological similarity can be exemplified by the manual numeral for the digit "1" and the fingerspelled letters "L" and "Z" (figure 1). The handshape for these three hand configurations share the same handshape and can thus be considered to be phonologically similar, despite differences in orientation. As is the case in spoken language, signed language phonology is used as the basis for poetry (Klima & Bellugi, 1976; Sutton-Spence, 2001) and nursery rhymes (Blondel & Miller, 2001).

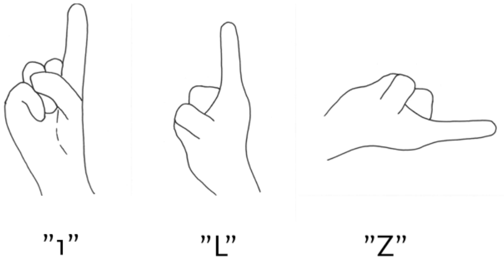


Figure 1. Signed language phonology. The manual numeral for the digit 1 and fingerspelled letter L and Z in SSL share the same handshape, while differing in orientation. The three signs are phonological similar.

Neural representation of spoken languages

Neurophysiologically, spoken language processing follows two main neural streams in the brain running on each side of the Sylvian fissure, constituting the perisylvian language network (figure 2; Hickok & Poeppel, 2007). Both streams are found bilaterally but with a left lateralized predominance (Specht, 2013). Each stream can be further subdivided into two pathways that originate from the superior temporal gyrus (STG), which is engaged in early cortical stages of language processing (Friederici & Gierhan, 2013; Hickok & Poeppel, 2004, 2007). The posterior dorsal pathway is thought to be concerned with auditory-motor integration and projects via the intraparietal cortex (including angular gyrus) to the premotor cortex. The anterior dorsal pathway is suggested to connect two structures important for complex syntactic processing projecting from STG to pars opercularis of the left inferior frontal gyrus (POPE). The ventral streams are suggested to be concerned with semantic processing and consist of a short pathway connecting STG and pars triangularis of the left inferior frontal gyrus (PTRI) and a long pathway connecting STG with both PTRI and middle temporal gyrus (MTG), angular gyrus (AG) and occipital cortices in the temporo-parieto-occipital junction.

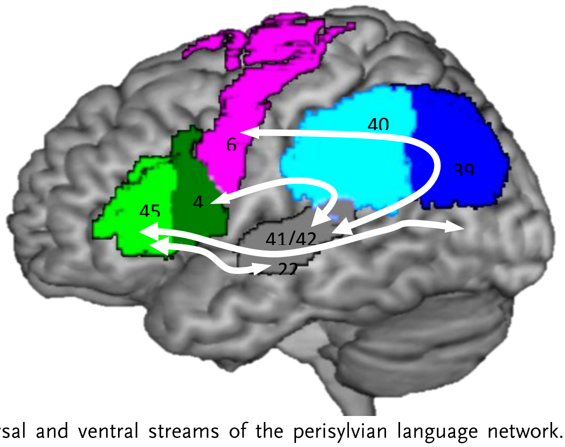


Figure 2. Dorsal and ventral streams of the perisylvian language network. All four pathways originate in the auditory cortex (BA 21/41/42). The posterior dorsal pathway runs through the intraparietal cortex to the premotor cortex and is thought to be involved in auditory-to-motor mapping in speech repetition, while the anterior dorsal pathway carries syntactic information about complex sentence structure to pars opercularis (BA44). The fronto-temporo-occipital pathway of the ventral stream is suggested to be involved in semantic processing and runs from the auditory cortex to pars triangularis (BA45) and to the occipital cortex. The final ventral pathway is thought to carry syntactic information from the anterior part of auditory cortex to pars triangularis (Friederici & Gierhan, 2013; Hickok & Poeppel, 2007).

Several structures in the perisylvian language network have been implicated in phonological processing. Left POPE, i.e. the posterior portion of Broca's area, is involved in phonological tasks, such as rhyme judgement (Bitan et al., 2007; Burton, LoCasto, Krebs-Noble, & Gullapalli, 2005; Hickok, 2009) and verbal short-term memory (Hickok, 2009; Hickok & Poeppel, 2004). Evidence of phonological processing has also been found in the anterior portion of Broca's area, i.e. lPTRI (Rudner, Karlsson, Gunnarsson, & Rönnberg, 2013). However, this region has primarily been associated with semantic processing (Poldrack et al., 1999; Vigneau et al., 2006). Rhyme judgement has further been found to activate lAG, which has been suggested to play an important role in orthographic-to-phonological conversion (Booth et al., 2004). The superior parietal lobule (SPL), which borders on the posterior part of the perisylvian language network, has also been shown to be involved in phonological processing (Shivde & Thompson-Schill, 2004).

Neural representation of signed languages

Evidence from both electrophysiological and brain imaging studies has shown similarities in the engagement of neural networks across the language modalities of speech and sign during phonological processing, suggesting that phonology may be represented amodally or supramodally (Macsweeney, Goswami, & Neville, 2013; MacSweeney, Waters, Brammer, Woll, & Goswami, 2008). However, there are modality-specific elements in phonological processing, evidenced by activation modulation relating to language-modality and hearing status (MacSweeney et al., 2008). Thus, partly different patterns of phonological activation have been found for sign and speech (MacSweeney et al., 2008; Rudner et al., 2013). In phonological tasks, which required matching of signed labels with pictures, an area anterior/dorsal to Broca's area, BA46, was found to be activated for deaf signers (MacSweeney et al., 2008; Rudner et al., 2013). In contrast, the corresponding task, which required matching the spoken labels of picture pairs and determining whether they rhymed, showed classical Broca activation in hearing non-signers. Therefore, the evidence suggests that signed language phonology engages an area anterior/dorsal to that of speech phonology. Behavioural findings suggest that there is a closer relationship between semantic and phonological processing in signed compared to spoken languages (Marshall, Rowley, & Atkinsson, 2013). In hearing individuals, abstract semantic processing has been found in the anterior portions of Broca's areas and in BA46 (Nagels, Chatterjee, Kircher, & Straube, 2013; Poldrack et al., 1999). Thus, the phonology-related activation found anterior to Broca's area for deaf signers may reflect a shift in the relative balance of semantic and phonological processing in signed language in the left inferior frontal gyrus (IFG; Hagoort, 2005; Marshall et al., 2013; Rudner et al., 2013). This is further supported by evidence showing that semantic production and comprehension tasks engage similar frontal regions for sign and speech in hearing signers (Emmorey, McCullough, Mehta, & Grabowski, 2014; MacSweeney et al., 2002).

In conclusion, there is diverging evidence about the extent to which language processing is modality-specific, especially when it concerns phonology where there is a potential confounding semantic factor in many of the previous studies. In the imaging studies included in the present thesis, we used a task that isolated phonological processing and precluded use of a semantic route to phonology.

Assessing phonology across modalities

There are many tests designed to test phonological processes (e.g. Anthony et al., 2010). A common way to invoke phonological processes in hearing individuals is by asking them to judge whether two orthographically dissimilar words rhyme (for a review see Classon, Rudner, & Rönnberg, 2013). If the two words are presented as text, as pictures of objects or as symbols, rhyme judgement require activating phonological representations of the words. For signed languages, phonological processing can be invoked by asking whether two signs share one or more of the three phonological characteristics of handshape, location and movement (Sandler & Lillo-Martin, 2006). As signed languages lack orthography, phonological processing in signed languages has often been assessed using picture-based tasks (MacSweeney et al., 2008; Rudner et al., 2013). However, digits and letters can be used to invoke phonological similarity judgements, based on fingerspelling. SSL shares a set of handshapes with both the manual alphabet and the manual numerals. Therefore, phonological judgement for signs can be based on pairing letters and digits and asking whether the manual equivalents share a handshape. In spoken Swedish there is a corresponding phonological overlap between digits and letters, and thus similar tasks based on identical stimuli can be used in Swedish and SSL. Another benefit of this approach is that it provides a phonological judgement task that is devoid of semantic content, making it a purely phonological task in both languages. This approach is used in the studies presented in the present thesis.

Memory

Phonological processing is closely connected to memory both in terms of semantic long-term memory that contains phonological representations and phonological short-term memory that is activated in speech perception and production as well as in learning new words (Baddeley, 2003). Memory can be divided into long-term memory (LTM) and immediate memory, which differ, not only in duration, but also in capacity and the way in which memories are stored (Braisby & Gellatly, 2012). LTM is a more or less permanent memory store that has a large capacity and LTM encoding requires neurobiological changes at the cellular level (Baddeley, 2012; Kandel, Schwartz, Jessell, Siegelbaum, & Huspeth, 2012). LTM can be divided in episodic memory that deals with memory of autobiographical events, semantic memory that deals with factual memory, including phonological representations, and procedural memories that include memory for performance of actions. Immediate memory is a short-term capacity-limited system for which encoding involves neurobiological modifications rather than cellular changes (Baddeley, 2012; Nyberg, 2008). The two main functions of immediate memory are temporary storage and processing of information (Baddeley, 2012). These two interrelated functions are typically divided into short-term memory (STM), which is restricted to temporary storage, and working memory (WM), which includes simultaneous storage and processing. The focus of the present thesis is on digit-based STM and WM.

Short-term and working memory

STM and WM refers to two interrelated but separable functions of a limited-capacity system and thus the two concepts are acknowledged as being distinct from each other (Unsworth & Engle, 2007). Thus, the key characteristic of WM is the function of combining temporary storage and processing of information while STM is limited to the temporary storage of information (Baddeley, 2012; Baddeley & Hitch, 1974). These short-term stores are essential for performing complex cognitive tasks that require storage and processing of information (Baddeley, 2003; Unsworth & Engle, 2007), such as language comprehension (Baddeley, 2003) and arithmetic (Gathercole, Alloway, Willis, & Adams, 2006). Overall, WM capacity has been shown to be a better predictor of overall cognitive skill than STM capacity (Unsworth & Engle, 2007).

The understanding of WM has been captured by several different theories that broadly can be divided into modular and functional theories (Baddeley, 2010, 2012). In modular, or system, theories, WM is divided into separate subsystems that involve somewhat distinct neural systems (e.g. Baddeley, 2012). Functional, or capacity, models, focus instead on the system as a whole and the total amount of mental resources available (e.g. Just & Carpenter, 1992). More recent theories, such as flexible resource models, incorporate elements from both modular and functional models and suggest that resources can be allocated in a continuous fashion with a trade-off between the quality and quantity of the representations (Fukuda, Awh, & Vogel, 2010).

However, the most influential WM theory during the past decades is the modular multicomponent model described by Baddeley and Hitch (Baddeley, 2003, 2012; Baddeley & Hitch, 1974). This model suggests a domain-general central component, the central executive, that directs and divides attention between two domain-specific slave systems, the phonological loop and the visuospatial sketchpad (for a review see Rudner & Rönnberg, 2008b). Also included in the model is an episodic buffer that can hold and bind information from different sources including LTM and the two slave systems. The visuospatial sketchpad can be divided into two separate subsystems that store and manipulate visual and spatial information, respectively (Repovš, 2006). The phonological loop contains two components. The first, a passive temporary storage component, holds phonological information for a few seconds, unless enhanced by the second component, the active articulatory rehearsal component, whose function is to revive the decaying representations by sub-vocal repetition (Baddeley, 2003). The effectiveness of the phonological loop is modulated by the content of the phonological information at hand. Thus, phonological similarity of information causes confusable traces (the phonological similarity effect) and words that take longer to pronounce take up more space in the loop (the word length effect), decreasing its capacity. Words are stored in the phonological loop while non-verbal information is stored in the visuospatial sketchpad. Hence, phonological processing is dependent on the capacity of the phonological loop. For example, the association between phonological awareness in children and WM/STM capacity has been suggested to reflect the crucial role for the short-term store in learning the phonological form of novel words, which is the first step towards building up vocabulary in the form of long-term phonological representations (Gathercole et al., 2006).

Assessing short-term and working memory

Both WM and STM are typically assessed using span tasks, where the span is the maximum number of items that can be stored in memory. WM capacity is often measured by complex dual span tasks, such as reading span, counting span or operation span in which there is a high load on both the processing and the storage component (Unsworth & Engle, 2007). Of these three tests, operation span, which requires solving arithmetical operations and simultaneously remembering specific items, loads most strongly on overall WM capacity (Unsworth & Engle, 2007) and has the highest correlation with measures of general intelligence (Unsworth & Engle, 2005).

STM capacity is typically assessed using simple spans, such as digit and letter span, which require encoding and recall of digit and letter strings. Simple spans put a high load on the storage component, and low load on the processing component. A variant of the digit and letter span is the backward digit and letter span, which requires reversing the sequence of presented items at recall. Backward spans are sometimes used as a measure of WM capacity because they are suggested to rely on more complex, visuo-spatial, processes than forward spans, which rely on phonological processes (Li & Lewandowsky, 1995).

However, manipulation of the phonological properties of the to-be-remembered items does not show any interaction with recall order, suggesting similar processing requirements for both tasks (Rosen & Engle, 1997). Rosen and Engle (1997) also showed that there was no difference between forward and backward spans in terms of predicting general cognitive abilities. Further, they showed that, in a structural equation model, both forward and backward spans loaded on the same STM component while operation span, reading span and counting span loaded on a WM component. Thus, they suggested that forward and backward recall require a similar level of processing complexity, disqualifying backward span as a measure of WM. Therefore, in the present thesis, digit and letter span, both forward and backward, are used as tests of STM which tax the phonological loop, and operation span as a test of WM.

Short-term and working memory in deaf individuals

There are only a few studies on WM in deaf signers, but they all point towards equal capacity irrespective of whether the items to be processed are signs or words (Boutla, Supalla, Newport, & Bavelier, 2004; Rudner et al., 2013). However, a substantial body of literature has shown that deaf signers perform at a lower level than hearing speakers on the most common tests of STM, i.e. digit span. Even when the test is administered in signed language to deaf signers, and despite equal performance on other cognitive tasks between deaf signers and hearing speakers, the difference in digit span persist (Bavelier, Newport, et al., 2008; Pintner & Paterson, 1917; M. Wilson et al., 1997). This difference in capacity has led to the conclusion that deaf persons have poorer STM than hearing speakers (e.g. Conrad, 1972; Hanson, 1982; Logan, Maybery, & Fletcher, 1996). However, this lower capacity for signs has been shown to apply to both hearing and deaf signers. Hearing persons that are fluent in both spoken and signed language have been shown to have poorer STM when tested with signed language than spoken language (Boutla et al., 2004; Hall & Bavelier, 2011; Rönnberg, Rudner, & Ingvar, 2004). Hence, the difference is most likely language modality-dependent and does not reflect over-all cognitive capacity, neither is it an effect of deafness.

Several possible explanations of shorter digit span for signers compared to speakers have been proposed. It has been suggested that the use of digit span as a measure of STM introduces a phonological similarity effect for signers (M. Wilson et al., 1997; M. Wilson & Emmorey, 2006b). This effect arises because numeral signs representing digits are phonologically similar in many signed languages, including SSL and BSL (figure 3), as they share location, movement and to some extent handshape, whereas in most spoken languages, including English and Swedish, digit names are phonologically dissimilar. Letter span has been suggested as a more neutral test as letters can be chosen to minimize phonological similarity (Boutla et al., 2004). Indeed, when matching the material for phonological similarity, Wilson and Emmorey (2006b) reported similar letter span for deaf signers and hearing non-signers. However, evidence of shorter letter span for deaf signers compared to hearing non-signers has also been reported (Bavelier, Newport, Hall, Supalla, & Boutla, 2006). Hence, results from studies on letter span are inconclusive.

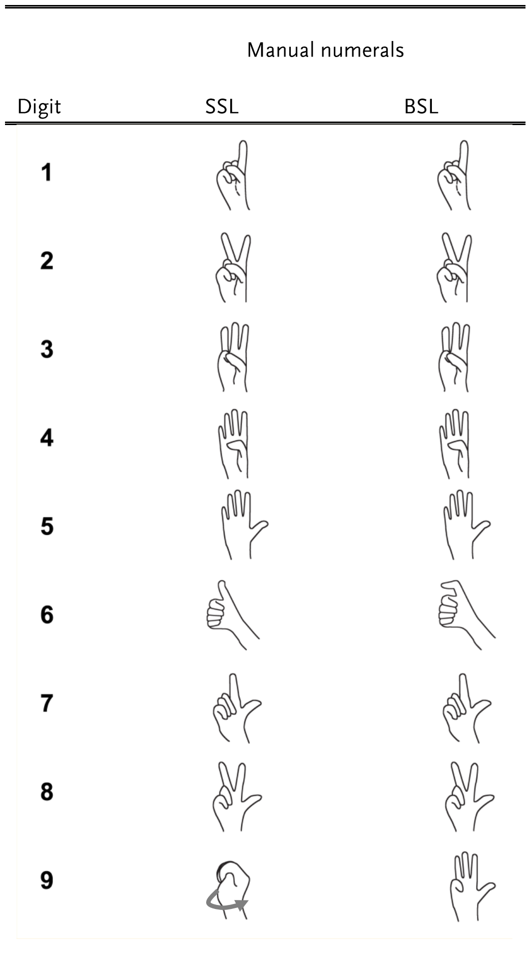


Figure 3. The phonological similarity of manual numerals. The manual numerals in signed languages, here shown for Swedish Sign Language (SSL) and British Sign Language (BSL), display phonological similarity within languages as the signs share location, lack movement (except "9" in SSL) and differ very little in handshape. Note also the phonological similarity across languages.

Further, span tasks require serial recall and thus make temporal processing demands. It has been suggested that temporal processing demands are another potential source of STM span differences between signers and speakers. However, when recall order is free, no differences are found between STM for spoken and signed language (Bavelier, Newport, et al., 2008; Hanson, 1982; Rudner & Rönnberg, 2008a). Recent studies investigating STM for signed language have used signed stimuli and response for signing people and auditory stimuli with spoken response for hearing people as this allows individuals to perform the task in their first language which may lead to optimized performance for both groups (Boutla et al., 2004; Hall & Bavelier, 2011; M. Wilson & Emmorey, 1998, 2006b). However, the disadvantage of this approach is that it introduces a confound related to the persistence of sensory memory traces, where auditory memory traces last longer than visual memory traces (Darwin, Turvey, & Crowder, 1972; Koo, Crain, LaSasso, & Eden, 2008; Sperling, 1960). Thus, hearing individuals can take advantage of a more capacious sensory buffer that takes the load off the rehearsal process (Cowan, 2000). In the present thesis we used printed stimuli and written response for both groups in an attempt to reduce this discrepancy.

Neural representations of STM and WM

Neurobiologically, STM and WM tasks engage a fronto-temporo-parietal network that is largely similar for deaf and hearing individuals (for a review see Rudner et al., 2009). However, there are language modality-specific differences. STM and WM tasks contrasting speech to signs show an increased engagement of the auditory cortices for speech compared to sign, probably relating to auditory processing (Pa, Wilson, Pickell, Bellugi, & Hickok, 2008; Rudner, Fransson, Ingvar, Nyberg, & Rönnberg, 2007; Rönnberg et al., 2004). For sign compared to speech, net activations have been found in the SPL and in the temporo-occipital region, possibly reflecting the spatial component of signed language. Importantly, similar findings for deaf and hearing signers suggest that the differences between sign and speech are related to language-modality rather than to sensory deprivation (Rudner et al., 2009).

Further, language modality-specific differences have also been identified during different stages of the STM task. It has been shown that deaf signers, compared to hearing non-signers, show less net parietal activation during STM encoding and rehearsal and more net activation during the response phase (Bavelier, Newman, et al., 2008). Therefore, Bavelier et al (2008) suggested that deaf signers tend to rely on passive memory stores while hearing non-signers use active strategies during the two initial phases.

Arithmetic

Mathematics is an umbrella term that includes several different abilities concerning quantities, space and numbers. It is divided into sub-disciplines such as arithmetic, algebra, calculus, trigonometry and geometry. Arithmetic is the most elementary branch of mathematics and concerns the basic operations of numbers, i.e. addition, subtraction, multiplication and division, but requires nevertheless, competence in several numerical processing domains. The ability to perform calculation involves multiple simultaneously engaged cognitive functions (Ashcraft, 1992; McCloskey, Caramazza, & Basili, 1985). These abilities include, among others, spatial manipulation of digits, retrieval of arithmetic facts, language and phonological processing and WM (Alloway & Passolunghi, 2011; Fehr, 2013).

Arithmetic is, hence, related to both phonological processing and WM capacity. The quality of long-term phonological representations are related to the efficiency with which arithmetic problems can be solved (De Smedt, Taylor, Archibald, & Ansari, 2010) and the dual process of breaking down and process various stages of an arithmetic problem is dependent on WM capacity (Hitch, 1978).

Basic competences underlying arithmetic processing

There are at least two different basic number processing abilities that have been suggested to be important for the development of calculation abilities in general; the approximate number system (ANS) and the small numerosity system (Butterworth, 2010; Piazza, 2010). ANS is the ability to represent numbers as approximate magnitudes along an analogue mental number line (Butterworth, 2010; Dehaene, 1997; Piazza, 2010). ANS is characterized by a rapidly increasing ability during the first years of life to approximately discriminate between sets of items of different magnitude (Piazza, 2010). The mental number line has been shown to be logarithmic in nature as indicated by the distance effect and the problem size effect. The distance effect refers to the phenomenon that the smaller the distance between two numbers, in terms of relative magnitude, the more difficult it is to separate them, and the problem size effect refers to the phenomenon that larger numbers are more difficult to distinguish than smaller numbers separated by the same distance (Dehaene, 1992).

The small numerosity system, sometimes also called the object tracking system or the parallel individuation system, is the primary system used to represent small numbers, typically in the range one to four (Butterworth, 2010). In contrast to ANS, which is considered domain-specific, the small number system is domain-general (Piazza, Fumarola, Chinello, & Melcher, 2011). The ability to quickly and accurately distinguish between sets of one to four items is called subitizing and is the main feature of the small numerosity system.

The ability to identify the exact number of items in larger sets involves the combination of approximate representation along the mental number line and exact representations of small numbers (Piazza, 2010). There are different theories concerning how these two competences are combined. One theory suggests that a third system, called the numerosity coding system, is responsible for exact number representation (Butterworth, 2010). Another suggestion is that language mediated modifications of the pre-existing representations of approximate quantities result in representations of exact numbers (Piazza, 2010). Practically, counting is learned through one-to-one correspondence, where each number-word will apply to one specific item in a set and subsequently the child learning to count will learn that the last word used when counting a set, the cardinal value, represents the total number of items (Jordan, Glutting, & Ramineni, 2010). The ability to represent numbers with Arabic digits appears as the final step in the development of counting competence (A. Wilson & Dehaene, 2007).

When the steps described above have been achieved, counting words are successfully mapped onto the mental number line and numerical knowledge, or number sense, has been established.

Arithmetic processing

When the basic skills of counting have been mastered, they can be used to perform simple addition first, and other arithmetic operations thereafter. Initially, counting strategies and magnitude manipulations within ANS are used, but these are eventually complemented and partly replaced by memory-based arithmetic fact retrieval strategies (A. Wilson & Dehaene, 2007). In older children and adults a combination of arithmetic fact retrieval and magnitude manipulation are used to solve arithmetic operations depending on the operation at hand and individual competence (Dehaene, Piazza, Pinel, & Cohen, 2003; Fehr, 2013; Lee & Kang, 2002). Prelearned facts are thought to be accessed through lexical representation in a phonological code store in LTM and magnitude information is thought to be accessed through online processing of a visual-analogue code. The arithmetic operations of multiplication, subtraction and addition can be considered to represent a continuum where multiplication, which relies most strongly on arithmetic fact retrieval, and subtraction, which relies most on magnitude manipulation, represent the two extremes. This notion is supported by a stronger involvement of language processing areas in multiplication than in addition and subtraction and in addition compared to subtraction (Benn, Zheng, Wilkinson, Siegal, & Varley, 2012; Lee & Kang, 2002; Zhou et al., 2007).

Several models of number processing have been formulated. For example, McCloskey's model proposes that all numerical operations, including magnitude manipulation and arithmetic fact retrieval rely on one and the same mental platform of abstract quantity representations (McCloskey, 1992). The modular processing model, by Campbell, proposes that different forms of representation are used for different operations (Campbell, 1994, 1997). However, perhaps the most influential account of number processing is Dehaene's triple code model (TCM; Dehaene, 1992; Dehaene et al., 2003). The TCM combines behavioural and neuroimaging evidence and proposes, in line with the modular processing model, that different forms of representation are used for different types of operation and that there are three different kinds of number codes in the human brain that are used and processed differently depending on the task at hand (Dehaene, 1992; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Dehaene et al., 2003).

Neural representations of arithmetic processing

For basic competences underlying arithmetic processing, brain imaging has shown that the bilateral intraparietal sulcus is activated for different tasks related to ANS, such as number comparisons (Eger et al., 2009) and approximate calculation (Dormal, Andres, Dormal, & Pesenti, 2010). Non-overlapping regions posterior to those involved in ANS, in the posterior parietal and occipital cortices, have been shown to be involved in the small numerosity system. In particular, the right parietal lobe is involved in subitizing and estimation while the left parietal lobe is involved in symbol processing (Ansari, Lyons, Van Eimeren, & Xu, 2007).

The most influential neurobiological model of arithmetic processing is the TCM (Dehaene et al., 2003). The three number codes that constitute the basis of the model form three separate representational systems that have been associated with different delimitated brain areas (figure 4, table 1).

Numbers are encoded as strings of Arabic numerals within the ***visual/attentional system*** that depend on the posterior SPL. This region is active during number comparison (Pinel, Dehaene, Rivière, & LeBihan, 2001), approximation (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999) and counting (Piazza, Mechelli, Butterworth, & Price, 2002) but is not number specific, since it plays a central role in many visuospatial tasks including mental rotation, spatial working memory and orienting of attention (Koenigs, Barbey, Postle, & Grafman, 2009; Simon, Mangin, Cohen, Le Bihan, & Dehaene, 2002).

The numerals are further represented verbally within the ***verbal system***, which depend on the lAG (Dehaene et al., 2003). This system belongs to the language network, but is involved in calculation tasks where there is a need for verbal coding and processing, such as arithmetic fact retrieval. Thus, this brain region is recruited more for exact, compared to approximate, calculation (Dehaene et al., 1999), more for small, compared to larger, digits (Stanescu-Cosson et al., 2000), more for multiplication than addition (Zhou et al., 2007) and subtraction (Lee & Kang, 2002) and more for addition than subtraction (Benn et al., 2012). It has also been suggested that the lIFG is involved in calculation tasks related to verbal processing (Dehaene et al., 2003). However, activation in this region has been suggested to be related to subvocalization or syntactic processing that is invoked in order to comprehend the arithmetic problem rather than calculation per se (Rickard et al., 2000). The association between verbal and arithmetic tasks is further strengthened by a relation between phonological awareness and both retrieval-based multiplication problems and small compared to large problems (De Smedt et al., 2010). This suggests that efficient arithmetic fact retrieval is related to the quality of phonological representations. This is especially true for children and for adults who experience difficulties in obtaining automatic arithmetic processing (De Smedt et al., 2010; Grabner et al., 2007).

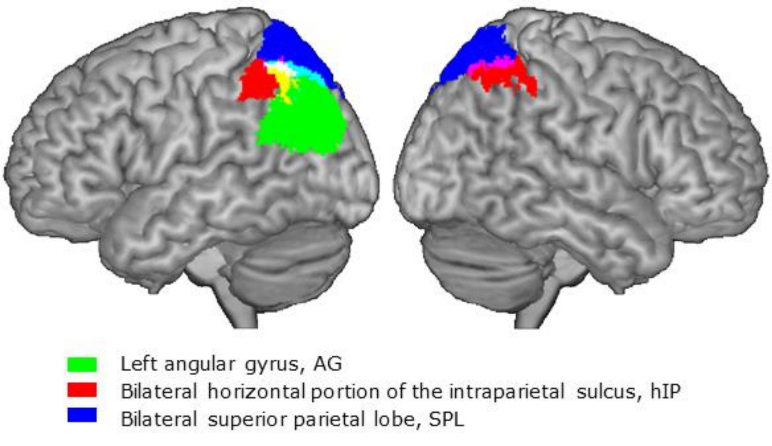


Figure 4. The localization of the three parietal areas included in the triple code model. Numbers are encoded as strings of Arabic numerals within the visual/attentional system in the bilateral superior parietal lobe (blue), these numerals are represented verbally within the verbal system in the left angular gyrus (green) and the magnitude of the numbers is represented in the quantity system in the bilateral horizontal portion of the intraparietal sulcus (red; Dehaene et al., 2003). (The areas are rendered on a model brain which is why overlap due to different depth of the areas are coloured in magenta, yellow and light blue.)

Within the ***quantity system***, which depends on the bilateral horizontal portion of the intraparietal sulcus (HIPS), representations relating to the magnitude of numbers are processed (Dehaene et al., 2003). This system is closely connected to the ANS and is involved in magnitude manipulation along the mental number line. Activation in this region has been reported for subtraction compared to multiplication (Chochon, Cohen, van de Moortele, & Dehaene, 1999; Dehaene et al., 2003), for approximate compared to exact calculation (Dehaene et al., 1999) and for number words compared to other words (Dehaene & Cohen, 1995). The quantity system can also be recruited when arithmetic fact retrieval fails (Dehaene & Cohen, 1995). The number specificity of this region makes it a candidate for a number-essential region (Dehaene et al., 2003).

Table 1. Overview of the three systems of the triple code model.

System	Code	Brain region	Main task	Subtasks
Visual/attentional	Arabic numerals	bilateral SPL	Attention	Number comparison Approximation Counting
Verbal	Verbal numerals	left AG	Arithmetic fact retrieval	Exact calculation Multiplication Small digits
Quantity	Analogue magnitude numerals	bilateral HIPS	Magnitude manipulation	Approximate calculation Subtraction Number words

SPL superior parietal lobule; AG angular gyrus; HIPS horizontal portion of the intraparietal sulcus

Several other parts of the brain have also been found to be activated by different arithmetic tasks. Arithmetic has been found to induce activation in right inferior parietal areas, left precuneus, left superior parietal areas and multiplication has been shown to activate bilateral medial frontal and cingulate cortices (Kong et al., 2005). Further, there is a WM involvement in arithmetic that increases with increased complexity and has been associated with increasing recruitment of prefrontal areas (Fehr, Code, & Herrmann, 2007; Kong et al., 2005).

Arithmetic in deaf individuals

The literature suggests that many deaf individuals lag several years behind hearing peers in formal mathematical skills (Bull, Marschark, & Blatto-Vallee, 2005; Traxler, 2000), despite comparable general cognitive abilities. The delay has been shown to occur before formal schooling starts and persists throughout adulthood (Bull et al., 2011; Kritzer, 2009). However, there do not seem to be any major differences between deaf and hearing individuals in basic competences such as subitizing (Bull, Blatto-Vallee, & Fabich, 2006), magnitude processing (Bull et al., 2006) and number comparisons (Bull et al., 2005), indicating that deaf individuals have access to the visual/attentional system and the quantity system of number processing. In fact, deaf children outperform hearing children on spatial problems related to the visual/attentional system (Zarfaty, Nunes, & Bryant, 2004) and on non-symbolic subtraction tasks (Masataka, 2006). Instead, tasks on which differences have been found between deaf and hearing individuals seem to be related to the verbal system. Specifically, hearing individuals perform better than deaf signers on relational statements (e.g. less than, more than, twice as many as; Kelly et al., 2003; Serrano Pau, 1995), arithmetic words problems that require reading (Hyde, Zevenbergen, & Power, 2003), fractions (Titus, 1995) and multiplicative reasoning (Nunes et al., 2009). The establishment of arithmetic facts and verbal number representations in deaf individuals might be altered or delayed, due to weaker associations between concepts and a high reliance on item-specific, compared to relational, processing (Marschark, 2003; Marschark, Convertino, McEvoy, & Masteller, 2004). Further, due to the simultaneous manner of signed languages, deaf children can make use of a "double counting" strategy where the two hands are used to represent different digits when modelling problems (Foisack, 2003). Such a strategy is effective on a surface level, but is possibly a hindrance when automatizing arithmetic facts (i.e. learning the multiplication tables).

The only imaging study to date that has investigated neural correlates for numerical processing in deaf signers, showed that learning numerals from a new signed language activates a network similar to that found for numerical processing in hearing individuals (Masataka, Ohnishi, Imabayashi, Hirakata, & Matsuda, 2006). However, there are no imaging studies investigating arithmetic in deaf signers. Given that arithmetic tasks relating to the verbal system of numerical processing appear to be problematic for deaf individuals, it is likely that neuronal circuits used when solving arithmetic problems differ between deaf and hearing individuals. Evidence suggests that deaf signers rely on the verbal system to a lesser extent than hearing individuals for arithmetic processing which would lead to less lAG involvement during such tasks, possibly with a greater involvement of supporting articulatory circuits in the frontal lobe due to less automatized arithmetic fact retrieval.

Summary

Deafness has been associated with a poor ability to deal with digits. This applies to both arithmetic and STM. In particular, deaf individuals have difficulties with arithmetic tasks that require language processing. Deaf signers also perform worse than hearing peers on digit span tests, possibly due to the greater phonological similarity of numeral signs compared to spoken digits. In deaf signers, the link between phonological processing and digit-based STM/WM on the one hand and mental arithmetic on the other has not hitherto been explored. The purpose of this thesis is to explore these associations using behavioural and neuroimaging methods.

General aims

The overall aim of the present thesis was to examine the role of phonological processing in digit-based arithmetic and memory tasks in adult deaf signers in order to find out whether language modality-specific differences in phonological processing between sign and speech can explain why they perform at lower levels than hearing peers when dealing with digits. To explore this aim, both behavioural and neuroimaging methods were used. Specific aims in the behavioural papers were to investigate digit-based WM and STM (paper I) and the relation between phonological and arithmetic processing (paper II). For the neuroimaging papers, the specific aims were to investigate the engagement of the language-calculation network for phonology and arithmetic in hearing non-signers (paper III) and in deaf signers (paper IV) and to investigate whether the network is recruited differently for the two groups (paper IV).

The following hypotheses were tested:

- Speech-based representations of digits are phonologically distinct whereas sign-based representations are not. Therefore a phonological similarity effect will cause poorer digit-based STM in deaf signers compared to hearing non-signers (paper I).
- When printed stimulus letters are chosen to maximize the phonological distinctiveness of both speech- and sign-based representations no difference is expected in performance on a letter-based STM task (paper I).
- Previous findings of similar WM capacity for lexical items in sign and speech will generalize to digit-based WM (paper I).
- Multiplication recruits the verbal system whereas subtraction recruits the quantity system of the language-calculation network. Therefore deaf signers, who have been shown to have good access to the quantity system but are less likely to rely on the verbal system, will perform worse that hearing non-signers on multiplication but not on subtraction (paper II).
- Before automatization is established, multiplication tasks recruit brain regions involved in phonological processing. If less well-established automatization is

the cause of poorer multiplication skills in deaf signers, multiplication will recruit phonological processing regions more in this group than in hearing non-signers. Therefore deaf signers are likely to have a stronger relationship between multiplication and phonology than hearing non-signers (paper II).

- In hearing individuals, multiplication and phonology tasks (which rely on the verbal system) will recruit lAG, whereas subtraction (which relies on the quantity system) will recruit parietal areas in the right hemisphere (paper III).
- As deaf signers are likely to rely less on the verbal system during arithmetic processing they will recruit lAG to a lesser extent than hearing non-signers (paper IV).
- To compensate for non-automatized multiplication processes the deaf signers will recruit phonological processes which will be manifested in activation of lPOPE. They will thus show a more similar pattern of activation for multiplication and phonology in the frontal part of the language-calculation network compared to that of the hearing non-signers, suggestive of a greater reliance on phonological processes during multiplication (paper IV).

Empirical studies

Disability research

This thesis is positioned in the field of disability research, a field where the individual's health functioning is viewed as a complex interaction between health condition, environmental and personal factors within the scope of the bio-psycho-social model (WHO, 2001). The overarching research question investigated in this thesis is why deaf individuals generally have poorer abilities in several domains related to digit processing compared to hearing individuals. To investigate this question thoroughly, disability research theory proposes an interdisciplinary analysis of the vertical and the horizontal dimension (Danermark, 2002, 2005). In the vertical dimension, aspects of biological, psychological and sociological perspectives are integrated (Danermark, 2002), whereas the horizontal dimension is used to describe the width of a phenomenon in relation to different populations (Danermark, 2005). In the present thesis some biological (neural activity) and psychological aspects (cognitive functions) are investigated. Although sociological aspects are not investigated per se, several sociological aspects have been controlled for by matching the deaf signing and hearing non-signing groups on age, sex, non-verbal intelligence and educational background. The deaf signing groups was further recruited to be as homogenous as possible on age of deafness onset and age of language acquisition. The careful matching on these sociological variables also distinguishes the studies in the present thesis from other studies on deaf individuals where groups have been less well-matched.

In this thesis, the horizontal dimension is represented by the comparison of deaf signers and hearing non-signers. Inevitable, a quasi-experimental approach must be taken in this case. Quasi-experimental designs reduce the ability to make generalizations from research findings to the general study population compared to randomized experimental designs, but provide an opportunity to compare non-randomized groups in a design resembling experimental designs. When employing a quasi-experimental design it is possible that the two groups differ in other aspects than the independent variable. We have tried to control for this by matching the groups as carefully as possible. Nevertheless, there can be other variables in which the groups differ that may have an impact on the dependent variables.

Ethical approval and informed consent

The studies included in this thesis were approved by the regional ethical board in Linköping, Sweden (Dnr 190/05). The part of study I that was carried out in London (i.e. experiment 2) was further approved by the University College London Graduate School Ethics committee. Written informed consent was given by all participants.

General method

Participants

The participant base can be divided into five groups. Participants from the two first study groups (group 1 and 2) are included in several of the papers. The three other groups (group 3, 4 and 5) are only included in the first paper. Specifics of the participant groups can be found in table 2.

The first group consisted of 22 Swedish prelingually deaf adults. Eight participants were native signers and 14 were very early signers. Participants from this group were included in paper I, II and IV. This group was the first to be recruited and was reached through advertisements and by personal communication with persons within the Swedish deaf community who were able to pass advertisement information on to people in the community.

The second group included 21 Swedish hearing adults who were unfamiliar with signed language. Participants from this group were included in all four papers. This group was recruited to match group 1 with regard to gender, age and educational background and was reached through advertisements at Linköping University, the police academy in Stockholm and through personal communication. With this approach we also managed to end up with two groups that were compared in paper I, II and IV, with no statistical differences in age, sex, education or general non-verbal intelligence as measured by Raven's standard progressive matrices.

The third group included 24 British prelingually deaf adults. Twenty-two of the participants were native signers, one was very early and one was an early signer.

The fourth group consisted of 30 British hearing adults that were unfamiliar with signed language. The participants in this group were recruited to match group 3 on age and non-verbal intelligence as measured by the block design from Wechsler Abbreviated Scale of Intelligence (WASI). All participants in the third and fourth group were included in paper I (experiment 2). They were recruited through the Deafness, Cognition and Language (DCAL) research centre's participant database in London.

The fifth group included 16 Swedish hearing adults who were unfamiliar with signed language. All participants in this group took part in paper I (experiment 3). They were recruited through advertisement and personal communication at Linköping University.

All participants had finished mandatory schooling in their respective country and reported having normal or corrected to normal vision. The participants did not report any psychological or neurological problems. Further, participants included in the fMRI study (paper III and IV) were right handed according to the Edinburgh handedness inventory, and reported not to be pregnant, on medications or having metal implants that were not MRI compatible. All participants filled out a medical screening questionnaire before entering the fMRI-experiment.

Table 2. Summary specifics of participants.

Group	*n*	Age *M (SD)*	Female/male	Included in paper
Swedish deaf signers (group 1)	22	27.6 (3.7)	16/6	I, II, IV
Swedish hearing non-signers (group 2)	21	28.3 (5.3)	15/6	I, II, III, IV
British deaf signers (group 3)	24	38.6 (12.2)	14/10	I
British hearing non-signers (group 4)	30	34.2 (12.4)	20/10	I
Swedish hearing non-signers (group 5)	16	32.6 (5.5)	8/8	I

Limitations

The group manipulation in this thesis is language modality. Therefore, it is of great importance to have homogenous groups regarding the language used. It could be argued that when language modality is the focus, the deaf group should contain only native signers that have had unlimited access to signed language in their home environment. However, because the deaf signing population in Sweden is limited and only around 15 % of them can be classified as native signers (Roos, 2009), we have chosen to include deaf persons that started their sign language acquisition before the age of three and thus are defined as very early signers. There is one exception in study I, experiment II where one of the deaf participants started to learn sign language at the age of five (thus being classified as early signer), but was considered to have a native-like knowledge in signed language.

Behavioural tests

Behavioural tests were included in all four papers (table 3). Below is a short description of the tests. Full details are found in the papers.

Simple symbol processing test

The simple symbol processing (SSP) test consisted of two subtests, where low level phonological and arithmetic knowledge were assessed using a matrix of ten rows and ten columns for each of the two subtests. In each cell of the matrix there was either a letter or a number, and the participants were instructed to circle characters in each horizontal row that were not in alphabetical or numerical order.

Complex symbol processing test

In brain imaging, controlling the visual properties of the stimuli are of utmost importance as it influences the incoming visual signal, which in turn influences brain activity. When different tasks are compared, stimuli must be as visually similar as possible. Therefore, we developed the complex symbol processing (CSP) test, which is constructed such that one type of stimulus can be used for different tasks, varying only the cue.

The CSP-test consists of 40 trials, where each trial is made up of three digit/letter pairs (figure 5). In the present version there are six tasks:

1. Digit order — are the digits presented in numerical order?
2. Letter order — are the letter presented in alphabetic order?
3. Multiplication — does one of the digits presented represent the product of the other two?
4. Subtraction — does one of the digits presented represent the difference between the other two?
5. Phonology — are the digit and letter within any of the presented pairs phonologically similar? For hearing non-signers, phonologically similarity was defined as rhyme and for deaf signers, as same handshape.
6. Visual control — are there two dots over any of the letters presented?

The deaf signers included in the present studies read and write in Swedish. Therefore, it is possible that they could perform the speech-based phonology task. Although they were not aware of the rhyme task used for the hearing participants, the phonology blocks were constructed such that the correct rhyme pairs and handshape pairs were in different trials in half of the cases. Thus, it was possible to, by error analysis, validate that the deaf signer did in fact do the handshape task and not the rhyme task. This also makes it possible to use the CSP-test in future studies to compare deaf signers' signed and spoken language phonological ability in the same fMRI study, using same stimulus material.

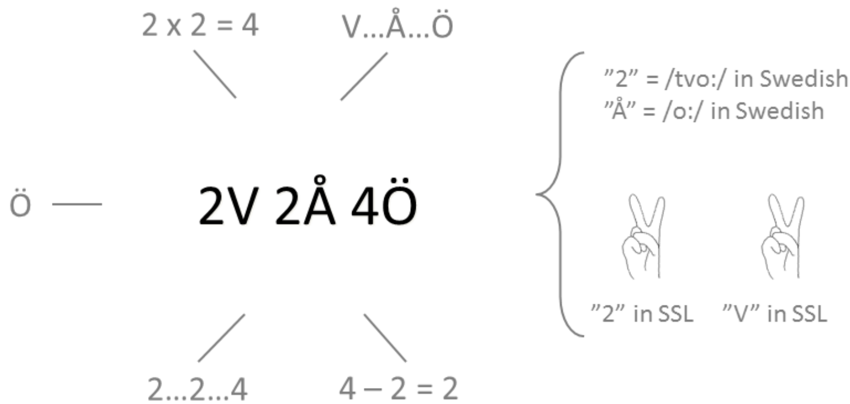


Figure 5. Overview of the complex symbol processing task. Phonological task, två rhymes with Å, 2 and V share the same handshape in Swedish Sign Language; subtraction, 4-2=2; multiplication task, 2x2=4; letter order, V-Å-Ö; digit order, 2 2 4; visual control task, dots over Ö. (Only the characters in black are visible upon presentation.)

Materials used for brain imaging should ideally yield high performance across tasks, ensuring that the intended cognitive task is being performed. Therefore the CSP-test is constructed to have close-to ceiling effects. This interferes with behavioural testing where ceiling effects compromise statistical analyses. To be able to analyse the results behaviourally, accuracy can be combined with response time to obtain a measure free from ceiling effects. In the behavioural paper (paper II), we used inverse efficiency scores (IE) calculated by dividing response time by percentage correct. It is, however, important to note that low IE reflects good performance, while high IE reflects poorer performance.

Short-term memory

Computerized digit and letter span tests were used to assess STM. Sequences of digits from 1 to 9 and of nine letters, chosen to minimize phonological similarity in SSL, Swedish, BSL and English, were created. The letters used in experiment 1 and 3 of paper I, where Swedish participants were tested, were G, H, J, L M, Q, R, S and X. In experiment 2, where British participants took part, J and X were changed to F and Z. All participants were first exposed to two trials consisting of a two-item sequence. Thereafter the sequence length increased progressively after every other sequence, by one digit/letter at a time up to the longest sequence, which consisted of nine digits/letters. After each sequence, participants were asked to reproduce the digit/letter strings forward or backward by keypad (experiment 1 and 3, paper I) or written response (experiment 2 and 3, paper I).

Working memory

WM was assessed by a computerized dual-task operation test, based on Turner and Engle (Turner & Engle, 1989). Sequences of equations, consisting of one operation related to multiplicative reasoning (multiplication or division) followed by one related to additive reasoning (addition or subtraction) were used as stimuli (e.g. $2 \times 4 + 1 = 7$). The task was to report, by key press, whether the stated answer was correct or not and to remember the last digit. All participants were first exposed to two trials consisting of two equations. Thereafter the sequence length increased progressively after every two sequences, by one equation at a time up to the longest sequence consisting of five equations. Single digit numbers 1-9 were used for all operands, sub-products and answers. After each sequence, participants were asked to reproduce the to-be-remembered digit strings using a keypad (experiment 1, paper I) or written response (experiment 2, paper I).

Picture rhyme

Phonological awareness was tested in the picture phonology judgement task, where the participants were instructed to assess phonological aspects of the lexical labels of pictures. The task was to determine whether the lexical labels for the two pictures shown simultaneously on a computer screen rhymed (hearing non-signers) or shared the same handshape (deaf signers). Participants answered by saying or signing their response to the experimenter.

Screening test

Non-verbal intelligence was measured using Raven's progressive matrices in experiment 1 in paper I and in paper II and IV, and by Wechsler's Abbreviated Scale of Intelligence (WASI) in experiment 2 in paper I. The screening results were used to match the hearing and deaf groups and to ensure that all of the participants performed above the lower limit of the normal range on the non-verbal IQ scale (i.e. above 80).

Table 3. Overview of the tests used in the four papers.

Test	Subtest	Measure of	Dependent variable	Paper
Span tasks				
	digit span	digit-based STM	span size	I
	letter span	letter-based STM	span size	I
	operation span	digit-based WM	span size	I, II
Simple symbol processing				
	letters	basic letter knowledge	no. correct	I
	digits	basic number knowledge	no. correct	I
Complex symbol processing				
	digit order	basic letter knowledge	inverse efficiency score	II
	letter order	basic number knowledge	inverse efficiency score	II
	multiplication	arithmetic	inverse efficiency score	II
			response time	III, IV
	subtraction	arithmetic	inverse efficiency score	II
			response time	III, IV
	phonology	phonological processing	inverse efficiency score	II
			response time	III, IV
Picture phonology judgement				
		phonological processing	no. correct	II
Screening tests				
	Raven's progressive matrices	general non-verbal intelligence	no. correct	I:1, II, IV
	Wechsler Abbreviated Scale of Intelligence	general non-verbal intelligence	no. correct	I:2

Statistical analyses of behavioural data

Parametric statistics were used in all four papers, i.e. means and standard deviations were used for descriptive statistics. Inference statistics used included independent *t*-tests, repeated measures ANOVA, mixed-design ANOVA and univariate regression analysis. All behavioural data were analysed using the Statistical Package for the Social Science (SPSS), version 18-22.

Functional imaging

Functional imaging has become an important tool for studying the neural correlates of cognitive concepts (e.g. Cabeza & Nyberg, 2000). Neuronal activity has consequences on the vascular system, caused by the increased requirement for oxygenated blood (Huettel, Song, & McCarthy, 2009). As deoxygenated and oxygenated blood have different magnetic properties, increased blood flow will cause alterations in the magnetic resonance signal. With functional magnetic resonance imaging (fMRI), these changes in blood oxygenation in the brain can be measured as the blood-oxygenation-level dependent (BOLD) signal. There are several methods of analyzing the BOLD signal. In the fMRI papers included in the present thesis the Statistical Parametric Mapping version 8 (SPM8, Wellcome Center for Neuroimaging, University College of London, UK) software was used for preprocessing, statistical modelling and for making inferences about the effects of interest.

Preprocessing of fMRI data

Before statistical processing can be performed, the imaging data need to be preprocessed to remove artefacts and variables of no interest. The preprocessing steps used in the present fMRI study are described below in the order that they were applied to the data.

Quality assurance. The quality of the image time series was initially examined using the TSDiffAna toolbox (Freidburg Brain Imaging), which is used to calculate slicewise differences between scans. Deviating scans may be corrupt and need to be inspected in detail.

Realignment. During the fMRI session, which lasts around 45 minutes, several image volumes are acquired over time, which is why participants are required to lie still. Their heads are supported by foam-rubber pads that are fitted inside the head coil. Nevertheless, it is nearly impossible not to move at all. Therefore, motion correction, or realignment, is a necessary preprocessing step. During realignment, the individual volumes are corrected for movement in six directions; along the x-axis (left-right), y-axis (front-back) and z-axis (up-down) as well as around the x-axis (pitch), y-axis (yaw) and z-axis (roll) and a mean functional image is created for each participant. This correction step positions all images from one participant in the same space, i.e. the new time series that is obtained corresponds to how it would have looked if the participant had remained absolutely still. However, if a participant has moved too much, it will be difficult to correct for the movement, therefore time series with a movement of more than 3 mm in any direction are removed from further analysis. In the papers included in the present thesis, five runs (of 160 in total) were excluded.

Trim. The trim preprocessing step allows for trimming of the structural and functional images such that slices from above or below the brain regions of interest can be trimmed off. During this step the brain is rotated such that the anterior and posterior commissures are on the same horizontal line (the AC-PC line), indicating that the brain is in Talairach space.

Co-registration. As anatomical structures are difficult to identify in the functional images, they need to be co-registered with high-resolution structural images in order to be able to localize where the activation takes place. Therefore, each subject's functional images are co-registered to their structural image.

Spatial normalization. All brains differ with regard to size and shape. To be able to compare the results from different individuals, the individual brain images need to be warped into a standard brain shape. This is done using a normalization process of the structural images with application of the functional time series and the mean functional image. The anatomical standard brain used as a template in the present thesis was the MNI152 template, which has coordinates in the Montreal Neurological Institute (MNI) space.

Spatial smoothing. Finally, the raw data needs to be spatially filtered, which means that activation is spread to neighbouring voxels. This reduces inter-subject anatomical variability and increases the signal-to-noise ratio. During this process a Gaussian kernel, in the present studies 10 mm full width at half maximum (FWHM), is used to convolve the data so that each voxel is replaced by an average calculated from surrounding voxels.

fMRI design

Signal changes induced by the BOLD effect are generally very small. To improve the possibility of capturing the blood flow changes caused by the neural response, paradigms with repeated stimulus presentation are used. There are three main types of fMRI designs; blocked, event related and mixed. In the papers included in the present thesis, a blocked design was used. In a blocked design, each condition is presented in blocks with resting periods in between. This allows for the BOLD response to build up and be sustained at the higher level for a longer period of time, which results in a robust, but relatively inflexible, design.

In the present fMRI-study, participants performed six different tasks (the CSP test as described above), of which one was a visual control task. Because fMRI is a contrast-based methodology, where one condition needs to be compared to another, the baseline used to compare activation against is an important aspect. The visual control, or baseline, task in this study is an active baseline as opposed to passive or rest baselines. The rationale behind using an active baseline is that it allows for subtraction of brain activity that is not associated with the task of interest. In the present case, the visual control task includes the same number of digits and letters as the testing conditions and requires the same type of response (button press). Therefore, when contrasted against each other, brain activity associated with the visual appearance of the stimulus or with motor response due to movement of the fingers is subtracted away and only brain activity invoked by the cognitive processes is detected.

Statistical analyses of imaging data

When statistically interpreting fMRI data, it is common to use the general linear model (GLM) where the BOLD signal is the dependent variable. The independent variables depend on the model's design matrix, which in the papers in this thesis are (paper III and IV) the subtraction, multiplication, phonology and visual control tasks included in the CSP test. The digit and letter order tasks were not assessed in this thesis. The regressors, corresponding to the four tasks, were defined based on the onset time and duration of each block. Included in the GLM is the influence of each predictor on the dependent variable, and variance in the data that cannot be described by the combination of the independent variables, as well as the six motion parameters derived from the realignment procedure.

In the studies presented in the present thesis, *t*-tests were used to make within- and between-group comparisons. In SPM the *t*-statistics are obtained by dividing the contrast of the parameters with the error variance estimate. Specifying the design matrix for each contrast of interest allows for testing whether there is a statistical difference between two or more tasks or between a task and rest. To identify brain regions that were commonly activated for both groups, conjunction analyses were performed in paper IV. Conjunction analysis tests which voxels are activated in both groups at a certain threshold.

Correction for multiple comparisons

Because each scanned brain volume contains hundreds of thousands of voxels, a significance level of $\alpha = .05$ would cause several thousand voxels to be activated by chance, which inevitably would lead to a large risk of making type I errors (false positives). There are several approaches to handling the problem of multiple comparisons. One way of correcting for multiple comparisons is to use a lower threshold, e.g. $\alpha > 0.001$ and to predefine a cluster size limit, e.g. 5 consecutively activated voxels. The rationale behind this approach is that although several thousand voxels throughout the brain will be randomly activated, it is unlikely that 5 adjacent voxels will be randomly activated at the same time. Another, more widely accepted approach is to use the family-wise error (FWE) correction procedure. The FWE correction builds on the Bonferroni correction for multiple statistical tests, whereby the alpha level for each individual test is divided by the total number of tests performed. Due to the spatial smoothness of the fMRI data the number of independent tests performed is considerably lower than the number of voxels. Nevertheless, whole-brain FWE correction can be overly conservative, resulting in a high risk of type II errors (false negatives). This can be handled by reducing the search volume by defining regions of interest (ROI) and performing small volume corrections (SVC) on them. However, this requires *a priori* hypotheses about the regions and cannot be used in explorative experiments.

In the fMRI analysis presented in this thesis, the FWE correction was applied to a small volume. However, because we had hypotheses about several brain regions, the "small volume" investigated was actually rather large and included lPOPE, lPTRI, lAG and bilateral HIPS and SPL (figure 6). Therefore, uncorrected results are presented alongside the FWE corrected results and referred to as tendencies. This is especially important in fMRI experiments where different populations are investigated. In the case of deaf signers, as investigated here, it has been shown that there is a larger degree of variability within this group, leading to less robust activation patterns and thus fewer comparisons that survive the FWE correction (Corina, Lawyer, Hauser, & Hirshorn, 2013).

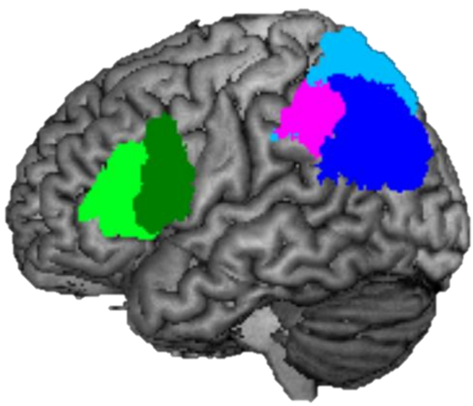


Figure 6. A small volume including pars opercularis (light green) and pars triangularis (dark green) of the left inferior frontal gyrus, the angular gyrus (dark blue) of the left parietal lobe, the horizontal portion of the intraparietal sulcus (magenta) and the superior parietal lobule (light blue) was used as region-of-interest in paper III and IV.

Procedure

The participants that took part in both the behavioural (paper I and II) and the fMRI (paper III and IV) study were tested in two separate sessions. The behavioural session took part at least one month before the fMRI session, and all participants included in the fMRI session completed the behavioural test session. However, some participants were included in the study after the writing of the behavioural papers, which is why their data are not included in papers I and II.

During testing of deaf participants an accredited SSL-Swedish interpreter was present performing verbatim interpretation of all test instructions and other communication.

Behavioural session - paper I and II

The behavioural session started with the provision of information about the study, collection of background data and signing of the consent form. Thereafter, the participants performed the SSP, the CSP test and the picture phonology test. After a break, the session continued with the digit span test forward and backward, the letter span test forward and backward, the operation span test and finally Raven's standard progressive matrices. Due to technical problems one participant performed the picture phonology task last. The SSP-test and Raven's standard progressive matrices were administered on paper whereas the rest of the tests were computerized.

fMRI session - paper III and IV

The fMRI session began with information about the session and MR safety. The participants filled in a standard MR screening questionnaire and were given the opportunity to ask questions. Thereafter they were reminded about the task and allowed to perform a practice run outside the scanner until they felt confident in performing the task. The participants were then put in the scanner and given earphones (only hearing), ear protection (both deaf and hearing) and fitted with a head coil equipped with an angled mirror through which they were able to see a screen positioned at their feet.

The scanning session consisted of four runs of the CSP tasks (app. 6 min. each), one resting state run (not analyzed in the present thesis), during which they were instructed to close their eyes (app. 8 min.) and an anatomical scan (app. 8 min.). According to new guidelines at the Karolinska Institute, where the scanning took place, the participants tested after January 2011 also went through a clinical screening scan (app. 8 min.) that was assessed by a radiologist. Between runs participants were reminded about the procedure by oral messages to the hearing participants and by written messages that were projected onto the test screen for the deaf participants. The deaf participants were instructed to gently wiggle their feet in response to the experimenter's questions while the hearing participants could answer orally, through a microphone.

Methodological considerations

The present work is based on data collected in a laboratory setting. This allows for good control of the conditions but might interfere with the ecological validity of the individual tests. A common difficulty in disabilities in general is that the studied groups display a larger heterogeneity compared to the normal population.

In this study, this is especially apparent in the fMRI-experiment where deaf populations have been shown to have a larger degree of variability, which leads to a less robust activation pattern at the group level and also makes group comparisons less robust (Corina et al., 2013). Another difficulty that may influence task compliance and performance is that all task instructions are interpreted from Swedish to SSL for the deaf signers. This makes the instruction time slightly longer for the deaf group, which might have been tiring. It is also difficult for the experimenter to know that instructions are being interpreted correctly. To deal with this, we aimed to use one interpreter, who was well informed about the study, to interpret all experiment. However, due to logistic problems, two other interpreters were involved during the testing of the last few deaf participants. They were briefed about the study and were equipped with the experimenters' test-instructions manuscript before each test session to guard against misinterpretations.

Functional imaging

When drawing conclusions from imaging experiments, it is common to infer the state of the independent variable from the outcome of the dependent variable, called reverse inference (Huettel et al., 2009). For example, if a multiplication task evokes an fMRI activation in POPE, a region previously shown to be engaged in language processing, it is tempting to draw the conclusion that language is involved in the processing of the multiplication task. This kind of inference is not a valid interpretation, which is why such conclusions alone do not provide any evidence that a particular brain region is associated with a specific cognitive process (Poldrack, 2006). However, reverse inference is not a fallacy *per se*, and can be of high predictive power in some instances (Hutzler, 2014). The predictability of reverse inference increases with the selectivity of the brain response, i.e. a brain response that occurs as a result of only one manipulation has high selectivity whereas responses that can be induced by several different manipulations have low selectivity (Huettel et al., 2009). Simultaneous activation in several connected brain regions, and the combination of behavioural results and imaging data, also enhance the capacity to draw valid conclusions from reverse inference. In the present study, we have enhanced selectivity by employing subtractive designs where tasks are contrasted to each other in order to extract underlying cognitive processes. As we were interested in investigating how brain regions commonly used for phonology processing were involved in arithmetic, we took great care in developing tasks of both arithmetic and phonology that could be compared in one and the same study. If instead we had only investigated arithmetic, we may have come to very different conclusions. As we used a design with all three tasks, we could draw conclusions on the regional division of responsibility, which we would have not been able to do if only arithmetic tasks had been included. Finally, in the present work behavioural and imaging results have been combined to increase the validity of the conclusions.

Summary of the papers

Paper I

Background and aim

Previous research has shown that deaf signers have poorer STM but not WM compared to hearing non-signers (e.g. Bavelier, Newport, et al., 2008; Boutla et al., 2004; Pintner & Paterson, 1917; Rudner et al., 2007; M. Wilson et al., 1997). In particular, STM measured by digit span has repeatedly been shown to be poorer in deaf signers. When STM is measured by letter span instead, the results are less clear-cut (Bavelier, Newport, et al., 2006; M. Wilson & Emmorey, 2006b). It has been proposed that the differences in digit span might be due to phonological similarities among manual numerals, whereas spoken digits and both spoken letter and letters from the manual alphabet are normally phonologically less similar. In the present study we investigate, for the first time, digit and letter span in one and the same study using the same, printed, stimuli for both the hearing and the deaf group. We also investigate, for the first time, WM using a digit-based operation span task for comparison of deaf signers and hearing non-signers. The tests were administered to a Swedish deaf signing group, distinguished by their strong emphasis on signed language during education, and to a British deaf signing group that, due to differences in national curriculums, are less likely to have such a strong signed language emphasis. Hearing non-signing control groups were recruited from both Sweden and Great Britain.

The aim of the study was to investigate STM for digits and letters as well as WM for digits in deaf signers and hearing non-signers. We predicted that 1) both groups would perform similarly on WM and 2) there would be STM differences between groups relating to temporal processing demands and language-specific phonological similarity differences.

Main results

- Deaf signers perform on par with hearing non-signers on digit-based WM in both the Swedish and the British population, extending previous findings of similar lexically based WM.
- Deaf signers perform poorer than hearing non-signers on digit span, but not on letter span, in the Swedish sample.

- There were no differences in digit span or letter span in the British sample, possibly due to a higher reliance on speech-based phonology in the British signing group.
- There were no differences between deaf and hearing individuals on the relative effect of temporal processing demands, possibly related to the use of printed stimuli.

Conclusions

- The poorer performance for deaf signers on the digit span test is probably due to greater phonological similarity for manual numerals compared to spoken digits, since no differences between groups were found for letter span.
- Deaf signers can have similar digit-based WM despite poorer digit span, possibly due to differences in allocation of resources during WM.
- WM is preferred when comparing deaf signers and hearing non-signers, since simple span tests might be confounded by phonological similarity.

Paper II

Background and aim

Deaf students generally perform poorer than hearing peers in arithmetic (e.g. Traxler, 2000), despite no apparent differences in general cognitive abilities. Several recent studies have demonstrated a link between signed language skills and reading ability (R. I. Mayberry, del Giudice, & Lieberman, 2011; Rudner et al., 2012), indicating the importance of native language skills for academic achievement.

The aim of the study was to investigate the relation between native language phonological processing and arithmetic in adult deaf signers. We predicted that deaf signers would perform more poorly than hearing non-signers on multiplication but not on subtraction, because multiplication has been shown to rely on speech-based phonology whereas subtraction is based on magnitude manipulation (Lee & Kang, 2002). We also predicted that there would be a stronger relationship between multiplication and phonology for deaf signers.

Main results

- There were no differences between deaf signers and hearing non-signers on low-level letter and digit processing.
- Deaf signers perform more poorly than hearing non-signers on multiplication, but not on subtraction. However, there was no difference between multiplication and subtraction performance for deaf signers, instead hearing non-signer's better performance on multiplication accounted for this effect.

- For deaf signers, multiplication performance is dependent on signed language phonology. Corresponding associations could not be found for hearing non-signers.

Main conclusion

- Deaf signers are better at arithmetic than previously shown.
- The reason for poorer multiplication, but equal subtraction, performance in deaf signers compared to hearing non-signers, may be associated with poorer access to the phonological code.
- Teaching strategies emphasizing signed language phonology might be useful for multiplication success in signers.

Paper III

Background and aim

Phonology and arithmetic processing engages similar neural networks. Thus, subtraction, multiplication and phonological processing have been shown to recruit left frontal and left parietal areas as part of the verbal system. Subtraction has further been found to engage right parietal regions due to dependence on the quantity system. However, the link between the activation for multiplication, subtraction and phonology has largely been implicated by investigating calculation dependent activation in language processing areas, rather than by explicitly comparing different tasks in one and the same experiment.

The aim of the study was to investigate the differential engagement of the language-calculation network for multiplication, subtraction and phonological processing using the same stimulus material for all tasks, ensuring similar visual activation across tasks in hearing non-signers. Our predictions were that there would be 1) largely similar activation for all three tasks, 2) larger similarities between activation for multiplication and phonology than for subtraction and phonology and 3) a bilateral activation for subtraction, involving HIPS, due to the use of magnitude manipulation.

Main results

- Activation within the left lateralized perisylvian language network was found for all tasks (figure 7).
- Phonology recruits lPOPE and anterior lAG, while multiplication recruits lPTRI and posterior lAG (figure 8).
- Simple subtraction resembles multiplication in its activation. This suggests that simple subtraction, just like multiplication, can be solved by arithmetic fact retrieval instead of by magnitude manipulation, and thus, recruiting lAG instead of HIPS.

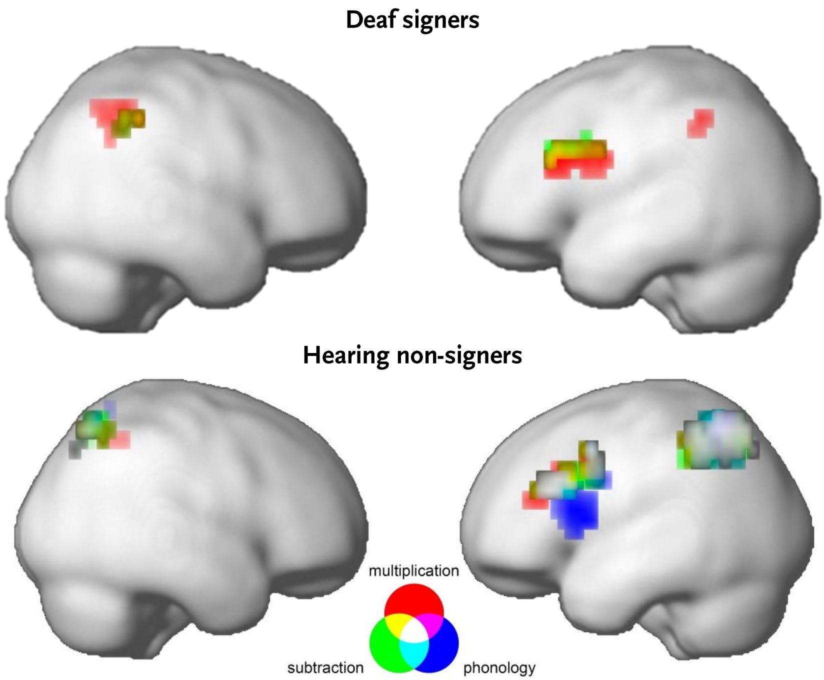


Figure 7. Activation patterns for multiplication (red), subtraction (green) and phonology (blue) for deaf signers (top panel) and hearing non-signers (bottom panel).

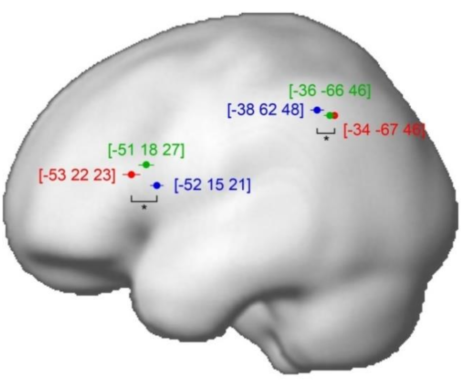


Figure 8. Within the left inferior frontal gyrus, the mean peak of activation for multiplication is located significantly anterior to that for phonology. Within the left angular gyrus the opposite is true. The activation peak for subtraction lies between those for multiplication and phonology in both areas. The dots represent mean coordinates and error bars shows standard error. Mean coordinates are shown in square brackets. Red multiplication; green subtraction, blue phonology. * $p < .05$.

Conclusions

- Despite similar activation patterns for multiplication, subtraction and phonology, there are some important differences. Specifically, phonology was the only task to engage lPOPE.
- There is a regional division of responsibility for multiplication and phonological processing within the perisylvian language network.

Paper IV

Background and aim

As deaf signers show specific problems with multiplication and multiplication performance was shown to be dependent on signed language phonology in paper II, it is possible that phonology-dependent arithmetic fact retrieval problems could explain group differences in performance. In the present study we used the stimulus material tested on hearing non-signers in paper III to investigate, for the first time, neural aspects of arithmetic processing in deaf signers.

The aims of the study were to investigate the involvement of the language-calculation network in arithmetic and phonological processing in deaf signers and to specifically investigate whether deaf signers show less reliance on the verbal system in multiplication compared to hearing non-signers. We predicted similar overall networks to be involved in phonological and arithmetic processing for both groups. We also predicted that, because deaf signers have been shown to have specific problems in tasks relating to the verbal system but not in tasks relating to the visual/attentional or the quantity system, deaf signers will show less reliance on the verbal system by recruiting lAG to a lesser extent.

Main results

- Multiplication was the only task to show significant activation within the predefined mask. A significant activation peak was found in lPOPE and tendencies towards significant activation were found in lPTRI and rHIPS (figure 7). Tendencies towards significant activation were also found in lPTRI, lPOPE and rHIPS for subtraction.
- Deaf signers showed significantly stronger activation compared to hearing non-signers in rHIPS for multiplication (figure 9). For subtraction, no differences were found.
- The phonological task did not result in any significant activation within the language-calculation network in deaf signers. However, the left middle occipital cortex was significantly activated by the phonological task in a whole-brain analysis.

Main conclusions

- Deaf signers recruit brain regions know to be associated with magnitude manipulation processes for multiplication where hearing non-signers use brain regions that are associated with arithmetic fact retrieval. This supports the hypothesis that deaf signers rely on the verbal system to a lesser extent than hearing non-signers and instead recruit the quantity system (figure 9).
- In contrast to previous studies, the neural correlates for phonological processing differ between deaf signers and hearing non-signers, possibly because previous studies on signed language phonology have been confounded by semantic processes.

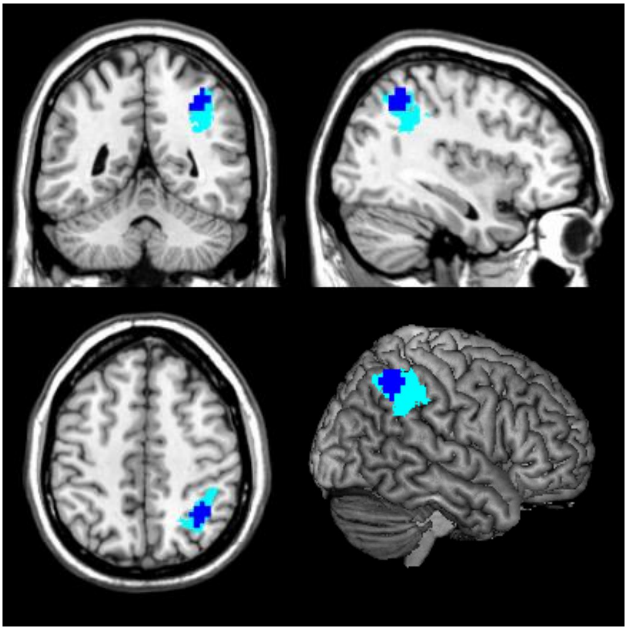


Figure 9. Deaf signers show significantly stronger activation for multiplication compared to hearing non-signers in the right intraparietal sulcus (outline in cyan). Image show deaf signers > hearing non-signers for the multiplication minus visual control contrast.

General discussion

Main findings and conclusions

In the present thesis, the role of phonological processing in different types of digit-related tasks was investigated in carefully matched groups of deaf signers and hearing non-signers. Tight experimental control was maintained over potential confounds. The findings suggest that the lower level of performance found on some digit-related tasks in deaf signers may be attributable to phonological processing. In STM, phonological similarity of the presented stimuli affects recall ability (Baddeley, 2003), which has been suggested to be the reason for shorter digit span in signed language users (Boutla et al., 2004). By administering both letter- and digit-based span tasks in the same study, using the same material for both groups and keeping presentation and response modes as well as recoding demands under tight control, we show that digit span but not letter span differed between deaf signers and hearing non-signers (paper I). This strongly supports the notion that the phonological similarity of signed digits influences digit processing in a memory task (c.f. M. Wilson et al., 1997). Interestingly, this pattern was not found in digit-based WM, where no differences in performance were found, suggesting that it is possible that deaf signers can outweigh STM storage decrements by allocating resources to the processing component during WM performance. This extends previous findings showing similar WM capacity for deaf signers and hearing non-signers with stimuli not based on digits (Boutla et al., 2004). Using carefully matched groups we showed that deaf signers performed on a par with hearing non-signers on all arithmetic operations except multiplication, which is the most phonology-dependent operation (paper II), suggesting that digit processing during arithmetic reasoning is also associated with phonological processes for this group. Further, while hearing non-signers recruited lAG for multiplication (paper III), indicating phonology-dependent arithmetic fact retrieval processes, deaf signers recruited rHIPS (paper IV), indicating the use of non-verbal magnitude manipulation processes, which may support multiplication to a lesser extent. Taken together, the results presented in the present thesis suggest that language modality-specific differences in phonological processing may explain poorer performance for deaf signers compared to hearing non-signers on some digit related tasks. The fact that the connection between phonology and digit processing was found for tasks as diverse as memory and arithmetic, and in both behavioural and neurobiological experiments, further strengthens this conclusion.

Phonological processing

In paper II and IV, phonological processing was investigated across the language modalities of sign and speech, using the phonology task in the CSP-test. The stimulus material was identical for both groups, but the cued task differed. The deaf signers were asked to judge handshape similarity, while the hearing non-signers were asked to make rhyme judgements. Despite the modality-specific surface description of the task, the meta-linguistic characteristics of the tasks are at the same theoretical level. The lack of behavioural differences between the groups further indicates that the tasks are comparable with each other. Previous work on deaf signers and hearing individuals has shown that there are similarities between the neural substrates of phonological processing across the modalities of sign and speech (Aparicio, Gounot, Demont, & Metz-Lutz, 2007; Macsweeney et al., 2013; MacSweeney et al., 2008), suggesting an amodal representation. In the present work, a different pattern was obtained. Although behavioural results show a role for phonological processing in deaf signers similar to that of hearing non-signers, the neurobiological correlates differ between groups. This pattern supports the notion of a clear role for signed language phonology in cognitive processing but with a language modality-specific neural representation.

Neural correlates of signed language phonology

In the imaging study presented in paper IV there was no evidence of significant activation for signed language phonology within the perisylvian language network, nor was there any common activation for phonology across groups, while, as expected, lPOPE and lAG were activated for the hearing group (paper III). Recent studies on picture-based phonology judgement have shown that there are some differences between language modalities, where signed language phonology has been suggested to activate more anterior regions compared to spoken phonology (Macsweeney, Brammer, Waters, & Goswami, 2009; MacSweeney et al., 2008; Rudner et al., 2013). In paper IV such an anterior shift would have resulted in activation for signed language phonology anterior to that of spoken phonology, possibly in lPTRI or pars orbitalis, which was not the case. In fact, for deaf signers there was no significant frontal activation within the perisylvian language network for the phonology task. Due to the inherent iconicity of signed languages, there is a closer relationship between phonological and semantic processing in signed languages compared to spoken languages (Marshall et al., 2013; Rudner et al., 2013), indicating that the similarities previously found between phonological processing in sign and speech may be confounded by semantic processes. In contrast to the studies mentioned above, where tasks based on pictures with semantic content were used (and thus offered a semantic route to phonology) the present study uses digit-letter tasks with higher demands on phonological processing as there is limited semantic content that can facilitate phonological judgement. In fact, the only region to show significant activation for phonological processing in the deaf group was the left middle occipital gyrus, an activation pattern that was not present in the hearing group. Therefore, our findings suggest that sign-based phonological processing does not necessarily activate the classical language network. Further imaging studies using tasks isolating phonological processes are needed to investigate this hypothesis.

Phonological processing in middle occipital gyrus

The only brain region that was significantly activated for phonology in the deaf group in the present thesis was the left middle occipital cortex (paper IV). A meta-analysis on rhyme judgement showed that the left occipital cortex was activated more in Chinese compared to in English and German (Tan, Laird, Li, & Fox, 2005). They reasoned that in alphabetic languages, including English and German, learning to read is based on awareness of phonological structures in the spoken language, which leads to a biological adaptation such that the neural representations of written words and speech sounds develop in an integrated fashion within temporo-parietal brain areas, where lAG is of particular importance. In contrast, the contribution of phonological awareness in learning to read Chinese, which is a logographic language, is minor (Tan, Spinks, Eden, Perfetti, & Siok, 2005). Instead awareness of the visual appearance of the Chinese sign is of importance for learning to read. In deaf signers, sign-related phonological awareness is correlated with reading ability (R. I. Mayberry, del Giudice, et al., 2011; Rudner et al., 2012), however, there is no correspondence between signed language phonology and the written word. This may explain why in the present work there is no evidence of phonological-orthographic integration in lAG. Instead, unexpected activation for phonology in the left middle occipital cortex in the present study might be caused by a close relationship between signed language phonology awareness and the visual characteristics of the sign.

The role of the angular gyrus in language processing

In the present thesis, the anterior portion of lAG (PGa) was engaged in phonological processing for hearing non-signers, whereas no such engagement was found for deaf signers. This suggests a different functional organization of this region for the two groups. As discussed above, it is possible that representations of written text and speech sounds develop in an integrated fashion such that lAG adapts to handle mapping between phonological and orthographic representations in hearing individuals (Booth et al., 2004; Tan, Laird, et al., 2005) but only if they are literate (Petersson, Silva, Castro-Caldas, Ingvar, & Reis, 2007). As deaf signers are deprived of auditory stimulation such integration cannot occur in the same manner.

Sensory deprivation is well-known to cause cross-modal plastic changes (Heimler, Weisz, & Collignon, 2014). Cross-modal recruitment of auditory regions in deaf individuals has been reported for sensory factors, including visual (e.g. Bavelier, Dye, & Hauser, 2006), and tactile inputs (Levänen, Jousmäki, & Hari, 1998), as well as cognitive factors, including linguistic processing (e.g. Cardin et al., 2013; R. I. Mayberry, Chen, et al., 2011). It has recently been shown that while both the left and right auditory cortices reorganize to support visual processing in deaf individuals, the left hemisphere seems to be reserved for language-related visual processing (Cardin et al., 2013). Other work suggests that the left-lateralized reorganization of language networks in temporo-parietal regions in deaf signers is related to semantic processes (MacSweeney et al., 2002). Thus, in contrast with the developmental pattern for hearing individuals (Booth et al., 2004; Tan, Laird, et al., 2005), there is independent evidence that in deaf sign language users lAG develops to support semantic rather than phonological processing. This may be an explanation of why we did not find activation of lAG for our non-semantic phonological task in deaf signers.

Memory

The main result of paper I was that deaf signers perform on a par with hearing non-signers on digit-based WM as well as on letter-based STM, but not on digit-based STM, indicating that deaf signers can have good digit-based WM despite poorer performance on digit-based STM. Taken together, these results show that STM and WM for deaf signers and hearing non-signers work in similar ways, probably relying on similar processes, as suggested in several previous studies (e.g. M. Wilson & Emmorey, 2006a). Importantly, previously findings of similar WM performance for deaf signers and hearing non-signers (Boutla et al., 2004; Rudner et al., 2013) can be generalized to digit-based WM.

The differences in performance between groups found in digit span can be explained by different phonological properties of the material used for the two languages compared. The stimulus material was the same for both groups, but the assumption was that all participants recoded the characters that were visually presented into their preferred language, i.e. sign and speech. Thus, for the deaf group, digits had a high degree of phonological similarity (figure 3) and for the hearing group, digits were phonologically dissimilar. This supports previous findings of a phonological similarity effect for signed languages (M. Wilson & Emmorey, 1997) and extend them by showing, in the same study, no difference in STM span between groups for letters chosen for their phonological dissimilarity. It would be interesting to further explore the involvement of phonological similarity in STM across groups by using letter span with phonologically similar letters for the hearing group, creating a situation similar to that for deaf signers in digit span.

Despite similar phonological differences between groups in the experiment with British participants (experiment 2, paper I), performance for deaf signers was on a par with that of the hearing non-signers on both digit- and letter-based STM. This was unexpected given the results from the experiment on Swedish participants (experiment 1, paper 1). However, one reason for this might be that the British deaf signers are more prone to rely on speech-based phonology, which has been shown to enhance digit-based STM performance in deaf signers (Hanson, 1982). This bias may be due to less emphasis on signed language in British schools.

Phonological similarity in WM

The STM and WM tasks required recall of presented characters. It is tempting to believe that the phonological similarity of manual numerals that seems to cause the deaf signers to perform more poorly than the hearing non-signers on digit-based STM would also influence performance in the WM task. Instead deaf signers performed on a par with the hearing signers in the WM task, suggesting that WM processing cancels out the STM storage decrement, even when the items are digits. One explanation for this may be a different, or more efficient, allocation of resources between the storage and the processing component in this group. One of the main functions of WM is related to the generation of propositions (Baddeley, 2003). As signers have the ability to produce propositions very efficiently (Bellugi & Fischer, 1972), it is possible that they have a greater ability to allocate resources to the process component of WM.

Another explanation for the similar performance across groups on WM could be that deaf signers rely on passive memory stores, whereas hearing non-signer use active memory strategies, during encoding and rehearsal (Bavelier, Newman, et al., 2008). The active memory strategies used by hearing individuals may interfere with the material manipulation required for the process component more than for deaf signers, resulting in the comparable results across groups seen in paper I of the present thesis. To further investigate the mechanisms of the two components of WM, studies aiming to isolate the two processes should be performed on both deaf and hearing populations.

Arithmetic

Previous findings of poorer performance in multiplication in deaf signers (Nunes et al., 2009) were replicated in paper II. The multiplication task used in the present thesis requires arithmetic fact retrieval which has been associated with phonological processes (Dehaene et al., 2003; Lee & Kang, 2002). In paper II, the picture phonology task together with alphabetic knowledge accounted for a significant amount of variance in the deaf group, but not in the hearing group, indicating that support from signed language phonology is important for multiplication success. Performance in subtraction, in which arithmetic fact retrieval is less involved, was not depressed in deaf signers, indicating better arithmetic performance overall than reported in several previous studies (Bull et al., 2005; Bull et al., 2011; Kritzer, 2009; Traxler, 2000). It should be noted that there was no difference between multiplication and subtraction performance for deaf signers, instead hearing non-signer's better performance on multiplication accounted for the main effect, supporting the hypothesis that multiplication compared to subtraction is performed using different codes in hearing non-signers but not in deaf signers. This hypothesis was further partly supported in papers III and IV where the neural substrate of multiplication differed significantly between groups.

The triple code model revisited – hearing non-signers

The TCM has been one of the most influential models of numerical neurocognition during the past decades. Despite attempts to update the model, it has remained robust (e.g. Arsalidou & Taylor, 2011). In papers III and IV, the focus was on the verbal and quantity systems, while the visual/attentional system was given less attention. In hearing individuals, multiplication processing was found to recruit lAG, as predicted by the model (paper III). This is the area that supports arithmetic fact retrieval and forms the verbal system within the model. According to the model, subtraction is expected to require magnitude manipulation and therefore recruit the quantity system in HIPS (Dehaene et al., 2003). However, because the subtraction problems used in the present study are simple, it is not surprising that they can be solved by arithmetic fact retrieval. This may explain why subtraction, just like multiplication, recruited lAG in hearing individuals. Similar findings relating to simple subtraction have been shown previously (Simon et al., 2002). To be able to thoroughly test the TCM, more elaborate subtraction tasks are needed.

Interestingly, despite activation peaks in lAG for all three tasks in paper III, there was a regional difference between the tasks, such that the activation peak for phonological processing was found in the anterior lAG (PGa) and that for multiplication was found significantly more posteriorly (in PGp). This is consistent with findings for phonological rhyme tasks where conversions between orthography and phonology have been shown to activate PGa (Booth et al., 2004). This indicates that the phonological processes recruited during rhyme judgement are not the same as those recruited for arithmetic. Thus, based on the conclusions from paper III, it is suggested that the arithmetic processes elicited by the tasks here should be defined as retrieval rather than verbal processes, and that it may be appropriate to rename the *verbal* system of numerical cognition as the *retrieval* system of numerical cognition.

Further, both multiplication and subtraction recruited lPTRI, although for subtraction the activation did not reach significance ($p_{fwe} = 0.073$), whilst neither showed any significant activation in lPOPE. The lIFG is not part of the TCM (Dehaene et al, 2003), but has repeatedly been implicated in arithmetic tasks (Benn et al., 2012; Ischebeck et al., 2006; Rickard et al., 2000). Previous studies have shown that lIFG is recruited more for multiplication than subtraction (e.g. Prado et al., 2011), and it has been inferred that multiplication requires phonological processes (Lee & Kang, 2002). In paper III, we show that although both the phonological and the multiplication task recruit left IFG, there is a regional differentiation, with phonology activating the posterior portion (lPOPE) and multiplication the anterior (lPTRI), again indicating different processes for phonology and multiplication. Arithmetic processing in the evolutionarily newer PTRI has been suggested to reflect a cognitive process similar to that of language but involving more complex sequence manipulation processes that are independent of linguistic processes (Friedrich & Friederici, 2009; Monti, Parsons, & Osherson, 2012). This region has also been shown to be involved in WM processes related to the central executive, especially domain-general selection processes (Badre & Wagner, 2007). In their metanalysis of number and calculation, Arsalidou and Taylor (2011) proposed an update to the TCM relating to WM. Based on the findings in paper III, it is plausible that the verbal system should be restricted to the posterior portion of lAG and renamed the retrieval system and that the model should be extended with a new executive system related to non-linguistic WM processes located in the lPTRI (figure 10). The exact role of the new executive system needs to be further investigated.

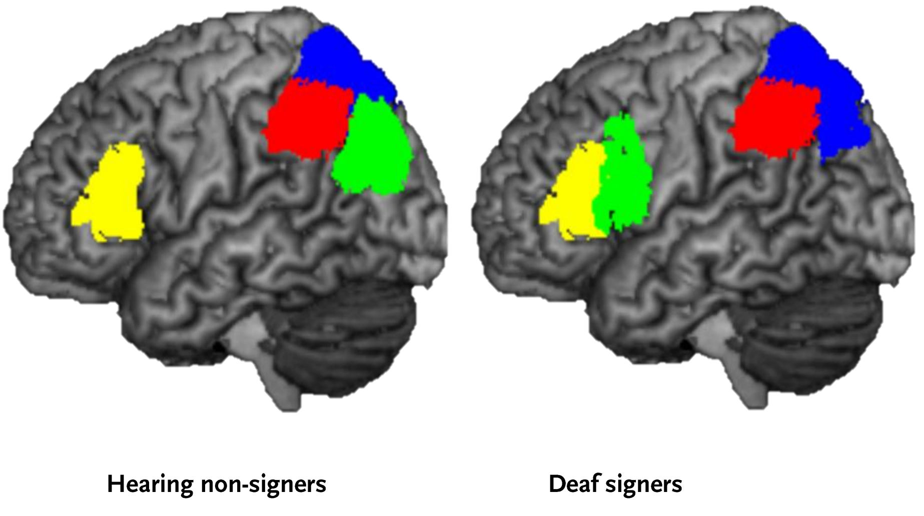


Figure 10. The triple code revisited. For hearing non-signers (to the left) the findings in the present thesis suggest a new system (yellow) involving pars triangularis which contributes executive, non-linguistic working memory information. There was no support for the quantity system (red), but it cannot be ruled out that it plays an important role in subtraction problems of larger magnitudes. For deaf signers (to the right), the findings suggest that the new executive system is present in pars triangularis (yellow) but that an additional frontal area, pars opercularis (green), contributes articulatory processes that take over the role of the parietal verbal system.

The triple code model revisited – deaf signers

In contrast to hearing non-signers, there was no activation peak in lAG for the deaf signers in either of the arithmetic tasks (paper IV). According to the TCM, this indicates that this population does not engage verbal processes in arithmetic problem solving. However, they did show frontal activation in both lPOPE and lPTRI, at least for multiplication. The lPTRI activation might reflect the new executive system described above, involving higher non-linguistic WM processes, whereas the opercular activation could indicate recruitment of phonological processes used due to incomplete arithmetic fact retrieval in lAG. However, because this group did not show activation for the phonological task in lPOPE, activation of this region during arithmetic tasks may point towards an involvement of sub-vocal rather than phonological processes (Rickard et al, 2000). This is supported by studies showing that lIFG is recruited during arithmetic processing in individuals where automatization of multiplication knowledge is incomplete (Ischebeck et al., 2006; Kawashima et al., 2004).

The deaf signers were also found to show stronger activation than hearing non-signers in rHIPS for multiplication (figure 9). The stronger activation in rHIPS in combination with the lack of activation in lAG indicates that deaf signers have a weaker involvement of the verbal system during multiplication, compensated for by a stronger activation of the quantitative system. Hence, for multiplication deaf signers seem to rely on the quantity system, with the addition of articulatory, sub-vocal, processes, where hearing individuals normally rely on the verbal system (figure 10).

Finally, it should be noted that the behavioural performance of the deaf signers in paper IV did not differ from that of the hearing non-signers in either subtraction or multiplication. This distinguishes this study from other studies on arithmetic in deaf signers. Because the deaf signers in this study were carefully matched with the hearing non-signers and represent a population for whom signed language conditions have been optimized, it is possible that this group of deaf signers is different from the deaf signing population as a whole when it comes to arithmetic skills. Hence, in this particular group it seems as though successful arithmetic strategies have been developed. Therefore, the patterns of activation identified in paper IV indicates that retrieval strategies for simple arithmetic might not be as advantageous for this group as they are for hearing non-signers (Ischebeck et al., 2006). The results of paper IV suggest that deaf signers, who have an extensive signed language background and show adequate performance on arithmetic tasks, successfully make use of qualitatively different processes, with lower reliance on verbal processes, compared to hearing individuals, when engaging in arithmetic tasks. However, it is possible that for deaf signers with less well-developed language skills, magnitude manipulation processes are not sufficient, and that this is reflected in other studies reporting worse arithmetic performance in deaf signers compared to hearing non-signers.

Future directions

In the present thesis, pioneering work on the role of phonology in digit processing for deaf signers has been described. Several of the findings presented here require further investigation and inspire the formulation of new research questions:

- It is possible that previous imaging studies on phonological processing in deaf signers have been confounded by semantic content. Therefore, more studies using isolated phonological tasks are needed to investigate sign-based phonological processing.
- Behavioural data show that phonological similarity of digits confuses rehearsal in deaf signers, and imaging data show that there are differences between deaf and hearing individuals in arithmetic processing. It would be interesting to investigate whether brain activation differences are present already at the level of simple digit processing for deaf signers and hearing non-signers. This could be done by investigating low level digit and letter processing and would lead to a better understanding of numerosity in different modalities.
- To further investigate similarities and differences in magnitude processing between deaf signers and hearing non-signers, more elaborate arithmetic problems, where hearing non-signers cannot rely on arithmetic fact retrieval for subtraction, should be used. It is hypothesised that in such circumstances, deaf signers would engage HIPS for both subtraction and multiplication whereas hearing non-signers would engage HIPS for subtraction and lAG for multiplication.
- For hearing non-signers, multiplication problems are solved faster than subtraction problems. This supports the notion of different processes for the two operation types. To further investigate the temporal component of arithmetic problem solving, it would be interesting to investigate event-related potentials during on-line processing of multiplication and subtraction.
- Based on the findings of paper II, it may be beneficial for deaf signers to increase their signed language phonological awareness, which may have positive effects on multiplication performance.
- The complex symbol-processing test could be used to investigate the relationship between phonological and arithmetic processing in other groups with phonological and/or arithmetic processing deficits, e.g. individuals with dyslexia, dyscalculia or specific language impairments. It would also be interesting to investigate the new generation of deaf children and adults who have had access to spoken language through cochlear implants using the same test.

Conclusions

In this thesis, both language modality-specific and amodal components of the role of phonology in digits processing, were identified. The main finding of the thesis is that the neural networks supporting multiplication show both language modality-specific and modality-general components. In particular, language modality-specific components were identified for the operation of multiplication. While hearing non-signers recruited lAG (paper III), indicating involvement of phonology-dependent arithmetic fact retrieval processes in line with previous work, deaf signers recruited rHIPS and lPOPE (paper IV), indicating increased reliance on non-verbal magnitude manipulation with the support of sub-vocal processes. It is important to note that the use of apparently non-verbal strategies by deaf signers was not associated with poorer performance (paper IV). However, such strategies may be the cause of poorer performance by deaf signers in other contexts (paper II). As regards language modality-general components of the neural networks supporting mental arithmetic, both groups recruited the lPTRI. It is proposed that the engagement of this region reflects reliance on general executive functions, irrespective of whether mental calculation takes place in signed or spoken language (papers III and IV). This notion is supported by the finding of no difference in digit-based WM between groups (paper I) as well as no difference in the capacity of the short-term store when phonological similarity is kept under control (paper I).

Another important finding of this thesis is that, in contrast with previous work, there was no evidence that phonological processing engaged the perisylvian language network in deaf signers (paper IV), calling into question the previously proposed amodality of phonology. Taken together, dealing with digits engages general executive functions irrespective of preferred language modality but compared to hearing non-signers, deaf signers seem to engage phonological processes in a different way and rely more on non-verbal strategies.

Acknowledgement

There were so many things I didn't know when I started this journey eight years ago. During my graduate studies I have been fortunate to meet and work with many persons from whom I've learned a lot, persons who have made this journey enjoyable in so many ways and kind persons who have provided the best of support when times have been tough. I would like to express my sincere gratitude to all my colleagues, friends and family who have joined me, in one way or the other, during this journey. Especially, I would like to express my thanks to some of you:

First and foremost, a very special thanks to my main supervisor, ***Mary Rudner***, who has patiently guided me from start to finish and has been very generous with both time and expertise. Mary, you are one of the most ambitious and sharp minded persons I know, and I admire you for that!

I would also like to thank my assistant supervisor, ***Jerker Rönnberg***, for providing me with a place at this interesting research milieu that is the Swedish Institute for Disability Research. Thanks you for all your constructive and insightful comments on everything from research to the Olympics.

I am very thankful for the support of my assistant supervisor, ***Örjan Dahlström***, for perceptive and supportive comments throughout the years. Thanks for sharing your knowledge on statistics, fMRI, farm maintenance, and on the art of being a doctoral student.

I would like to express my gratitude to all volunteers who took part in the studies. Thank you for your time and engagement! I also want to acknowledge the valuable work done by the Swedish-SSL interpreters that have helped me during testing. Thank you ***Lena Davidsson***, ***Susanne Blockert*** and ***Lena Ekevid***.

Many thanks are due to people that in different ways have helped me in carrying out the imaging study. First of all, thanks to ***Peter Fransson***, for your help in designing and launching the study and for co-authoring paper III and IV. A warm thank you to ***Shahram Moradi***; thank you for sitting by my side through hours and hours of scanning and car traveling. Thanks for all the laughs and interesting conversations we have shared. Thank you, ***Ingrid Johnsrude***, for generously sharing your huge knowledge in fMRI and cognitive neuroscience. Many thanks to all staff at the MR centre at the Karolinska Institute, especially ***Birgitta Löwegren*** and ***Yords Österman***.

There are a few people without whom I would probably not have survived these years. ***Elin Hultman***, you are such a wonderful, generous person. I miss you so much here at the department! ***Emelie Nordquist***, thanks for all your support and for sharing both ups and downs in life and at work and of course thanks for all our short (?) fika breaks. ***Cecilia Henricson***, I admire your huge knowledge in all areas, your thoughtfulness and your kindness. Thanks for sharing! ***Lisa Classon***, you have been very important to me; thanks for your support and for all your comments on the kappa. Thank you all for being wonderful friends and colleagues!

I'm grateful for the help in making high resolution vector graphics, provided by ***Niklas Rönnberg***. Thanks for all the work you put into perfecting the pictures in paper I and II, the Venn diagram in paper III and IV and for your contribution to the final look of this text.

My warmest thanks to ***all past and present colleagues*** within the division for Cognition, Development and Disability, the Disability Research Division, the Swedish Institute for Disability Research and the HEaring And Deafness environments, for providing a friendly and stimulating work place. Special thanks to ***Gisela Eckert***, ***Gunvor Larsson-Abbad, Anneli Frostell, Anett Sundqvist, Stefan Gustafson*** and ***Björn Lidestam*** for encouragement, ***Ulrika Birberg-Thornberg*** for friendship and for letting me borrow your neuropsychology courses, ***Linda Olsson*** for being an enthusiastic inspiration, you make me smile. Thanks to ***Anna Levén*** for your engagement in all doctoral students, including me, to ***Emil Holmer*** and ***Camilla Warnicke*** for sign language and deafness discussions, ***Henrik Danielsson*** for running our division meritoriously, and ***Maria Hugo-Lindén***, ***Marie-Louise Mattson*** and ***Helen Johansson*** for your help in all matters throughout the years. A special thanks to you, Marie-Louise, for helping me with the cover of this thesis.

My sincere thanks to all friends and colleagues at the Deafness, Cognition and Language research centre (DCAL) at University College London. ***Ruth Campbell***, thank you for you engagement, helpful comments and kindness. ***Velia Cardin***, ***Bencie Woll***, ***Cheryl Capek*** and ***Eleni Orfanidou***, thanks for collaboration on paper I, interesting discussions and nice get-togethers both here in Linköping and in London.

The state of the present thesis has benefitted greatly from all of you who have taken your time to read and comment on all, or parts, of it. First of all, thank you, ***Rachel Ellis***, for proofreading the text and for finding all the missing commas. Thanks also to ***Daniel Västfjäll***, ***Rickard Östergren***, ***Keith Nelson***, ***Björn Lyxell***, Lisa Classon, Gunvor Larsson-Abbad, Emelie Nordquist, Cecilia Henricson, Anna Levén, Camilla Warnicke, Ingrid Johnsrude and of course all of my supervisors.

My family and friends have been invaluable to me not only during this time but always. Thanks to both my syjuntor, both my house/cell groups and all other friends who have supported me. My grateful thanks go to my lovely brother, ***Karl***, who has helped us with babysitting and provided company many evenings. Thanks to ***Viktoria***, for all our phone calls and ***Matilda***, for friendship and comments on the Swedish abstract. My parents, ***Ulla*** and ***Gunnar***, I'd like thank you for believing in me and pushing me all my life and for always being available for your grandchildren.

During this long journey I have had the fortune of becoming a mother of the two loveliest boys in the world, ***Helmer*** and ***Valter***. I did not know that there could be another person as stubborn as myself, but both of you exceed me. I hope that your strong will power will take you wherever you want to go in life. I love you so much! The book is finished and I promise that mummy will not work on Saturday. I am also in debt to you, ***Christoffer***, for listening and for supporting me all the way to journey's end. ♥

"Numbers and lightsabers" by Helmer

References

1980/81:100 (1980). *Proposition 1980/81:100, Bilaga 12.* Stockholm.

Ahlgren, I., & Bergman, B. (2006). Det svenska teckenspråket [The Swedish sign language] i Teckenspråk och teckenspråkiga, *SOU* 2006:29, Stockholm, Sweden.

Alloway, T. P., & Passolunghi, M. C. (2011). The relationship between working memory, IQ, and mathematical skills in children. *Learning and Individual Differences, 21*(1), 133-137. doi: 10.1016/j.lindif.2010.09.013

Ansari, D., Lyons, I. M., Van Eimeren, L., & Xu, F. (2007). Linking visual attention and number processing in the brain: The role of the temporo-parietal junction in small and large symbolic and nonsymbolic number comparison. *Journal of Cognitive Neuroscience, 19*(11), 1845-1853. doi: 10.1162/jocn.2007.19.11.1845

Anthony, J. L., Williams, J. M., Aghara, R. G., Dunkelberger, M., Novak, B., & Mukherjee, A. D. (2010). Assessment of individual differences in phonological representation. *Reading and Writing, 23*(8), 969-994. doi: 10.1007/s11145-009-9185-7

Aparicio, M., Gounot, D., Demont, E., & Metz-Lutz, M. N. (2007). Phonological processing in relation to reading: An fMRI study in deaf readers. *Neuroimage, 35*(3), 1303-1316. doi: 10.1016/j.neuroimage.2006.12.046

Arlinger, S. (2007). *Nordisk lärobok i audiologi [Nordic textbook in audiology]* (1st Ed.). Bromma, Sweden: C.A. Tegnér AB.

Aronoff, M., Meir, I., Padden, C. A., & Sandler, W. (2008). The roots of linguistics organization in a new language. *Interaction Studies, 9*(1), 133-153. doi: 10.1075/is.9.1.10aro

Arsalidou, M., & Taylor, M. J. (2011). Is 2+2=4? Meta-analyses of brain areas needed for numbers and calculations. *Neuroimage, 54*(3), 2382-2393. doi: 10.1016/j.neuroimage. 2010.10.009

Ashcraft, M. H. (1992). Cognitive arithmetic: A review of data and theory. *Cognition, 44*(1-2), 75-106.

Baddeley, A. (2003). Working memory and language: an overview. *Journal of Communication Disorders, 36*(3), 189-208. doi: 10.1016/S0021-9924(03)00019-4

Baddeley, A. (2010). Long-term and working memory. In L. Bäckman & L. Nyberg (Eds.), *Memory, aging and the brain: a festschrift in honour of Lars-Göran Nilsson*. East Sussex, UK: Psychologi Press.

Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. In S. T. Fiske, D. L. Schacter, & S. E. Taylor (Eds.), *Annual Review of Psychology, Vol 63* (Vol. 63, pp. 1-29). Palo Alto: Annual Reviews.

Baddeley, A., & Hitch, G. (1974) Working Memory. *Vol. 8. Psychology of Learning and Motivation - Advances in Research and Theory* (pp. 47-89).

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia, 45*(13), 2883-2901.

Bagga-Gupta, S. (2004). *Literacy and deaf education - A theoretical analysis of the international and Swedish literature*. Stockholm, Sweden.

Bavelier, D., Dye, M. W., & Hauser, P. C. (2006). Do deaf individuals see better? *Trends in Cognitive Sciences, 10*(11), 512-518. doi: 10.1016/j.tics.2006.09.006

Bavelier, D., Newman, A. J., Mukherjee, M., Hauser, P., Kemeny, S., Braun, A., & Boutla, M. (2008). Encoding, rehearsal, and recall in signers and speakers: Shared network but differential engagement. *Cerebral Cortex, 18*(10), 2263-2274. doi: 10.1093/cercor/bhm248

Bavelier, D., Newport, E. L., Hall, M., Supalla, T., & Boutla, M. (2006). Persistent difference in short-term memory span between sign and speech: Implications for cross-linguistic comparisons. *Psychological Science, 17*(12), 1090-1092. doi: 10.1111/j.1467-9280.2006.01831.x

Bavelier, D., Newport, E. L., Hall, M., Supalla, T., & Boutla, M. (2008). Ordered short-term memory differs in signers and speakers: Implications for models of short-term memory. *Cognition, 107*(2), 433-459. doi: 10.1016/j.cognition.2007.10.012

Bellugi, U., & Fischer, S. (1972). A comparison of sign language and spoken language. *Cognition, 1*(2-3), 173-200.

Benn, Y., Zheng, Y., Wilkinson, I. D., Siegal, M., & Varley, R. (2012). Language in calculation: A core mechanism? *Neuropsychologia, 50*(1), 1-10. doi: 10.1016/j.neuropsychologia.2011.09.045

Bergman, B., & Wikström, L.-Å. (Writers). (1981). Supplement till Forskning om teckenspråk, videogram I: Svenska handalfabetet och bokstaverade tecken [Supplement to Research on sign language, videogram I; Swedish manual alphabet and fingerspelled signs]. Stockholm.

Bitan, T., Cheon, J., Lu, D., Burman, D. D., Gitelman, D. R., Mesulam, M. M., & Booth, J. R. (2007). Developmental changes in activation and effective connectivity in phonological processing. *Neuroimage, 38*(3), 564-575. doi: 10.1016/j.neuroimage.2007.07.048

Blondel, M., & Miller, C. (2001). Movement and rhythm in nursery rhymes in LSF. *Sign Language Studies, 2*(1), 24-61. doi: 10.1353/sls.2001.0022

Booth, J. R., Burman, D. D., Meyer, J. R., Gitelman, D. R., Parrish, T. B., & Mesulam, M. M. (2004). Development of brain mechanisms for processing orthographic and phonologic representations. *Journal of Cognitive Neuroscience, 16*(7), 1234-1249. doi: 10.1162/ 0898929041920496

Boutla, M., Supalla, T., Newport, E. L., & Bavelier, D. (2004). Short-term memory span: Insights from sign language. *Nature Neuroscience, 7*(9), 997-1002. doi: 10.1038/nn1298

Braisby, N., & Gellatly, A. (2012). Cognitive psychology (2 ed.). Oxford, UK: Oxford University Press.

Brentari, D. (1998). *A Prosodic Model of Sign Language Phonology*. Cambridge, MA: MIT Press.

Bull, R., Blatto-Vallee, G., & Fabich, M. (2006). Subitizing, magnitude representation, and magnitude retrieval in deaf and hearing adults. *Journal of Deaf Studies and Deaf Education, 11*(3), 289-302. doi: 10.1093/deafed/enj038

Bull, R., Marschark, M., & Blatto-Vallee, G. (2005). SNARC hunting: Examining number representation in deaf students. *Learning and Individual Differences, 15*(3), 223-236. doi: 10.1016/j.lindif.2005.01.004

Bull, R., Marschark, M., Sapere, P., Davidson, W. A., Murphy, D., & Nordmann, E. (2011). Numerical estimation in deaf and hearing adults. *Learning and Individual Differences, 21*(4), 453-457. doi: 10.1016/j.lindif.2011.02.001

Burton, M. W., LoCasto, P. C., Krebs-Noble, D., & Gullapalli, R. P. (2005). A systematic investigation of the functional neuroanatomy of auditory and visual phonological processing. *Neuroimage, 26*(3), 647-661. doi: 10.1016/j.neuroimage.2005.02.024

Butterworth, B. (2010). Foundational numerical capacities and the origins of dyscalculia. *Trends in Cognitive Sciences, 14*(12), 534-541. doi: 10.1016/j.tics.2010.09.007

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience, 12*(1), 1-47.

Campbell, J. I. D. (1994). Architectures for numerical cognition. *Cognition, 53*(1), 1-44.

Campbell, J. I. D. (1997). On the relation between skilled performance of simple division and multiplication. *Journal of Experimental Psychology: Learning Memory and Cognition, 23*(5), 1140-1159.

Cardin, V., Orfanidou, E., Rönnberg, J., Capek, C. M., Rudner, M., & Woll, B. (2013). Dissociating cognitive and sensory neural plasticity in human superior temporal cortex. *Nature Communications, 4*, 5. doi: 10.1038/ncomms2463

Carlson, N. R. (2010). *Physiology of Behaviour* (10th ed.). Boston, MA: Allyn & Bacon, Pearson Education Inc.

Chochon, F., Cohen, L., van de Moortele, P. F., & Dehaene, S. (1999). Differential contributions of the left and right inferior parietal lobules to number processing. *Journal of Cognitive Neurosciences, 11*(6), 617-630.

Classon, E., Rudner, M., & Rönnberg, J. (2013). Working memory compensates for hearing related phonological processing deficit. *Journal of Communication Disorders, 46*(1), 17-29. doi: 10.1016/j.jcomdis.2012.10.001

Conrad, R. (1972). Short-term memory in the deaf: a test for speech coding. *The British journal of psychology, 63*(2), 173-180. doi: 10.1111/j.2044-8295.1972.tb02097.x

Corina, D. P., Lawyer, L. A., Hauser, P., & Hirshorn, E. (2013). Lexical Processing in Deaf Readers: An fMRI Investigation of Reading Proficiency. *PLoS ONE, 8*(1), e54696. doi: 10.1371/journal.pone.0054696

Cowan, N. (2000). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87-185. doi: 10.1017/ S0140525X01003922

Cutler, A. (2008). The 34th Sir Frederick Bartlett Lecture The abstract representations in speech processing. *Quarterly Journal of Experimental Psychology, 61*(11), 1601-1619. doi: 10.1080/ 13803390802218542

Danermark, B. (2002). Interdisciplinary research and critical realism: the example of disability research. *International Journal of Critical Realism, 1*, 56-64.

Danermark, B. (2005). Handikappforskning som tvärvetenskap. Möjligheter och utmaningar [Disability as interdisciplinary science. Possibilities and challenges]. In M. Söder (Ed.), *Forskning om funktionshinder. Problem, utmaningar och möjligheter. [Research about disability. Problems, challenges and possibilities]*. Lund: Studentlitteratur.

Darwin, C. J., Turvey, M. T., & Crowder, R. G. (1972). An auditory analogue of the sperling partial report procedure: Evidence for brief auditory storage. *Cognitive Psychology, 3*(2), 255-267. doi: 10.1016/0010-0285(72)90007-2

De Smedt, B., Taylor, J., Archibald, L., & Ansari, D. (2010). How is phonological processing related to individual differences in children's arithmetic skills? *Developmental Sciences, 13*(3), 508-520. doi: 10.1111/j.1467-7687.2009.00897.x

Dehaene, S. (1992). Varieties of numerical abilities. *Cognition, 44*(1-2), 1-42. doi: 10.1016/0010-0277(92)90049-N

Dehaene, S. (1997). *The number sense - How the mind creates mathematics*. New York, NY: Oxford University Press.

Dehaene, S., & Cohen, L. (1995). Towards an anatomical and functional model of number processing. *Mathematical Cognition, 1*, 83-120. doi: 10.1016/S0010-0277(00)00123-2

Dehaene, S., Dehaene-Lambertz, G., & Cohen, L. (1998). Abstract representations of numbers in the animal and human brain. *Trends in Neurosciences, 21*(8), 355-361. doi: 10.1016/S0166-2236(98)01263-6

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). Three parietal circuits for number processing. *Cognitive Neuropsychology, 20*(3), 487-506. doi: 10.1080/02643290244000239

Dehaene, S., Spelke, E., Pinel, P., Stanescu, R., & Tsivkin, S. (1999). Sources of mathematical thinking: Behavioral and brain-imaging evidence. *Science, 284*(5416), 970-974. doi: 10.1126/science.284.5416.970

Dormal, V., Andres, M., Dormal, G., & Pesenti, M. (2010). Mode-dependent and mode-independent representations of numerosity in the right intraparietal sulcus. *NeuroImage, 52*(4), 1677-1686. doi: 10.1016/j.neuroimage.2010.04.254

Eger, E., Michel, V., Thirion, B., Amadon, A., Dehaene, S., & Kleinschmidt, A. (2009). Deciphering Cortical Number Coding from Human Brain Activity Patterns. *Current Biology, 19*(19), 1608-1615. doi: 10.1016/j.cub.2009.08.047

Emmorey, K. (2002). *Language, cognition & the brain - Insights from sign language research*. Mahwah, NJ: Lawrence Erlbaum Associates.

Emmorey, K., McCullough, S., Mehta, S., & Grabowski, T. J. (2014). How sensory-motor systems impact the neural organization for language: Direct contrasts between spoken and signed language. *Frontiers in Psychology, 5*(MAY). doi: 10.3389/fpsyg.2014.00484

Eriksson, P. (1999). *Dövas historia. I Sverige och något om övriga Norden. [History of the deaf. In Sweden and the Nordic countries.]*. Örebro: SIH Läromedel.

Fehr, T. (2013). A hybrid model for the neural representation of complex mental processing in the human brain. *Cognitive Neurodynamics, 7*(2), 89-103. doi: 10.1007/s11571-012-9220-2

Fehr, T., Code, C., & Herrmann, M. (2007). Common brain regions underlying different arithmetic operations as revealed by conjunct fMRI-BOLD activation. *Brain Research, 1172*(1), 93-102. doi: 10.1016/j.brainres.2007.07.043

Foisack, E. (2003). *Döva barns begreppsbildning i matematik [Deaf children's conceptualization in mathematics]*. (PhD), Malmö university college, Malmö. (7)

Friederici, A. D., & Gierhan, S. M. E. (2013). The language network. *Current Opinion in Neurobiology, 23*(2), 250-254.

Friedrich, R., & Friederici, A. D. (2009). Mathematical logic in the human brain: Syntax. *PLoS ONE, 4*(5). doi: 10.1371/journal.pone.0005599

Fukuda, K., Awh, E., & Vogel, E. K. (2010). Discrete capacity limits in visual working memory. *Curr Opin Neurobiol, 20*(2), 177-182. doi: 10.1016/j.conb.2010.03.005

Gathercole, S. E., Alloway, T. P., Willis, C., & Adams, A. M. (2006). Working memory in children with reading disabilities. *Journal of Experimental Child Psychology, 93*(3), 265-281. doi: 10.1016/j.jecp.2005.08.003

Grabner, R. H., Ansari, D., Reishofer, G., Stern, E., Ebner, F., & Neuper, C. (2007). Individual differences in mathematical competence predict parietal brain activation during mental calculation. *Neuroimage, 38*(2), 346-356. doi: 10.1016/j.neuroimage.2007.07.041

Hagoort, P. (2005). On Broca, brain, and binding: A new framework. *Trends in Cognitive Sciences, 9*(9), 416-423.

Hall, M., & Bavelier, D. (2011). Short-term memory stages in sign vs. speech: The source of the serial span discrepancy. *Cognition, 120*(1), 54-66. doi: 10.1016/j.cognition.2011.02.014

Hanson, V. L. (1982). Short-term recall by deaf signers of American Sign Language: Implications of encoding strategy for order recall. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8*(6), 572-583. doi: 10.1037/0278-7393.8.6.572

Heimler, B., Weisz, N., & Collignon, O. (2014). Revisiting the adaptive and maladaptive effects of crossmodal plasticity. *Neuroscience*. doi: 10.1016/j.neuroscience.2014.08.003

Hickok, G. (2009). The functional neuroanatomy of language. *Physics of Life Reviews, 6*(3), 121-143. doi: 10.1016/j.plrev.2009.06.001

Hickok, G., & Poeppel, D. (2004). Dorsal and ventral streams: A framework for understanding aspects of the functional anatomy of language. *Cognition, 92*(1-2), 67-99. doi: 10.1016/j.cognition.2003.10.011

Hickok, G., & Poeppel, D. (2007). The cortical organization of speech processing. *Nature Reviews Neuroscience, 8*(5), 393-402. doi: 10.1038/nrn2113

Hitch, G. J. (1978). The role of short-term working memory in mental arithmetic. *Cognitive Psychology, 10*(3), 302-323.

Hopkins, J. (2008). Choosing how to write sign language: A sociolinguistic perspective. *International Journal of the Sociology of Language*(192), 75-89. doi: 10.1515/IJSL.2008.036

Huettel, S. A., Song, A. W., & McCarthy, G. (2009). *Functional magnetic resonance imaging*. Sunderland, MA, USA: Sinauer Associates, Inc.

Hutzler, F. (2014). Reverse inference is not a fallacy per se: Cognitive processes can be inferred from functional imaging data. *NeuroImage, 84*, 1061-1069. doi: 10.1016/ j.neuroimage.2012.12.075

Hyde, M., Zevenbergen, R., & Power, D. (2003). Deaf and hard of hearing students' performance on arithmetic word problems. *American Annals of the Deaf, 148*(1), 56-64. doi: 0002-726X

Ibertsson, T. (2009). *Cognition and communication in children/adolescents with cochlear implant.* (Doctoral), Lund University, Lund, Sweden.

Ischebeck, A., Zamarian, L., Siedentopf, C., Koppelstätter, F., Benke, T., Felber, S., & Delazer, M. (2006). How specifically do we learn? Imaging the learning of multiplication and subtraction. *Neuroimage, 30*(4), 1365-1375. doi: 10.1016/j.neuroimage.2005.11.016

Jordan, N. C., Glutting, J., & Ramineni, C. (2010). The importance of number sense to mathematics achievement in first and third grades. *Learning and Individual Differences, 20*(2), 82-88. doi: 10.1016/j.lindif.2009.07.004

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review, 99*(1), 122-149.

Kandel, E., Schwartz, J. H., Jessell, T. M., Siegelbaum, S. A., & Huspeth, A. J. (2012). *Principles of Neural Science* (5 ed.): McGraw-Hill Professional.

Kawashima, R., Taira, M., Okita, K., Inoue, K., Tajima, N., Yoshida, H., . . . Fukuda, H. (2004). A functional MRI study of simple arithmetic - a comparison between children and adults. *Cognitive Brain Research, 18*(3), 227-233. doi: 10.1016/j.cogbrainres.2003.10.009

Keating, E., Edwards, T., & Mirus, G. (2008). Cybersign and new proximities: Impacts of new communication technologies on space and language. *Journal of Pragmatics, 40*(6), 1067-1081. doi: 10.1016/j.pragma.2008.02.009

Kelly, R. R., Lang, H. G., Mousley, K., & Davis, S. M. (2003). Deaf college students' comprehension of relational language in arithmetic compare problems. *Joural of Deaf Studies and Deaf Education, 8*(2), 120-132. doi: 10.1093/deafed/eng006

Klima, E. S., & Bellugi, U. (1976). Poetry and song in a language without sound. *Cognition, 4*(1), 45-97. doi: 10.1016/0010-0277(76)90010-x

Koenigs, M., Barbey, A. K., Postle, B. R., & Grafman, J. (2009). Superior parietal cortex is critical for the manipulation of information in working memory. *Journal of Neuroscience, 29*(47), 14980-14986. doi: 10.1523/JNEUROSCI.3706-09.2009

Kong, J., Wang, C., Kwong, K., Vangel, M., Chua, E., & Gollub, R. (2005). The neural substrate of arithmetic operations and procedure complexity. *Cognitive Brain Research, 22*(3), 397-405. doi: 10.1016/j.cogbrainres.2004.09.011

Koo, D., Crain, K., LaSasso, C., & Eden, G. F. (2008). Phonological Awareness and Short-Term Memory in Hearing and Deaf Individuals of Different Communication Backgrounds. *Learning, Skill Acquisition, Reading, and Dyslexia, 1145*, 83-99. doi: 10.1196/annals.1416.025

Kritzer, K. I. (2009). Barely started and already left behind: A descriptive analysis of the mathematics ability demonstrated by young deaf children. *Journal of Deaf Studies and Deaf Education, 14*(4), 409-421. doi: 10.1093/deafed/enp015

Lee, K. M., & Kang, S. Y. (2002). Arithmetic operation and working memory: Differential suppression in dual tasks. *Cognition, 83*(3), B63-B68. doi: 10.1016/S0010-0277(02)00010-0

Levänen, S., Jousmäki, V., & Hari, R. (1998). Vibration-induced auditory-cortex activation in a congenitally deaf adult. *Current Biology, 8*(15), 869-872.

LGr 80. (1983). *Supplement till LGr 80, Läroplan för speicalskolan. Kompletterande föreskrifter till LGr 80.* Stockholm: Liber UtbildningsFörlaget.

Liddell, S. K. (2003). *Grammar, gesture, and meaning in American Sign Language*. Cambridge: Cambridge University Press.

Logan, K., Maybery, M., & Fletcher, J. (1996). The short-term memory of profoundly deaf people for words, signs, and abstract spatial stimuli. *Applied Cognitive Psychology, 10*(2), 105-119.

Macsweeney, M., Brammer, M. J., Waters, D., & Goswami, U. (2009). Enhanced activation of the left inferior frontal gyrus in deaf and dyslexic adults during rhyming. *Brain, 132*(7), 1928-1940. doi: 10.1093/brain/awp129

Macsweeney, M., Goswami, U., & Neville, H. (2013). The neurobiology of rhyme judgment by deaf and hearing adults: an ERP study. *Journal of Cognitive Neuroscience, 25*(7), 1037-1048. doi: 10.1162/jocn_a_00373

MacSweeney, M., Waters, D., Brammer, M. J., Woll, B., & Goswami, U. (2008). Phonological processing in deaf signers and the impact of age of first language acquisition. *NeuroImage, 40*(3), 1369-1379. doi: 10.1016/j.neuroimage.2007.12.047

MacSweeney, M., Woll, B., Campbell, R., McGuire, P. K., David, A. S., Williams, S. C. R., . . . Brammer, M. J. (2002). Neural systems underlying British sign language and audio-visual English processing in native users. *Brain, 125*(7), 1583-1593.

Marschark, M. (2003). *Cognitive functioning in deaf adults and children*. New York: Oxford University Press.

Marschark, M., Convertino, C., McEvoy, C., & Masteller, A. (2004). Organization and Use of the Mental Lexicon by Deaf and Hearing Individuals. *American Annals of the Deaf, 149*(1), 51-61. doi: 10.1353/aad.2004.0013

Marshall, C., Rowley, K., & Atkinsson, J. (2013). Modality-dependent and -independent factors in the organisation of the signed language lexicon: Insights from semantic and phonological fluency tasks in BSL. *Journal of Psycholinguistic Research, Epub ahead of print*. doi: 10.1007/s10936-013-9271-5

Masataka, N. (2006). Differences in arithmetic subtraction of nonsymbolic numerosities by deaf and hearing adults. *Journal of Deaf Studies and Deaf Education, 11*(2), 139-143. doi: 10.1093/deafed/enj016

Masataka, N., Ohnishi, T., Imabayashi, E., Hirakata, M., & Matsuda, H. (2006). Neural correlates for numerical processing in the manual mode. *Journal of Deaf Studies and Deaf Education, 11*(2), 144-152.

Mayberry, R. I., Chen, J. K., Witcher, P., & Klein, D. (2011). Age of acquisition effects on the functional organization of language in the adult brain. *Brain and Language, 119*(1), 16-29. doi: 10.1016/j.bandl.2011.05.007

Mayberry, R. I., del Giudice, A. A., & Lieberman, A. M. (2011). Reading achievement in relation to phonological coding and awareness in deaf readers: A meta-analysis. *Journal of Deaf Studies and Deaf Education, 16*(2), 164-188. doi: 10.1093/deafed/enq049

Mayberry, R. I., & Eichen, E. B. (1991). The long-lasting advantage of learning sign language in childhood: Another look at the critical period for language acquisition. *Journal of Memory and Language, 30*, 486-512.

Mayberry, R. I., & Lock, E. (2003). Age constraints on first versus second language acquisition: Evidence for linguistic plasticity and epigenesis. *Brain and Language, 87*(3), 369-384. doi: 10.1016/S0093-934X(03)00137-8

McCloskey, M. (1992). Cognitive mechanisms in numerical processing: Evidence from acquired dyscalculia. *Cognition, 44*(1-2), 107-157.

McCloskey, M., Caramazza, A., & Basili, A. (1985). Cognitive mechanisms in number processing and calculation: Evidence from dyscalculia. *Brain and Cognition, 4*(2), 171-196.

Meristo, M., Falkman, K., Hjelmquist, E., Tedoldi, M., Surian, L., & Siegal, M. (2007). Language access and theory of mind reasoning: evidence from deaf children in bilingual and oralist environments. *Developmental Psychology, 43*(5), 1156-1169. doi: 10.1037/0012-1649.43.5.1156

Monti, M. M., Parsons, L. M., & Osherson, D. N. (2012). Thought Beyond Language: Neural Dissociation of Algebra and Natural Language. *Psychological Science, 23*(8), 914-922. doi: 10.1177/0956797612437427

Morere, D. A., & Roberts, R. (2012). Fingerspellning. In D. A. Morere & T. Allen (Eds.), *Assessing Literacy in Deaf Individuals: Neurocognitive Measurement and Predictors,* (pp. 179-198). New York: Springer Science+Business Media.

Musselman, C. (2000). How Do Children Who Can't Hear Learn to Read an Alphabetic Script? A Review of the Literature on Reading and Deafness. *Journal of Deaf Studies and Deaf Education, 5*(1), 9-31. doi: 10.1093/deafed/5.1.9

Nagels, A., Chatterjee, A., Kircher, T., & Straube, B. (2013). The role of semantic abstractness and perceptual category in processing speech accompanied by gestures. *Frontiers in Behavioural Neuroscience, 7*, 181. doi: 10.3389/fnbeh.2013.00181

Nunes, T., Bryant, P., Burman, D., Bell, D., Evans, D., & Hallett, D. (2009). Deaf Children's Informal Knowledge of Multiplicative Reasoning. *Journal of Deaf Studies and Deaf Education, 14*(2), 260-277. doi: 10.1093/deafed/enn040

Nyberg, L. (2008). *Kognitiv neurovetenskap* (2 ed.). Lund, Sweden: Studentlitteratur AB.

Pa, J., Wilson, S. M., Pickell, H., Bellugi, U., & Hickok, G. (2008). Neural organization of linguistic short-term memory is sensory modality-dependent: Evidence from signed and spoken language. *Journal of Cognitive Neuroscience, 20*(12), 2198-2210. doi: 10.1162/jocn.2008.20154

Padden, C., & Gunsauls, D. C. (2003). How the alphabet came to be used in a sign language. *Sign language studies, 4*(1), 10-33. doi: 10.1353/sls.2003.0026

Petersson, K. M., Silva, C., Castro-Caldas, A., Ingvar, M., & Reis, A. (2007). Literacy: A cultural influence on functional left-right differences in the inferior parietal cortex. *European Journal of Neuroscience, 26*(3), 791-799. doi: 10.1111/j.1460-9568.2007.05701.x

Piazza, M. (2010). Neurocognitive start-up tools for symbolic number representations. *Trends in Cognitive Sciences, 14*(12), 542-551. doi: 10.1016/j.tics.2010.09.008

Piazza, M., Fumarola, A., Chinello, A., & Melcher, D. (2011). Subitizing reflects visuo-spatial object individuation capacity. *Cognition, 121*(1), 147-153. doi: 10.1016/j.cognition.2011.05.007

Piazza, M., Mechelli, A., Butterworth, B., & Price, C. J. (2002). Are subitizing and counting implemented as separate or functionally overlapping processes? *NeuroImage, 15*(2), 435-446.

Pinel, P., Dehaene, S., Rivière, D., & LeBihan, D. (2001). Modulation of parietal activation by semantic distance in a number comparison task. *NeuroImage, 14*(5), 1013-1026.

Pintner, R., & Paterson, D. G. (1917). A comparison of deaf and hearing children in visual memory for digits. *Journal of Experimental Psychology, 2*(1), 76-88. doi: 10.1037/h0072870

Poldrack, R. A. (2006). Can cognitive processes be inferred from neuroimaging data? *Trends in Cognitive Sciences, 10*(2), 59-63. doi: 10.1016/j.tics.2005.12.004

Poldrack, R. A., Wagner, A. D., Prull, M. W., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. E. (1999). Functional specialization for semantic and phonological processing in the left inferior prefrontal cortex. *Neuroimage, 10*(1), 15-35. doi: 10.1006/nimg.1999.0441

Prado, J., Mutreja, R., Zhang, H. C., Mehta, R., Desroches, A. S., Minas, J. E., & Booth, J. R. (2011). Distinct Representations of Subtraction and Multiplication in the Neural Systems for Numerosity and Language. *Human Brain Mapping, 32*(11), 1932-1947. doi: 10.1002/hbm.21159

Repovš, G. B., A. (2006). The multi-component model of working memory: Explorations in experimental cognitive psychology. *Neuroscience, 139*(1), 5-21. doi: 10.1016/j.neuroscience.2005.12.061

Rickard, T. C., Romero, S. G., Basso, G., Wharton, C., Flitman, S., & Grafman, J. (2000). The calculating brain: An fMRI study. *Neuropsychologia, 38*(3), 325-335. doi: 10.1016/S0028-3932(99)00068-8

Roos, C. (2006). Teckenspråk och pedagogik [Sign language and pedagogy] i Teckenspråk och teckenspråkiga, *SOU* 2006:29, Stockholm, Sweden.

Roos, C. (2009). Fakta om döva barn? En förstudie om döva små barn [Facts about deaf children. A pilot study on young deaf children]: Karlstad university.

Rosen, V. M., & Engle, R. W. (1997). Forward and backward serial recall. *Intelligence, 25*(1), 37-47. doi: 10.1016/S0160-2896(97)90006-4

Rudner, M., Andin, J., & Rönnberg, J. (2009). Working memory, deafness and sign language. *Scandinavian Journal of Psychology, 50*(5), 495-505. doi: 10.1111/j.1467-9450.2009.00744.x

Rudner, M., Fransson, P., Ingvar, M., Nyberg, L., & Rönnberg, J. (2007). Neural representation of binding lexical signs and words in the episodic buffer of working memory. *Neuropsychologia, 45*(10), 2258-2276. doi: 10.1016/j.neuropsychologia.2007.02.017

Rudner, M., Karlsson, T., Gunnarsson, J., & Rönnberg, J. (2013). Levels of processing and language modality specificity in working memory. *Neuropsychologia, 51*(4), 656-666. doi: 10.1016/j.neuropsychologia.2012.12.011

Rudner, M., Orfanidou, E., Cardin, V., Capek, C., Woll, B., & Rönnberg, J. (2012). *Reading ability in adult deaf native signers is positively associated with their ability to judge the grammatically of their native sign language*. Paper presented at the Neurobiology of Language, San Sebastian.

Rudner, M., & Rönnberg, J. (2008a). Explicit processing demands reveal language modality-specific organization of working memory. *Journal of Deaf Studies and Deaf Education, 13*(4), 466-484. doi: 10.1093/deafed/enn005

Rudner, M., & Rönnberg, J. (2008b). The role of the episodic buffer in working memory for language processing. *Cognitive Processing, 9*(1), 19-28. doi: 10.1007/s10339-007-0183-x

Rönnberg, J., Rudner, M., & Ingvar, M. (2004). Neural correlates of working memory for sign language. *Cognitive Brain Research, 20*(2), 165-182. doi: 10.1016/j.cogbrainres.2004.03.002
Rönnberg, J., Söderfeldt, B., & Risberg, J. (2000). The cognitive neuroscience of signed language. *Acta Psychologica, 105*(2-3), 237-254.
Sandler, W., & Lillo-Martin, D. (2006). *Sign language and linguistic universals*. Cambridge, NY: Cambridge university press.
Senghas, A., & Coppola, M. (2001). Children Creating Language: How Nicaraguan Sign Language Acquired a Spatial Grammar. *Psychological Science, 12*(4), 323-328. doi: 10.1111/1467-9280.00359
Serrano Pau, C. (1995). The deaf child and solving problems of arithmetic. The importance of comprehensive reading. *American Annals of the Deaf, 140*(3), 287-290. doi: 10.1353/aad.2012.0599
Shivde, G., & Thompson-Schill, S. L. (2004). Dissociating semantic and phonological maintenance using fMRI. *Cognitive, Affective and Behavioral Neuroscience, 4*(1), 10-19.
Simon, O., Mangin, J. F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe. *Neuron, 33*(3), 475-487. doi: 10.1016/s0896-6273(02)00575-5
SOU 2007:87 (2007). *Ökad likvärdighet för elever med funktionshinder [Increased equivalence for pupils with disabilities]*. Stockholm, Sweden
Specht, K. (2013). Mapping a lateralization gradient within the ventral stream for auditory speech perception. *Frontiers in Human Neuroscience, 7*, 629. doi: 10.3389/fnhum. 2013.00629
Sperling, G. (1960). The information available in breif visual presentation. *Cognitive Psychology, 74*, 1-29.
Stanescu-Cosson, R., Pinel, P., van De Moortele, P. F., Le Bihan, D., Cohen, L., & Dehaene, S. (2000). Understanding dissociations in dyscalculia: a brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. *Brain, 123 (Pt 11)*, 2240-2255.
Sutton-Spence, R. (2001). Phonological "deviance" in British sign language poetry. *Sign Language Studies, 2*(1), 62-83. doi: 10.1353/sls.2001.0029
Sutton-Spence, R., & Woll, B. (1999). *The linguistics of British sign language*. Cambridge: Cambridge University Press.
Tan, L. H., Laird, A. R., Li, K., & Fox, P. T. (2005). Neuroanatomical correlates of phonological processing of Chinese characters and alphabetic words: a meta-analysis. *Human Brain Mapping, 25*(1), 83-91. doi: 10.1002/hbm.20134
Tan, L. H., Spinks, J. A., Eden, G. F., Perfetti, C. A., & Siok, W. T. (2005). Reading depends on writing, in Chinese. *Proceedings of the National Academy of Sciences of the United States of America, 102*(24), 8781-8785. doi: 10.1073/pnas.0503523102
Svenskt teckenspråkslexikon [Swedish sign langugae dictionary]. (2009). *http://130.237.171.78/fmi/iwp/cgi?-db=Svenskt%20teckenspr%C3%A5kslexikon&-loadframes*.
Titus, J. C. (1995). The concept of fractional number among deaf and hard of hearing students. *American Annals of the Deaf, 140*(3), 255-262. doi: 10.1353/aad.2012.0582
Traxler, C. B. (2000). The Stanford Achievement Test, 9th Edition: National Norming and Performance Standards for Deaf and Hard-of-Hearing Students. *Journal of Deaf Studies and Deaf Education, 5*(4), 337-348. doi: 10.1093/deafed/5.4.337
Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language, 28*(2), 127-154. doi: 10.1016/0749-596X(89)90040-5

Unsworth, N., & Engle, R. W. (2005). Working memory capacity and fluid abilities: Examining the correlation between Operation Span and Raven. *Intelligence, 33*(1), 67-81. doi: 10.1016/j.intell.2004.08.003

Unsworth, N., & Engle, R. W. (2007). On the division of short-term and working memory: An examination of simple and complex span and their relation to higher order abilities. *Psychological Bulletin, 133*(6), 1038-1066. doi: 10.1037/0033-2909.133.6.1038

Vigneau, M., Beaucousin, V., Herve, P. Y., Duffau, H., Crivello, F., Houde, O., . . . Tzourio-Mazoyer, N. (2006). Meta-analyzing left hemisphere language areas: Phonology, semantics, and sentence processing. *Neuroimage, 30*(4), 1414-1432. doi: 10.1016/j.neuroimage. 2005.11.002

Werngren-Elgström, M., Dehlin, O., & Iwarsson, S. (2003). A Swedish prevalence study of deaf people using sign language: A prerequisite for deaf studies. *Disability and Society, 18*(3), 311-323.

WHO. (2001). International classification of functioning, disability and health: ICF. In W. H. Organization (Ed.). Geneva.

WHO. (2012). Prevention of blindness and deafness - Estimates.

WHO. (2014). Grades of hearing impairment. from http://www.who.int/pbd/deafness/ hearing_impairment_grades/en/

Wilson, A., & Dehaene, S. (2007). Number sense and developmental dyscalculia In D. Coch, G. Dawson, & K. Fischer (Eds.), *Human behaviour and the developing brain: atypical development* (pp. 212-238). New York, NY: Guilford Press.

Wilson, M., Bettger, J., Niculae, I., & Klima, E. (1997). Modality of language shapes working memory: Evidence from digit span and spatial span in ASL signers. *Journal of Deaf Studies and Deaf Education, 2*(3), 150-160. doi: 10.1093/oxfordjournals.deafed.a014321

Wilson, M., & Emmorey, K. (1997). A visuospatial "phonological loop" in working memory: Evidence from American Sign Language. *Memory and Cognition, 25*(3), 313-320. doi: 10.3758/BF03211287

Wilson, M., & Emmorey, K. (1998). A 'word length effect' for sign language: Further evidence for the role of language in structuring working memory. *Memory and Cognition, 26*(3), 584-590. doi: 10.3758/BF03201164

Wilson, M., & Emmorey, K. (2006a). Comparing sign language and speech reveals a universal limit on short-term memory capacity. *Psychological Science, 17*(8), 682-683. doi: 10.1111/j.1467-9280.2006.01766.x

Wilson, M., & Emmorey, K. (2006b). No difference in short-term memory span between sign & speech. *Psychological Science, 17*(12), 1093-1094. doi: 10.1111/j.14679280.2006.01835.x

Zarfaty, Y., Nunes, T., & Bryant, P. (2004). The performance of young deaf children in spatial and temporal number tasks. *Journal of Deaf Studies and Deaf Education, 9*(3), 315-326. doi: 10.1093/deafed/enh034

Zhou, X. L., Chen, C. S., Zang, Y. F., Dong, Q., Chen, C. H., Qiao, S. B., & Gong, Q. Y. (2007). Dissociated brain organization for single-digit addition and multiplication. *Neuroimage, 35*(2), 871-880. doi: 10.1016/j.neuroimage.2006.12.017

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