Modalities of Mind

Modality-specific and nonmodality-specific aspects of working memory for sign and speech

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Linköping Studies in Arts and Science • No. 337
Studies from the Swedish Institute for Disability Research • No. 18

Linköpings universitet
The Swedish Institute for Disability Research
at the Department of Behavioural Sciences
Linköping, 2005

Linköping Studies in Arts and Science • No. 337
Studies from the Swedish Institute for Disability Research • No. 18

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Distributed by:
The Department of Behavioural Sciences
Linköpings universitet
581 83 Linköping
Sweden

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Upplaga 1:1
ISBN: 91-85457-10-8
ISSN: 0282-9800
ISSN: 1650-1128

Cover illustration: Lucy Roth
Tryckeri: UniTryck, Linköping, 2005

‘Surprising as it may sound, the mind exists in and for an integrated organism; our minds would not be the way they are if it were not for the interplay of body and brain during evolution, during individual development, and at the current moment. The mind had to be first about the body, or it could not have been. On the basis of the ground reference that the body continuously provides, the mind can then be about many other things, real and imaginary.’ (Antonio Damasio, *Descartes’ Error)*

Abstract

Language processing is underpinned by working memory and while working memory for signed languages has been shown to display some of the characteristics of working memory for speech-based languages, there are a range of anomalous effects related to the inherently visuospatial modality of signed languages. On the basis of these effects, four research questions were addressed in a series of studies:

1. Are differences in working memory storage for sign and speech reflected in neural representation?
2. Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?
3. Is working memory for sign language enhanced by a spatial style of information presentation?
4. Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

The results of the studies showed that:

1. Working memory for sign and speech is supported by a combination of modality-specific and nonmodality-specific neural networks.
2. Switching between sign and speech during a working memory task is supported by semantic rather than executive processes.
3. Working memory performance in educationally promoted native deaf signers is enhanced by a spatial style of presentation.
4. Word reversal is a matter of mind-twisting, rather than tongue-twisting.

These findings indicate that working memory for sign and speech has modality-specific components as well as nonmodality-specific components. Modality-specific aspects can be explained in terms of Wilson's (2001) sensorimotor account, which is based on the component model (Baddeley, 1986;

2000), given that the functionality of the visuospatial sketchpad is extended to include language processing. Nonmodality-specific working memory processing is predicted by Rönnberg's (2003) model of cognitive involvement in language processing. However, the modality-free, cross-modal and extra-modal aspects of working memory processing revealed in the present work can be explained in terms of the component model, providing the functionality and neural representation of the episodic buffer are extended.

A functional ontology is presented which ties cognitive processes to their neural representation, along with a model explaining modality-specific findings relating to sign language cognition. Predictions of the ontology and the model are discussed in relation to future work.

Papers

This thesis is based on the following papers which will be referred to as Papers I, II, III, IV & V in the text.

I. Rönnberg, J., Rudner, M. & Ingvar, M. (2004). Neural correlates of working memory for sign language. *Cognitive Brain Research, 20,* 165-182.
II. Rudner, M., Fransson, P., Ingvar, M., Nyberg, L. & Rönnberg, J. (Submitted). Speech-sign switching in working memory is supported by semantic networks.
III. Rudner M. & Rönnberg, J. (Manuscript). Space for compensation – further support for a visuospatial array for temporary storage in working memory for deaf native signers.
IV. Rudner, M. & Rönnberg, J. (2004). Perceptual saliency in the visual channel enhances explicit language processing. *Iranian Audiology, 3 (1),* 16-26.
V. Rudner M., Rönnberg, J. & Hugdahl, K. (2005). Reversing spoken items – mind twisting not tongue twisting. *Brain and Language, 92 (1),* 78-90.

Contents

Introduction

Working memory is those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition, including novel as well as familiar, skilled tasks (Miyake & Shah, 1999). Thirty years ago, Baddeley and Hitch (1974) proposed a component model of working memory where a central executive controls two slave loops, one for verbal information and one for visuospatial information of a non-linguistic nature. This model has proved to be remarkably robust and over the years its cognitive contours have gradually become more clearly delineated (Baddeley, 2000) and its neural substrates revealed (Jonides, Lacey & Nee, 2005). However, it does not specifically take into account languages that are visuospatially based; the sign languages of the Deaf[1]. Thus, sign language processing provides an interesting challenge to the component model of working memory.

Working memory for sign language has been shown to display some of the characteristics of working memory for speech (Wilson & Emmorey, 2003) but at the same time there are a range of anomalous effects relating to sign language cognition (Rönnberg, Söderfeldt & Risberg, 2000). Specifically, working memory for sign language has a temporary storage component that seems to be spatially organised (Wilson, Bettger, Niculae & Klima, 1997), and sign language use appears to enhance visual mental imagery skills, suggesting a link between language processing and non-linguistic visuospatial cognition (Emmorey, Kosslyn & Bellugi, 1993).

The work presented in this thesis investigates working memory processing in deaf signers, hearing signers and hearing non-signers, by measuring

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[1] Following convention, in this thesis, lowercase *deaf* is used to denote audiological status while uppercase *Deaf* is used to denote the use of sign language and membership of the Deaf community.

performance during a range of cognitive tasks. Performance is measured in terms of traditional behavioural measures, accuracy and reaction time, and cerebral haemodynamic response. The specific questions addressed are:

1. Are differences in working memory storage for sign and speech reflected in neural representation?
2. Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?
3. Is working memory for sign language enhanced by a spatial style of information presentation?
4. Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

1
Sign language

Just as spoken languages are the natural mode of communication for hearing people, signed languages are the natural mode of communication for deaf people. There is no universal sign language, instead there are many distinct sign languages that have evolved independently of each other. For example, American Sign Language (ASL) and British Sign Language (BSL) are mutually unintelligible, despite the fact that they are surrounded by the same spoken language (Emmorey, 2002). Sign languages are usually named after the country or region where they are used and the exact number of sign languages in the world is not known (Emmorey, 2002). Unlike spoken languages, sign languages lack a written form, although they do lend themselves to poetry and theatre (Klima & Bellugi, 1976).

Status of sign language

Sign languages have been used by Deaf people since time immemorial, but they have not always been accepted as functionally adequate: Aristotle, for example, noted that without hearing, people cannot learn. The importance of sign language in education was recognised and implemented by Abbé Charles Michel de L'Épée in Paris in the eighteenth century. The work of Abbé de L'Épée inspired a number of educationalists internationally, including Pär Aron Borg in Sweden and Thomas Hopkins Gallaudet in North America. Borg started the first deaf school in Sweden in 1809. To begin with, sign language was used, but in the 1860s, the use of speech and lip-reading, known as oralism, was introduced. Oralism gained acceptance at the international congress of deaf teachers in Milan in 1880 and sign language was dismissed as situationally determined gestures and diffuse gesticulation. The oralist mode of communication dominated internationally for over a hundred years until the mid 1970s, when advances in sign language research established signed languages as languages in their own right. Swedish Sign Language (SSL) was officially recognised in 1981, which led to a rapid increase in the status of sign language in Sweden, both inside and outside the classroom (Fredäng, 2003), and the rise of a new generation of educationally promoted signers.

Language modality

The recognition of signed languages as natural human languages laid the foundation for a new field of study: sign language cognition. Spoken languages are transmitted in the form of a sound signal produced by the lungs, vocal chords, vocal tract and lips and an accompanying visual signal, and received either in the form of a sound signal perceived by the auditory system or in the form of a visual signal perceived by the visual system or both. This is the spoken language modality. Signed languages, on the other hand, are transmitted in the form of a visual signal alone, which is produced partly by a different set of articulators, the fingers, hands and arms, and also partly by facial expressions. This is the signed language modality. Thus, signed languages and spoken languages represent two different language modalities. Due to this, sign and speech, used together, can provide a powerful tool for investigating the nature of human language and cognition.

Sign language linguistics

The first widely recognised scientific paper to address the underlying regularities of any sign language was *Sign Language Structure: An Outline of the Visual Communication Systems of the American Deaf* (Stokoe, 1960). This paper shows that signed languages can be described in the same kind of structural terms as spoken languages. Since then, work has continued to highlight similarities and differences in the structures of signed and spoken languages. The bulk of this work has been performed in relation to ASL. However, it is reasonable to apply hypotheses generated by work on ASL to SSL (B. Bergman, personal communication, April 27, 2001). For example, it has been shown that both ASL and SSL employ classifier-like morphemes (Siple, 1997).

Signed languages can be analysed in terms of a hierarchical structure in which sign components combine to form individual signs and individual signs, in turn, can be combined to form sentences. This distinguishes primary sign languages from pantomime, in which transparent iconic gestures are strung together without any systematic combinatorial structure (Emmorey, 2002).

Although the structure of signed languages can be described in the same terms as that of spoken languages, it is not dependent on spoken languages for its development. The grammar of new sign languages emerges independently of the grammar of the spoken languages that surround them (e.g. Nicaraguan Sign Language, Senghas, 2003), showing that they constitute self-sufficient languages. Similarly, children growing up in a signing environment attain their sign language milestones in the same order as speakers and with roughly the same timetable. For example, hearing babies born to profoundly deaf parents produce silent, signed babble at the same age as hearing babies born to hearing parents produce vocal babble (Petitto, Holowka, Sergio & Ostry, 2001).

Phonology

The structure of language can be analysed at a number of different levels. Phonology is concerned with organisation at the sublexical level, in other words, the internal structure of words and signs, whereas syntax is concerned with organisation at the supralexical level, in other words, how signs or words are combined to form phrases and sentences. The work presented in this thesis focuses on sublexical and lexical organisation.

The term ‘phonology’ comes from the Greek phone = voice/sound and logos = word/speech and thus, we tend to associate it with speech and sound patterns. Indeed, phonology has been defined as the organisation of speech within specific languages (Clark & Yallop, 1995). However, abstracting to a higher level, phonology may be said to concern the mental organisation of language.

Phonological analysis has played a central role in the study of languages for more than two millenia. In contrast, the formal investigation of the linguistic structure of signed languages dates back only to the mid twentieth century, and thus, is only half a century old. In view of this, it is not surprising that the first sign language linguists looked to the more mature sister field for inspiration concerning theories and methods.

Sign language phonology

The study of the phonology of spoken language is concerned with the patterning of sounds at a sublexical level. Sign language phonology is concerned with the patterning of sign components at a sublexical level. Both are concerned with the mental organisation of language.

Stokoe's (1960) pioneering work laid the foundation for phonological analysis of signed languages by postulating that all lexical signs could be analysed in terms of the manual features constituting their execution: handshape, hand position and hand movement. These features can be compared to phonemes in spoken language which have a contrastive function. For example, the fact that *led* and *red* are distinct words in English indicates that [l] and [r] are distinct phonemes, as they are the only sounds that distinguish the two words. A similar logic can be applied to sign languages where manual features have a contrastive function. For example, in SSL the signs for *dog* and *hat* are executed with the same handshape and movement but in different positions in relation to the body, see Figure 1.

The other two features, handshape and movement can also be contrastive. In the same way that phonemes are language specific, in that not all spoken languages make use of the same sound contrasts, the specific features of signed languages are not universal. For example, in BSL there is a handshape in which the index and middle fingers are held down by the thumb; this sign handshape is not contrastive in SSL.

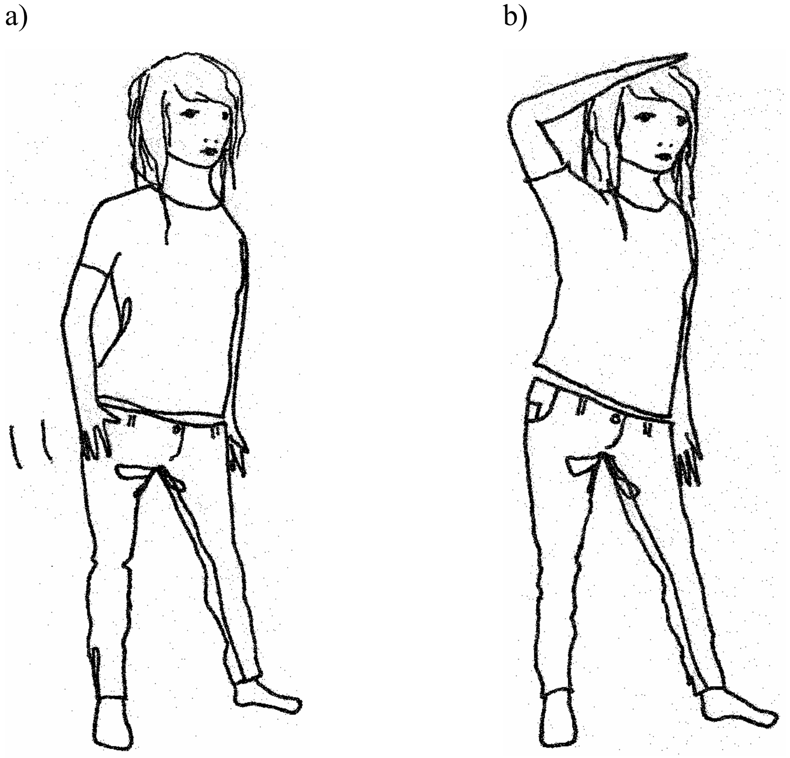

Figure 1. SSL signs for a) *dog* and b) *hat* share handshape and movement but are distinguished by hand position.

Phonological similarity

The initial phonemes of the English words *led* and *red* serve a contrastive function, while the final phonemes, which are identical, make them phonologically similar. Analogously, the SSL signs for *dog* and *hat* are also phonologically similar, because they share both a handshape and a movement, although one common feature is sufficient to constitute phonological similarity (Klima & Bellugi, 1976). Just as poetry and prose often rely on stylistic use of phonological similarity, for example, in the form of rhyme, phonological similarity in sign language plays a functional role in signed nursery rhymes and poetry (Sutton-Spence, 2001).

The role of the syllable

Whereas a phoneme is the smallest contrastive unit in the sound system of a spoken language, a syllable is a word or part of a word that can be pronounced with one impulse from the voice. A syllable always contains a vowel sound, and most syllables have consonants associated with the vowel. Thus, word syllables can be phonologically analysed in terms of phonemes. The features of signs are contrastive in the same way as phonemes, and functional similarities between vowels and sign movements have been pointed out (Liddell & Johnson, 1986), paving the way for a description of the sign-language syllable as a sign unit with a single movement (Brentari, 1998).

It is becoming increasingly apparent that the role of the syllable outweighs that of the phoneme in language processing. The first utterances of children are syllables rather than phonemes and speech perception research shows the prominence of the former in speech understanding (Plomp, 2002). The apparent importance of the phoneme has been explained as an artefact of our facility with written language, which is based on phoneme representations in the form of letters of the alphabet. Indeed, reading research has shown that phoneme segmentation and syllable based rhyme judgement are supported by distinct cognitive processes (Höien, Lundberg, Stanovich, & Bjaalid, 1995). Thus, not all phonological tasks require segmentation of speech into phonemes, in many cases, the syllable, a unit at a higher level of abstraction, is the appropriate level of analysis. Other phonological phenomena are based on the syllable; one of them is perceptual saliency.

Perceptual saliency

A syllable may be more or less perceptually salient depending on its sonority profile. Sonority is another field of phonological analysis where parallels can be drawn between signed and spoken languages. In relation to spoken languages, sonority can be defined in acoustic terms as a sound's loudness relative to that of other sounds with the same length, stress and pitch and it can be defined in articulatory terms as being correlated with the relative openness of the oral cavity of the vocal tract (Blevins, 1995). Thus, it may be said that if one speech segment is more sonorous than another, it is more perceptually salient both acoustically and visually. Similarly, one sign is more sonorous than another if it is more visually salient. This means that a sign articulated from the shoulder is more sonorous than one articulated from the finger (Brentari, 1998).

Each syllable has a sonority profile that can be described as rising to a sonority peak, associated with the vowel in speech or movement in sign, and then falling away. Thus, it is possible to categorise syllables according to their sonority profile. For example, syllables containing a vowel with a relatively low degree of sonority, for example, one of the high vowels [i, y, u], may be categorised as having a low sonority peak, and syllables containing a vowel with a relatively high degree of sonority, for example, one of the low vowels [a, ɑ], may be categorised as having a high sonority peak. As information about vowel height is carried by the first format (F1), relative sonority can also be related to relative frequency of F1 (Borden, Harris & Raphael, 1994).

There is evidence to suggest that phonological patterning relating to sonority has cognitive significance. This evidence comes from speech perception in infants (Lacerda, 1992; 1993) speech production in children (Ohala,1999) and speech production in persons with aphasia (Romani & Calabrese, 1998).

Sign language users

In Sweden today, SSL is the recognised first language of deaf people. All deaf children, whether or not they are born into Deaf families, and whether or not they are fitted with cochlear implants, are offered the opportunity to learn sign language. Early language experience, whether signed or spoken, is important for the development of language skills in later life (Mayberry, Lock & Kazmi, 2002). Despite this, not all congenitally deaf persons learn sign language from birth. On the other hand, hearing children of deaf parents learn sign language automatically in their home environment.

For the purposes of this thesis it is important to distinguish between sign language users with different backgrounds. Persons who have been exposed to sign language from birth and grown up using sign language are referred to as native signers, either deaf or hearing. Persons who have not been exposed to sign language from birth but who have come into contact with sign language early in life and used it during childhood are referred to as early signers, deaf or hearing. Persons who have learnt sign language as adults are referred to as late signers and persons who have no knowledge of sign language are non-signers.

Native, early and late signers have been shown to have different levels of sign language proficiency. Indeed, age of acquisition of sign language is correlated with sign language performance at all levels of linguistic structure (Mayberry & Eichen, 1991).

Neurocognition of sign language

Despite the inherently visuospatial nature of sign language, the literature on the neurocognition of sign language (see Rönnberg et al., 2000, for a review) indicates that, generally speaking, the neural correlates of sign language are very similar to those of spoken language, with involvement of the classical language areas in the left hemisphere. In addition, there is evidence to show more right hemisphere involvement in language processing for sign than speech (Bavelier et al., 1998; Neville et al., 1997, 1998).

Left for language

Pioneering work in the field of the neurocognition of sign language was performed by Söderfeldt in the 1990s. Söderfeldt showed in a series of studies

(Risberg, Rönnberg & Söderfeldt, 1993; Söderfeldt et al., 1997; Söderfeldt, Rönnberg & Risberg, 1992; Söderfeldt., Rönnberg & Risberg, 1994; Söderfeldt, Rönnberg & Risberg, 1996) that, contrary to expectations, sign language engaged the classical left hemisphere language areas, that are closely linked to the functions of speech and hearing, rather than right hemisphere regions related to the processing of visuospatial information. This work confirmed early lesion studies which had pointed in the same direction. For example, the origins of sign aphasia, like those of spoken aphasia, tend to be in Broca's and Wernicke's areas, the classical language areas of the left side of the brain (Hickok, Love-Geffen & Klima, 2002; Poizner, Bellugi & Klima, 1990).

Addressing the language processing system in greater detail, it has been found that sign production both overt (Braun, Guillemin, Hosey & Varga, 2001; Corina, San Jose-Robertson, Guillemin, High & Braun, 2003; Petitto et al., 2000) and covert (Kassubek, Hickok & Erhard, 2004; McGuire et al., 1997) engages the same classical language areas in the left hemisphere as speech production, while sign comprehension, like speech comprehension, activates the superior temporal lobes (MacSweeney, Woll, Campbell, McGuire et al., 2002; Petitto et al., 2000). Neural systems underlying lexical retrieval are also similar for sign and speech, engaging differentiated areas of the temporal lobe for different semantic categories (Emmorey, Grabowski et al., 2003).

Neuropsychological case studies have revealed double dissociations between linguistic and nonlinguistic processing in the visuospatial domain, such that processing of linguistic information may be selectively spared although processing of nonlinguistic visuospatial information is impaired, and vice versa. For example, it has been found that signing performance can remain relatively intact although performance is impaired on the Corsi Blocks task, a standard neuropsychological test of non-linguistic visuospatial ability, (Corina, Kritchevsky & Bellugi, 1996), and in the presence of Williams syndrome (a condition characterised by relatively good language abilities but poor visuospatial cognition) (Atkinson, Woll, & Gathercole, 2002). Conversely, sign language aphasia can coexist with unimpaired non-linguistic visuospatial abilities (Hickok, Say, Bellugi & Klima, 1996) and unimpaired production of non-linguistic gesture (Corina et al., 1992; Marshall, Atkinson, Smulovitch, Thacker & Woll, 2004).

The distinction between neural networks supporting sign language and non-linguistic gesturing is further enhanced by fMRI data which shows differences in neural networks supporting BSL and sign-like gesturing for signers but not for non-signers (MacSweeney et al., 2004); and by PET data showing that even when the form of a sign is indistinguishable from a pantomimic gesture, the neural systems underlying its production mirror those engaged in speech rather than gesturing (Emmorey et al., 2004).

Right hemisphere engagement in sign language

Although sign, like speech, seems to be reliant on left hemisphere regions, there is evidence of right hemisphere involvement from both lesions studies and neuroimaging studies, indicating that the dissociation between sign language abilities and non-linguistic visuospatial processing is not complete and that the right hemisphere may be involved in some specific aspects of sign language processing (Campbell & Woll, 2003).

It has been shown that right hemisphere damage may impair some aspects of sign language processing, including maintaining topical coherence, employing spatial discourse devices (Hickok et al., 1999), using space grammatically (Atkinson, Marshall, Woll & Thacker, 2005) and processing prosody (Atkinson, Campbell, Marshall, Thacker & Woll, 2004). Neuroimaging work has shown sign-specific right hemisphere engagement in naming spatial relations in ASL (Emmorey et al., 2002).

Sign-specific left hemisphere engagement

Sign language specificity is not confined to the right hemisphere. Syntactic and phonological processing in sign language are known to engage Broca's area (McGuire et al., 1997) and while there seems to be a common representation for sign and speech in the anterior region of Broca's area, which is devoted to semantic processing, there are separate representations for sign and speech in the posterior portion of the same area, which is devoted to phonological and syntactic processing (Horwitz et al., 2003). From a linguistic point of view, phonology and syntax constitute two fundamental organisational principles in language, but while phonology is about the internal structure of words and signs, syntax is about the internal structure of sentences. In other words, phonology concerns sublexical organisation and syntax concerns supralexical organisation. From a neurocognitive point of view, it seems that although phonological and syntactic processing engage similar mechanisms within languages, they may interact with language modality.

MacSweeney and co-workers (MacSweeney, Woll, Campbell, Calvert et al., 2002) found that the left inferior and superior parietal lobules are activated during processing of topographic sentences in BSL. Topographic sentences use *sign space* in front of the body to map detailed *real-world* spatial relationships directly. The authors argue that the left parietal lobe is specifically involved in processing the precise configuration and location of hands in space to represent objects, agents, and actions. Sign language specific bilateral engagement has been found for phonological encoding and articulation in the temporal, parietal, and occipital lobes (San Jose-Robertson, Corina, Ackerman, Guillemin & Braun, 2004).

Facial expressions have a grammatical function in sign language and it has been shown that perception of linguistically meaningful facial expressions is left-lateralised in signers but not in non-signers (McCullough, Emmorey & Sereno, 2005).

Bilingualism

Persons who use more than one language to communicate are bilinguals. With increasing international mobility and communication technology, these days most people are bilingual to some degree. Degree of bilingualism can vary according to a number of parameters relating to the languages concerned: age of acquisition, frequency of use and proficiency (Francis, 1999).

According to the critical period hypothesis (Lenneberg, 1967), native language competence cannot be attained after childhood. Indeed, there is evidence to suggest that normal language learning occurs only when exposure to the language begins early in life, with the effects of age of first exposure being approximately linear through childhood (Newport, 1990). Thus, although relative language proficiency is obtained in second languages acquired before puberty, all aspects of language skill and processing may not be identical in persons learning a second language from birth and persons learning a second language before puberty but not from birth. Second language skills may differ across different components of the language system. While the vocabulary of a second language can be learned at any age, the use of prepositions and syntax (Neville, Mills & Lawson, 1992) and in particular the phonological system (Sebastián-Gallés & Soto-Faraco, 1999) may be harder to master after childhood.

The question of how the language systems of bilinguals are organised is yet to be settled. Some evidence supports the notion of a single store while other evidence suggests dual stores. Lesion studies show that aphasia may affect the two languages of speech-speech bilinguals differently (Paradis, 1995). This is also true of sign-speech bilinguals (Marshall, Atkinsson & Woll, 2005; Gallego, Quinones & de Yebenes, 2003). Some investigators have attributed this phenomenon to dual stores (e.g., Albert & Obler, 1978), while others have argued for a single store and explained different patterns for different languages in terms of extraneous psychological factors (e.g., Penfield & Roberts, 1959).

Current theories of bilingual lexical processing often take a hierarchical view by assuming that concepts are represented at both lexical and conceptual levels (Alvarez, Holcomb & Grainger, 2003), which means that bilinguals have two separate lexical representations for each concept but only one semantic representation.

Hearing children of Deaf parents generally grow up to become bilingual hearing signers. They acquire their two languages on the same timetable as monolinguals with translation equivalents in two similarly organised lexicons (Capirici, Iversen, Montanari, & Volterra, 2002; Holowka, Brosseau-Lapre & Petitto, 2002). This pattern of language development mirrors that of bilinguals in two spoken languages, suggesting that whatever the relative organisation of multiple languages in bilinguals, language modality may not be a critical factor.

Neuroimaging studies investigating differences in neural organisation for early and late bilinguals have produced partly conflicting results. Early bilinguals seem to have both their languages organised in a similar way in the classical language areas (Kim, Relkin, Less, & Hirsch, 1997). However, the picture for late bilinguals is less clear, with some work indicating similar organisation of languages learned before and after puberty (Chee, Tan, & Thiel, 1999; Illes et al.,1999; Klein, Milner, Zatorre, Meyer & Evans, 1995) and some work indicating differences (Dehaene et al. 1997; Kim et al., 1997; Klein, Zatorre, Milner, Meyer & Evans, 1994; Perani et al., 1996). An investigation of neural activation during sign language processing in early and late hearing signers (Newman, Bavelier, Corina, Jezzard & Neville, 2002) showed different patterns of activation for the two groups with the right angular gyrus being more active during ASL processing in early, than late signers, suggesting that neural organisation of sign language is sensitive to age of acquisition.

Irrespective of whether the languages of bilinguals are organised as one system or two, there must be some mechanism to allow them to keep their languages apart and switch between them as appropriate.

Language switching

Penfield and Roberts (1959) proposed the existence of a language switch, a cognitive mechanism that allows bilinguals to keep their two languages separate and at the same time switch between them. On the basis of lesion data, various proposals have been put forward as to the neural localisation of a language switch. These proposals have included frontal, temporal and parietal areas. However, counterexamples have been demonstrated in all these cases, and thus neuropsychological case studies have not been able to isolate any single neural regions on which language switching may depend (Hernandez, Martinez & Kohnert, 2000). This suggests that language switching depends on a network of multiple neural regions, none of which is indispensable.

Green (1998) has proposed that language switching is controlled by mechanisms similar to those that regulate other forms of action, and can be explained in terms of an inhibitory control model (Green, 1998). This model postulates a selection mechanism that operates on a range of competing language task schemas. Any given stimulus may evoke a number of different potential actions on the part of the language user. Each of these actions will have its own schema, and thus, selecting a particular action will involve actively selecting one schema and suppressing the others. Where a task has been previously performed, the relevant schema can be retrieved and adapted from memory. For novel tasks, a supervisory attentional system controls construction of new schemas or modification of old ones, as well as monitoring performance with respect to goals. This model predicts the involvement of multiple neural regions in language switching, reflecting both executive control, which will be task independent, and action schema, which will be task specific.

In a test of the inhibitory control model (Green, 1998), Price, Green & von Studnitz, (1999) compared brain activation networks during two different language–switching tasks. Both tasks were based on the same stimulus material, words presented either in English or German, or alternately in both. The first task involved reading these words while the second task involved translating them into the other of these two languages. Thus, in terms of the model, at least two competing task schemas were involved, a reading schema and a translation schema. Findings supported the hypothesis that the translation task would require activation of the translation schema and suppression of the reading schema, leading to activation of executive networks in the frontal lobe. Other imaging studies have confirmed the role of executive processes in language switching (Hernandez, Dapretto, Mazziotta & Bookheimer, 2001; Hernandez et al, 2000). Language-switching in speech-sign bilinguals has not previously been studied.

2
Working Memory

Different empirical and theoretical approaches to the study of working memory have resulted in a variety of models. Miyake and Shah (1999) reviewed ten of these models and came to the conclusion that although the focus and details of the different models differed, a common core of issues could be discerned. On the basis of this common core they put forward an all-encompassing definition of working memory:

> Working memory is those mechanisms or processes that are involved in the control, regulation, and active maintenance of task-relevant information in the service of complex cognition, including novel as well as familiar, skilled tasks. It consists of a set of processes and mechanisms and is not a fixed “place” or “box” in the cognitive architecture. It is not a completely unitary system in the sense that it involves multiple representational codes and/or different subsystems. Its capacity limits reflect multiple factors and may even be an emergent property of the multiple processes and mechanisms involved. Working memory is closely linked to LTM[2], and its contents consist primarily of currently activated LTM representations, but can also extend to LTM memory representations that are closely linked to activated retrieval cues and, hence, can be quickly reactivated.

This definition restricts itself to the cognitive level of explanation but work has also been done on investigating the neural base of working memory. This work shows that working memory requires cooperation among scattered regions of the brain with precise regions depending on the modality of the to-be-remembered information (Wickelgren, 1997). Moreover, there is evidence to suggest that working memory storage is supported by the same neural substrates as sensory and perceptual systems (Goldman-Rakic, Ó Sacaidhe & Chafee,

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[2] Long-term memory

2000), while rehearsal mechanisms are controlled by the same circuitry as selective attentional mechanisms (Jonides et al., 2005).

The Seven Ages of Working Memory

The concept of working memory goes back to the Enlightenment, and its history has been described in a number of stages which have been referred to as the Seven Ages of Working Memory (Logie, 1996). This description traces the roots of the concept back to the seventeenth century philosopher John Locke who distinguishes between *contemplation* as a temporary workspace for a currently entertained idea and *memory* as a more permanent storehouse of ideas. Thus, Locke's concept of contemplation marks the first age of working memory. The second age of working memory is indexed by the work of William James (1891/1952), who proposed two memory systems, a *primary memory system* for short-term storage and a *secondary memory system* for long-term storage.

The subsequent ages described by Logie (1996) cover a range of approaches to the study of working memory. Initial empirical work supported the dual-component theory (Brown, 1958; Peterson & Peterson, 1959) and Atkinson and Shiffrin (1968) proposed that information from the environment entered a temporary short-term storage system before being transferred to the more durable long-term memory. This is known as the gateway theory (Logie, 1996). This gateway view of working memory was challenged by evidence from neuropsychological patients. In some cases, damage to the medial temporal lobes led to long-term memory defects, while leaving short-term memory unaffected (Baddeley & Warrington, 1970). This evidence supported the dual-component theory and did not of itself challenge the gateway theory, but other neurological cases were found with the opposite pattern of short-term memory defects but unimpaired long-term memory (Shallice & Warrington, 1970). The fact that short-term memory could be impaired while long-term memory was left intact posed a severe challenge to the role of short-term memory as the gateway to other cognitive functions (Baddeley, 2003). This challenge to the gateway theory has spawned a number of different approaches that focus on a general cognitive capacity.

Capacity approaches

Capacity approaches avoid the gateway problem by postulating that working memory is part of a general cognitive capacity. One such approach suggests that cognitive capacity is limited by an available budget of activation and that, within this budget, activation can be allocated flexibly (Just & Carpenter, 1992). Once all the available capacity has been allocated, however, any new processing or storage can be accomplished only by reducing the level of activation elsewhere. Applying this approach, working memory is tested using tasks that combine processing and storage. These tasks are often referred to as complex span tasks. One such task is the reading span task (Daneman & Carpenter, 1980). The reading span task requires participants to read aloud a series of short sentences while retaining the last word from each sentence for subsequent immediate serial recall. The test typically starts with two sentences and increases to a point at which participants are no longer able to recall all the terminal words. This point is designated the subject's working memory span. Working memory span as measured by the reading span task has been found to predict a range of other cognitive skills, such as reading, comprehension, and reasoning (Baddeley, 2003). An analysis of the key components of complex span tasks indicates that they are multiply determined, and that differences in task structure can influence the relative importance of multiple constraints and the predictive power of a complex span measure (Bayliss, Jarrold, Baddeley & Gunn, 2005).

Another version of the capacity approach is the activation and attention approach (Cowan, 1993) which postulates that working memory has two key components, activation and attention, that collaborate within a hierarchical structure. Activation refers to the set of items stored in long-term memory that are just beyond the attention threshold but which are more highly activated than other long-term memory representations. Attention refers to the smaller subset of activated representations which fill current attention and awareness.

A related approach which avoids the gateway problem is Rönnberg's (2003) model for cognitive involvement in language processing. This model is based on multiple sources of behavioural and neuroscience data which support the notion of general modality-free cognitive functions in speech and sign processing and includes four important parameters for language understanding: quality and precision of *phonology*, long-term memory access *speed*, degree of *explicit* processing, and general processing and storage *capacity*. It is proposed that these four parameters interact to generate predications about language processing in signed and spoken modalities. One of these predictions is that similar neural networks will be activated for signed and spoken working memory tasks.

All these approaches fit the view, put forward by Logie (1996) and confirmed in Miyake and Shah's definition (1999), that working memory is better thought of a system that operates after access to long-term memory has taken place, rather than acting as a means of transport for sensory input to long-term memory. Logie (1996) also argues that the idea of a single, flexible system underlying cognitive capacity is too simple and that working memory is better thought of as a set of specialised mechanisms that act in concert according to the demands of the task in question. This is known as the component approach.

The component approach

According to the component approach (Baddeley & Hitch, 1974), working memory can be fractionated into a controlling central executive and two slave loops which process incoming information. More recently a further component, the episodic buffer has been added (Baddeley, 2000), see Figure 2. In the original model, the two slave loops were labelled the articulatory loop and the visuospatial scratchpad. As evidence has accumulated to delineate the model these terms have been revised and are now known as the phonological loop and the visuospatial sketchpad.

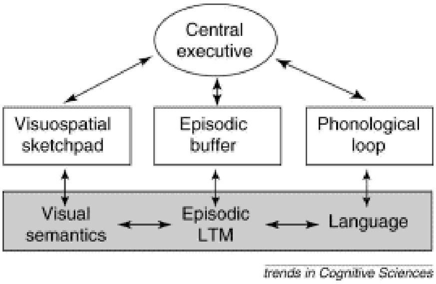

Figure 2. The component model of working memory (Baddeley, 2000)[3]

The phonological loop

The phonological loop is the most studied part of the component model (Baddeley, 2003). It comprises a temporary phonological store in which auditory memory traces decay over a period of a few seconds, unless revived by articulatory rehearsal. This model accommodates a number of characteristic effects including the phonological similarity effect, the word-length effect and the effect of articulatory suppression (Baddeley, 2000).

The phonological similarity effect refers to the robust finding that in an immediate serial recall task, where a memorised list of items has to be reproduced in the correct order, words that are similar in sound are harder to remember accurately (e.g. *man, cat, map, cab, can* is harder than *pit, day, cow, sup, pen* (Baddeley, 1966), whereas visual or semantic similarity has little effect on performance, implying a phonological code.

The word-length effect refers to the fact that participants are better at recalling a sequence of short words than long words (e.g. *wit, sum, harm, bag, top* is easier than *university, aluminium, opportunity, constitutional,*

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[3] Reprinted from Trends in Cognitive Sciences, Volume 4, Alan Baddeley, The episodic buffer: a new component of working memory? Pages 417-423, Copyright (2000), with permission from Elsevier.

auditorium). This is explained by the fact that it takes longer to rehearse the polysyllables, and to produce them during recall, allowing more time for memory traces to deteriorate (Baddeley, Thomson & Buchanan, 1975).

The effect of articulatory suppression refers to the phenomenon that participants' performance deteriorates when they are prevented from rehearsing to-be-remembered items, by having to repeat an irrelevant sound such as the word *the* (Baddeley et al., 1975). Suppression removes the word-length effect because if items cannot be rehearsed anyway, their length is immaterial.

The phonological loop also supports transfer of information between codes (Baddeley, 2000). Participants tend to subvocally rehearse visually presented items, thus transferring visual information to an auditory code. Articulatory suppression prevents transfer between codes, and thus, removes the effect of phonological similarity for visually presented items. Articulatory suppression does not remove the phonological similarity effect for auditory items, as these enter the phonological store directly (Murray, 1968).

In evolutionary terms, the phonological loop may have developed to support speech perception (the phonological store) and production (the articulatory rehearsal component), and its pronounced reliance on serial order makes it well suited for speech-based language processing (Baddeley, 2000). A range of results indicate that the phonological store also seems to be involved in learning new vocabulary (Baddeley, 2003).

Patients with phonological loop deficit may show few signs of general cognitive impairment, although they may have difficulty comprehending complex sentences (Vallar & Baddeley, 1987). This suggests that the phonological store serves as a backup system for comprehension of speech under taxing conditions, but may be less important for straightforward communication (Baddeley, 1992).

Neuropsychological double dissociations also suggest that the phonological loop has two components (Baddeley, 2000). Some persons with aphasia show store deficits with intact rehearsal (Vallar, Corno & Basso, 1992) while others with dyspraxia show rehearsal deficits, because they are unable to set up the speech motor codes necessary for articulation (Waters, Rochon & Caplan, 1992). Persons with dysarthria, whose speech problems are peripheral, show normal rehearsal, suggesting that rehearsal is a central, rather than peripheral, cognitive mechanism (Baddeley & Wilson, 1985).

The neural substrate of the phonological loop

Studies aimed at localising various components of working memory have shown that the rehearsal component of the phonological loop engages three left-hemisphere regions known to be involved in higher-level aspects of speech: Broca's area, the premotor area, and the supplementary motor area (Smith & Jonides, 1997), whereas storage engages mainly left-lateralised posterior parietal regions, although the exact location within in the parietal lobe has yet to be determined (Becker, MacAndrew & Fiez, 1999).

Working memory tasks with a phonological component, requiring segmentation of the speech stream, activate the posterior portion of Broca's area in the left inferior frontal lobe while semantic tasks, such as category judgment, activate the anterior portion of the same region (Clark & Wagner, 2003; Fiez, 1997; McDermott, Petersen, Watson & Ojeman, 2003).

It has been shown (Fiebach, Schlesewsky, Lohman, von Cramon & Friederici, 2005) that Broca's area plays a critical role in syntactic working memory during online sentence comprehension and that this region supports the cognitive resources required to maintain long-distance syntactic dependencies during the comprehension of grammatically complex sentences (Cooke et al., 2002). A dissociation between the neural substrates of syntactic and semantic processes in sentence processing has been shown whereby semantic processing engages the anterior portion of Broca's area and syntactic processing the posterior portion of the same region (Newman, Just, Keller, Roth & Carpenter, 2003). A similar dissociation is found for semantic and phonological processes in Broca's area, with semantic mechanisms anterior to phonological mechanisms. Thus, there is an interesting common neural representation of syntax and phonology. This is just one example of a particular neuronal structure performing multiple functions. Price and Friston (2005) argue for a systematic functional ontology for cognition that would facilitate the integration of cognitive and anatomical models and organise the cognitive components of diverse tasks in a single hierarchical framework. As we have seen, phonology and syntax can be analysed in similar terms and are thus good candidates for incorporation in a framework of this nature.

The visuospatial sketchpad

The pattern of evidence generated by work on visuospatial working memory has not resulted in the same degree of theoretical clarity as that relating to the phonological loop (Logie, 1995). The original proposal for the articulatory loop (Baddeley & Hitch, 1974) was based on an accumulation of evidence and subsequent work has elucidated detail (Baddeley, 1986; 2000). However, evidence for the visuospatial sketchpad does not provide such a clear picture.

Like the phonological loop, the visuospatial sketchpad comprises two components: a passive visual cache maintaining visual sensory information (colour, shape and static locations) and an active inner scribe maintaining dynamic visual information (movements) (Logie, 1995). This differentiation is supported by a double dissociation whereby a visual working memory task is more disrupted by visual than spatial interference and a spatial working memory task is more disrupted by spatial than visual interference (Klauer & Zhao, 2004). The visual cache provides temporary storage of visual material and is closely linked to visual perception. The inner scribe provides a rehearsal mechanism to refresh the information and retains sequential spatial information. Furthermore, it is considered to be involved in the manipulation of visuospatial images and is thus linked to the central executive and to planning of movements (Logie, Engelkamp, Dehn, & Rudkin, 2000). Both processing and storage components are important for predicting performance on spatial thinking tasks (Shah & Miyake, 1996).

The capacity of visual working memory seems to be limited to four simultaneously presented visual features, e.g. colours, or four integrated objects, e.g., shapes in a specific colour and orientation (e.g., Luck & Vogel, 1997) but it has also been argued that these estimations are contaminated by long-term memory support and that the true maximum capacity of visual working memory is one item (Olsson & Poom, 2005).

The concept of visuospatial working memory is closely linked to the concept of mental imagery.

Mental imagery

The study of mental imagery addresses the question of how information is stored in memory. Shepard and Metzler (1971) used visual cues to study the phenomenon of mental rotation. Subjects were asked to determine whether two pictures represented the same object but from different angles. The time required to respond was a linear function of the degree of rotation between the pictured objects. This suggests that the mental images generated by subjects, in order to solve the task, are manipulated in the mind in a way reminiscent of how we would turn an object in our hands, rather than on the basis of a mathematical calculation which would take the same time to perform, irrespective of angle of rotation.

On the basis of the results of mental scanning experiments (e.g. Kosslyn, Ball & Reiser, 1978), Kosslyn (e.g. 1994) argues that mental imagery is a form of mental representation that relies on our ability to generate analogies, rather than our ability to describe phenomena in words. But this view has not gone unchallenged. For example, Pylyshyn (1984) noted that participants in experiments have tacit knowledge of visual scanning rates which may cause them to emulate visual scanning. At any rate, storage and manipulation of mental imagery takes place in working memory.

Most of the work on mental imagery has focused on visual imagery. However, some work has addressed auditory imagery and mental representation of linguistic units can be conceptualised in terms of auditory mental imagery (Smith, Wilson & Reisberg, 1995). It has been shown that language modality can affect the degree to which imagery is involved in language (Vigliocco, Vinson, Woolfe, Dye & Woll, 2005) and that deaf and hearing signers have an enhanced ability to generate mental imagery and to detect mirror image reversals (Emmorey et al, 1993). This ability may be tied to specific linguistic requirements of ASL such as referent visualisation, topological classifiers, perspective shift, and reversals during sign perception.

The neural substrate of visuospatial working memory

It has been found that different neural circuits mediate spatial and object working memory, with spatial working memory being right lateralised and object working memory typically being left lateralised (Smith & Jonides, 1997). Spatial storage seems to engage right parietal areas while rehearsal engages right premotor areas (Smith & Jonides, 1997). There is also evidence to suggest that neural networks involved in working memory processing mirror the dual stream organisation of a dorsal (where) and a ventral (what) stream revealed for visual perception (Cabeza & Nyberg, 2000; Courtney, Ungerleider, Keil & Haxby, 1996). The dorsal path, from occipital to parietal cortex, processes spatial information, whereas the ventral path, from occipital to temporal cortex, processes object information (Ungerleider, & Haxby, 1994). This is in keeping with the general picture that information in working memory is stored by the same structures in the parietal and temporal lobes that are specialised for perceptual processing, and rehearsed using the same selective attention mechanisms in the parietal and frontal cortex used to modulate incoming information (Jonides et al., 2005).

Visual mental imagery, like visual memory, is supported by the same two streams as visual perception: Imagining static objects activates occipital and occipito–temporal regions in the ventral stream (Kosslyn & Thompson, 2000) and imagining spatial relations, such as the angle between the hands of a clock activates superior parietal regions in the dorsal stream (Trojano et al., 2002). Imagining movement of objects, for example, mental rotation, also activates occipital and occipito–parietal regions in the dorsal stream (Jordan, Heinze, Lutz, Kanowski, & Jäncke, 2001; Podzebenko, Egan, & Watson, 2002; Vanrie, Bátse, Wagemans, Sunaert, & Van Hecke, 2002; Vingerhoets, de Lange, Vandemaele, Deblaere, & Achten, 2002). Even in language comprehension, parietal areas are active when high-imagery sentences are processed (Just, Newman, Keller, McEleney & Carpenter, 2004).

Recently, it has been proposed that there is a common supra-modal spatial processing component in working memory supported by occipito-parietal structures (Zimmer, Magnussen, Rudner & Rönnberg, in press). This notion is supported by electrophysiological data showing a grading of potential amplitudes for both visuospatial (Mecklinger & Pfeifer, 1996) and auditory-spatial memory load (Lehnert, Zimmer, & Mecklinger, under revision) at the same parieto-occipital location, and the observation that auditory-spatial and visuospatial memory loads draw on the same capacity (Lehnert & Zimmer, in press).

In the case of active spatial rehearsal in working-memory, spatial attention plays an important role (Awh & Jonides, 2001). In general, spatial attention changes the visual representation of attended stimuli (cf. Postle, Awh, Jonides, Smith & D'Esposito, 2004) and it may therefore also influence working memory. The presence or absence of this attentional process might be the difference between active and passive storage (Zimmer et al., in press). In imagery tasks, the control of action might play a similar role because attention is necessary for an effective control of voluntary actions.

The central executive

The central executive is responsible for the attentional control of working memory (Baddeley, 2003) and executive processes are probably one of the principal factors determining individual differences in working memory span (Daneman & Carpenter, 1980). One role of the central executive is coordinating information from the slave systems. This is demonstrated by Alzheimer's patients in whom deterioration of central executive function interferes with the ability to coordinate information (Baddeley, 1992).

The central executive engages dorsolateral prefrontal regions (Smith & Jonides, 1997). The dorsolateral prefrontal response has been shown to be load-sensitive (Braver et al., 1997) while the anterior cingulate responds to task difficulty (Barch et al., 1997).

The episodic buffer

The episodic buffer is a limited-capacity temporary storage system that is capable of integrating information from perception, other components of working memory, and long-term memory (Baddeley, 2000). It is controlled by the central executive, which is capable of retrieving information from the store in the form of conscious awareness, of reflecting on that information and, where necessary, manipulating and modifying it. The term *episodic* refers to an information content that is integrated across space and potentially extended across time. The term *buffer* refers to a role as an interface between different systems with different codes. This is achieved by using a common multi-dimensional code. The episodic buffer provides a mechanism for modelling the environment, and for creating new cognitive representations, which in turn might facilitate problem solving (Baddeley, 2000). There is evidence to show that a key neural component of the episodic buffer is located in the frontal regions (Baddeley, 2002; Prabhakaran, Narayanan, Zhao & Gabrielli, 2000).

Theoretical strengths of different approaches

The theoretical strength of the component approach lies in its ability to make strong predictions about cognitive organisation, whereas tests that are based on capacity approaches have proved a useful tool in predicting cognitive and linguistic capacities. The component approach accommodates differences in cognitive organisation according to the sensory modality in which information is presented but it does not specifically address the issue of language modality. On a general level, Rönnberg's (2003) model predicts similarities in the organisation of working memory for sign and speech, whereas Wilson's (2001) sensorimotor model predicts certain differences.

Working memory for sign language

The sign language of the deaf, which transfers information in the visuospatial modality, provides an interesting challenge to the component model. Wilson (2001) has proposed a sensorimotor model of working memory, based on Baddeley and Hitch (1974) and Baddeley (1986) in which language is processed according to the sensory modality in which it is delivered (Wilson, 2001). In other words, the sensorimotor model (Wilson, 2001) predicts language-modality-specific processing in working memory. In contrast, Rönnberg's (2003) model predicts that working memory for sign language will be supported by the same neural networks as working memory for speech. There is evidence both for and against cognitive components dedicated to sign language. These data come from behavioural studies and the field of neurocognition of sign language.

Common components

Working memory for sign language largely conforms to Baddeley and Hitch's (1974) model, displaying a number of classic effects: a phonological similarity effect, a sign length effect, a suppression effect and an irrelevant pseudosign effect. The phonological similarity effect is demonstrated by the fact that the performance of deaf signers on immediate serial recall of ASL signs is disrupted by interitem similarity of handshape (Wilson & Emmorey, 1997). The sign length effect is demonstrated by the fact that long signs (signs with path movement) are more difficult to remember than short signs (signs with no path movement) (Wilson & Emmorey, 1998). The suppression effect is demonstrated by the fact that performance deteriorates when the relevant articulators, the hands, are occupied with a meaningless gesture (Wilson & Emmorey, 1997), and the irrelevant pseudosign effect is demonstrated by the fact that recall of signs is disrupted by the presentation of pseudosigns during the retention interval (Wilson & Emmorey, 2003). Further, interactions among these effects mirror equivalent interactions for speech (Wilson & Emmorey, 2003). Working memory for sign language also conforms with speech data by not showing any semantic similarity effect (Poizner, Bellugi & Tweney, 1981).

Sign-specific components

Although working memory for sign language seems to share many aspects of its organisation with working memory for speech, it also shows some modality-specific components.

Spatial organisation

Evidence is accumulating to indicate that the temporary storage component of working memory for sign language is organised on principles reflecting the inherently visuospatial nature of the language rather than on the temporal principles that applies to working memory for speech-based information. For example, native signers, unlike non-signers, perform equally well on forward and reverse recall of serially presented stimuli (Wilson et al., 1997), indicating that working memory for sign and speech differ in how they represent serial order information. Further work by Wilson and Emmorey (Emmorey, 2002) supports the notion that temporary storage in working memory for sign language may be supported by a visuospatial array.

Span capacity

Overall working memory capacity, as measured by complex span tests, is comparable for deaf signers and hearing speakers (Boutla, Supalla, Newport & Bavelier, 2004). However, the working memory loops are consistently found to be shorter for sign than for speech when loop capacity is tested using simple span tasks, involving immediate serial recall. This span deficit for sign is found in both deaf and hearing signers, indicating that the effect is related to language modality rather than deafness. One explanation is that differences in the capacity of the sign and speech loops are directly due to differences in articulation rates between modalities (Marschark & Mayer, 1998). This suggestion fits in with findings from spoken languages that show that when digits take longer to articulate in a particular language, e.g., Welsh, digit span is lower (Ellis & Hennelly, 1980).

However, Boutla and co-workers (2004) found that sign loop size did not correlate with articulation rate, and suggested two other possible reasons for loop size discrepancies, both postulating inherent differences in cognitive systems due to reliance on different sensory modalities (Boutla et al., 2004). The first suggestion is that speech-like information decays at a slower rate than visually encoded information. This is supported by the unequal duration of the primary sensory memory stores for sound and vision. The longer duration of echoic memory compared to iconic memory would mean that words could be maintained longer than signs without rehearsal being required. The second suggestion is that apparent differences in loop size are really due to a measuring problem, highlighting inherent differences in the retention of serial order information across modalities. The digit span test, which is an immediate serial recall task used for measuring simple span size, requires retention of serial order, but whereas the auditory system is known to be highly efficient in retaining the order of occurrence of sounds, the capacity of the visual system in this respect is more limited. Thus, the visuospatial array, which has been proposed as a storage component in working memory for sign, would not be intrinsically suited to retention of temporal information, and in order to assess the capacity of the sign loop more adequately, a test must be devised that taps capacity and order without relying on temporal aspects (Zimmer et al., in press).

Neural evidence

A recent paper by Buchsbaum and colleagues (Buchsbaum et al., in press), combining an fMRI experiment with deaf native signers and a case study, provides evidence to indicate that there are both similarities and differences in the neural organisation of verbal short-term memory for speech and sign language. The paper shows that both systems seem to rely on a widely distributed network, including frontal, parietal, and temporal cortices and that within this broad network, there are regions that appear to be common to the two language formats. Common areas are to be found in posterior frontal regions, the left temporal-parietal junction, and the posterior superior temporal sulcus bilaterally, while working memory for sign language shows a greater reliance on a parieto-frontal circuit.

Other cognitive processes

The issue of working memory for sign language is further illuminated by a number of features of other types of cognitive and linguistic processing in native sign language users. For example, signers are better at face discrimination (McCullough & Emmorey, 1997) and more accurate in identifying emotional facial expression (Goldstein & Feldman, 1996). Signers have an enhanced ability to generate images and detect mirror image reversals (Emmorey et al., 1993). On the other hand, no language-modality effects have been found for low-level visual processing (Poizner & Tallal, 1987) or memory for visual images (McCullough & Emmorey, 1997). Thus, it is not only working memory that shows a complex mix of modality-free and modality-specific effects but also other aspects of cognition and language processing.

Working memory for sign and speech

Evidence indicates that working memory systems mediated by visuospatial languages are functionally very similar to those mediated by spoken languages. Many of the components of working memory for sign seem to have the same structure as equivalent components for speech. This applies to executive functions and the rehearsal component of the language-supporting loop in both modalities. However, working memory for sign also differs from working memory for speech in a number of important respects relating to the temporary storage of memorised items, and these differences reflect the inherently visuospatial nature of the language. In this thesis, the component model of working memory (Baddeley, 2000) is an important starting point for theoretical discussion.

3
Methodological considerations

The work presented in this thesis is based on experimental methods from the fields of psychological and neurocognitive research, applied within the field of disability research

Disability research

Within the field of disability research there have traditionally been two approaches driven by two different theoretical models, the medical model and the social model (Bickenbach, Chatterji, Badley & Üstün, 1999). According to the medical model, disability is a characteristic of a person, requiring medical care. According to the social model, disability is a socially created problem that requires a political response. The more recent biopsychosocial model attempts to synthesise these two models by considering disability arising as an interaction between the health condition of the individual and contextual factors. This model is associated with the International Classification of Function (ICF, http://www3.who.int/icf).

ICF divides contextual factors into environmental factors and personal factors, which together with health condition, body functions and structures and participation influence activity. Cognitive functions such as working memory and language communication can usefully be regarded, within the framework of ICF, in terms of environmental and personal factors, feeding into activity. However, an even more analytical approach can be obtained by applying horizontal and vertical dimensions (Rönnberg & Melinder, in press).

A horizontal dimension can be obtained by comparing performance across participant groups that differ in terms of personal factors such as sensory function or who have grown up in different cultural environments with different ambient languages. Another way of applying a horizontal dimension is to compare performance across different cognitive tasks. The advantage of applying a horizontal dimension is that it can indicate to what extent cognitive phenomena are specific to a particular participant group or task and to what extent they can be generalised across participant groups and tasks.

A vertical dimension can be obtained by analysing a phenomenon at different levels of description by combining different methods, for example, working memory and language can be examined at the cognitive level by applying behavioural methods and at the neural level by applying neuroimaging methods. The advantage of applying a vertical dimension is that it can indicate what levels of description are valid for a particular phenomenon.

Apart from being a useful tool for the analysis of particular phenomena, the application of horizontal and vertical dimensions together is likely to be useful in testing the generality of theoretical concepts (Rönnberg & Melinder, in press).

The work presented in this thesis focuses on personal and contextual factors within the ICF framework and applies horizontal and vertical dimensions. The personal factor is audiological status and the contextual factor is ambient language. A horizontal dimension is applied in two ways. Firstly, working memory function is tested across groups with different audiological status and ambient language. Secondly, working memory function is tested by administering different tasks. A vertical dimension is applied by using traditional behavioural measures, accuracy and reaction time, as well as neuroimaging methods, PET and fMRI.

A horizontal approach which involves using different groups of participants with different personal factors, or subject to different contextual factors, requires careful selection of participants. The participants in the studies reported in this thesis have been chosen with regard to their audiological status and ambient language environment. Profound deafness is limited to, at most, one in a thousand, and hearing children of deaf parents are probably no more numerous. This means that it is often impractical to carry out large-scale studies involving deaf persons and their hearing offspring, particularly in a sparsely populated country like Sweden.

Deafness and hearing impairment

Hearing impairment is a common sensory deficit affecting about 10 percent of the population. It can be caused by either genetic or environmental factors, or a mixture of both (Carlsson, 2005). There is no internationally accepted terminology for degree of hearing impairment. However, in Sweden, hearing loss in excess of 70 dB is referred to as severe, and in excess of 95 dB, profound. Clinically speaking, deafness refers to profound hearing impairment and the rate of congenital deafness is generally reported as being 0.1-0.2 percent (e.g. Avraham, 1997). However, whether or not an individual considers him or herself to be Deaf is a matter of identity that is not necessarily related to measured hearing impairment.

Gender issues

Generally speaking, little attention has been paid to the issue of whether there are gender differences in working memory processing. Evidence suggests that there are gender differences on some cognitive tasks with women showing superior performance when language skills are involved and men performing better when spatial skills are required (Kimura, 1999). In the domain of memory, it has been shown that women have superior episodic memory skills (Herlitz, Nilsson & Bäckman, 1997) and episodic memory seems to be unique in the sense that it is the only memory system showing any gender difference in performance throughout the adult lifespan (Nilsson, 2003). Thus, although some cognitive skills may show gender differences, working memory does not seem to be one of them. Despite this, potential gender differences were monitored in all the studies presented in this thesis, even when gender was not included as a variable in the design. Where gender differences were detected they are discussed in Chapter 4.

Behavioural measures

Behavioural measures are an important tool in the work reported in this thesis and are applied in all the studies reported. The behavioural measures used are accuracy, reaction time and self-report. Papers III & IV rely exclusively on behavioural measures, whereas behavioural measures and neuroimaging techniques are combined in Papers I, II & IV. Neuroimaging techniques allow us to identify neural regions associated with a certain cognitive task (Cabeza & Nyberg, 2000). However, where measures of neural activity are combined with behavioural measures the former may be regarded as simply comprising another dependent variable that can be used to test competing theories (Henson, 2005). In neuroimaging studies, behavioural measures also fill an important control function, in that performance indicators, such as accuracy, provide an index of how well the participant is solving the cognitive task during scanning. Adequate task performance must be attained for imaging results to be interpreted correctly.

Statistical analysis of behavioural data has been performed using the SPSS 11.5.1 and analysis of neuroimaging data was performed using SPM99 and SPM2 (http://www.fil.ion.ucl.ac.uk/spm/).

Functional brain scanning

Over the past decades, a number of different methods of scanning the brain have been developed. These methods can be used to investigate what regions of the brain are involved in different cognitive processes. Some of these methods are based on measuring the electromagnetic activity of the brain while others are based on measuring blood flow, which is generally agreed to be a good index of neural activity (Cabeza & Nyberg, 2000). Two haemodynamic methods of brain scanning are used in the work presented in this thesis, PET and fMRI.

PET

During PET (Positron Emission Tomography), a radioactive tracer is introduced into the bloodstream by injection of a liquid. The tracer emits positrons which collide with electrons in brain tissue, resulting in two gamma rays. The gamma rays travel in opposite directions through the brain and the skull and are registered by detectors in the PET scanner. It can then be calculated where in the brain the gamma rays were generated and thus relative blood flow during the measuring period can be determined. Blood flow changes are registered over a period of 60 seconds. Patterns of blood flow during different cognitive activities and rest periods can be compared and inferences drawn about which neural regions support specific components of cognitive tasks (Nyberg, 2002). The spatial and temporal resolution of PET is inferior to that of fMRI but at the same time it is less sensitive to motor activity. This means that PET can be used to advantage to investigate neurocognitive activity during tasks that require articulation of sign or speech.

fMRI

fMRI (functional Magnetic Resonance Imaging) is based on measurement of the Blood Oxygen Level Dependent (BOLD) signal. This is achieved by measuring the behaviour of oxygen molecules under the influence of a strong magnetic field. In contrast to PET, fMRI allows a certain degree of analysis of signal change over time. A typical experimental paradigm is the blocked design where periods of active cognitive task solving are alternated with periods of rest. Another paradigm is the event-related design where the signal change is traced between individual events (Nyberg, 2002). Recently, a hybrid design has been developed that allows the separation of signals relating to sustained block-related activity and signals relating to transient event-related activity (e.g. Burgund, Lugar, Miezin & Petersen, 2003). fMRI has a better spatial and temporal resolution than PET but is sensitive to head movement which means that the motor responses of participants must be kept to a minimum. Often responses are given by pressing a button.

With either method, measurements are made during experimental conditions involving well-defined cognitive activity, based on solving a task in response to stimulus material presented through the visual, or auditory channel, or both. Differences in neural networks engaged in different task components can be identified by subtracting activation obtained in one condition from activation obtained in another, while similarities in neural networks can be identified by conjunction analysis (Nichols, Brett, Anderson, Wagner & Poline, 2005). On the assumption that there is some systematic mapping from psychological function to brain structure, two types of inference can be drawn: function-to-structure deduction and structure-to-function-induction (Henson, 2005). With function-to-structure deduction, different patterns of cerebral activity under two experimental conditions imply at least one different function between the two conditions. With structure-to-function induction, activity in the same brain region under two conditions implies a common function.

4
Empirical studies

The study of cognition through different language modalities has shown that while cognitive systems are generally amodal, some aspects of cognition are modified by sign language use. Specifically, working memory for sign language has a temporary storage component that seems to be spatially organised, and sign language use appears to interact with mental imagery skills, suggesting a link between language processing and non-linguistic visuospatial cognition. These findings generate a number of research questions which are addressed in this thesis:

1. Are differences in working memory storage for sign and speech reflected in neural representation?
2. Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?
3. Is working memory for sign language enhanced by a spatial style of information presentation?
4. Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

Paper I
Neural correlates of working memory for sign language

Paper I addresses research question 1. Are differences in working memory storage for sign and speech reflected in neural representation? The study reported in the paper makes a direct comparison between the neural correlates of sign and speech, in order to identify common and dedicated system components. A direct comparison is achieved by using early hearing signers who are proficient in SSL and Swedish as participants and administering tasks that are identical across language modality in all aspects bar language modality.

Method

Eight early hearing signers performed three different cognitive tasks in the sign language modality and the speech modality during PET-scanning. The tasks were a working memory task (WM), a semantic control task (SC), and a baseline task (BL), and all were based on encoding and storing a list of six lexical items, presented audiovisually. The WM task required immediate serial recall of all six items. The SC task required generation of six members of the category represented by the sixth list item and the BL task required six repetitions of the sixth list item.

PET data were analysed using SPM99. Five of the participants were native rather than just early signers and so a separate analysis of the results for this group (n=5) was performed.

Results

Behavioural results showed higher performance in speech than sign on the WM task but this difference was not accounted for by response time or response rate, indicating that intermodality differences in performance cannot be explained by articulation rate as has been suggested previously (Marschark & Mayer, 1998).

Imaging results showed bilateral superior parietal and occipito-temporal activation for sign language only, in all three tasks, see Figure 3. Function-to-structure deduction (Henson, 2005) suggests that there is a function in operation for all three memory tasks that is specific to sign language. We can also make the structure-to-function induction that all these tasks have at least one function in common.

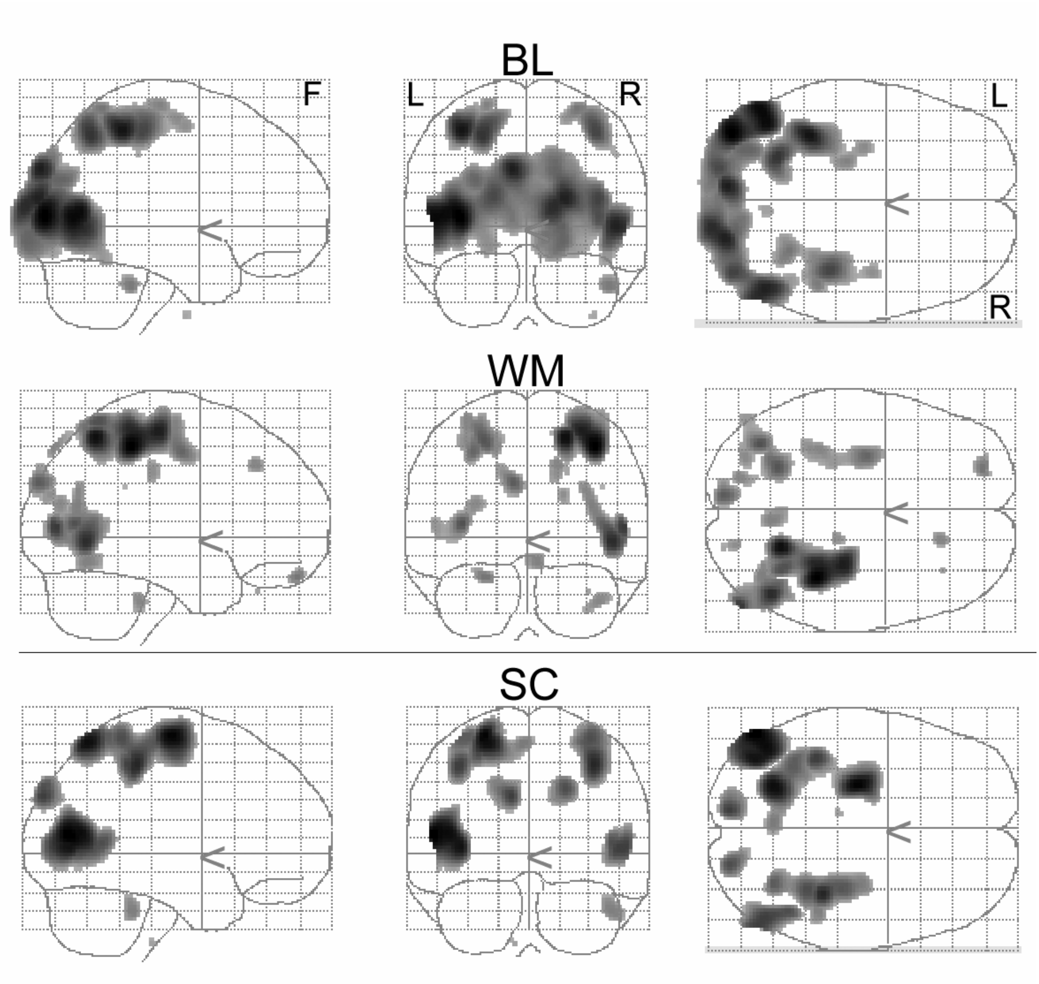

Figure 3[4]. (Figure 2, Paper I). Brain activity associated with sign language minus brain activity associated with speech (sign > speech) for each of the three memory tasks: Baseline (BL), Working Memory (WM) and Semantic Control (SC). (n=8). P < 0.001.

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[4] All imaging results are shown on transparent ”glass brains”, showing views from the side (sagittal), from the rear (coronal) and from above (axial).

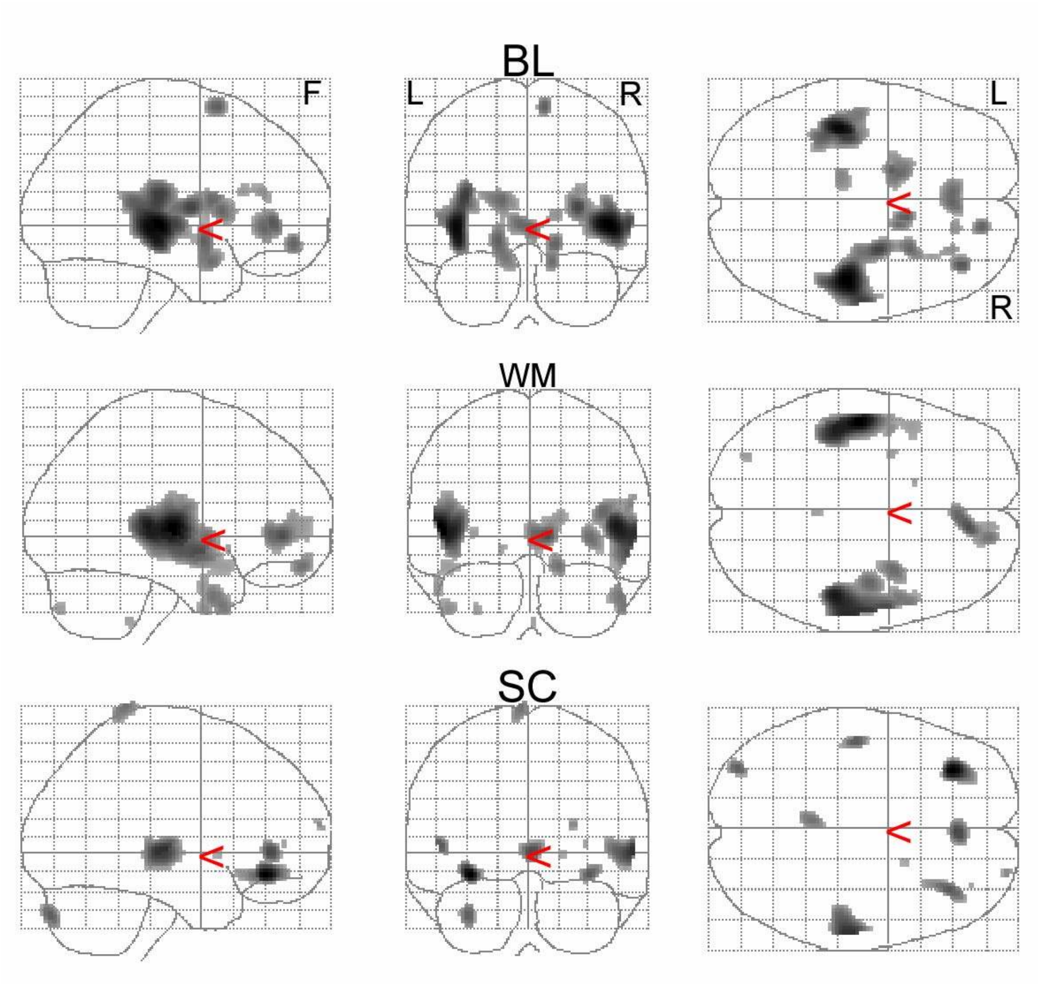

Figure 4. (Figure 3, Paper I). Brain activity associated with speech minus brain activity associated with sign language (speech > sign) for each of the three memory tasks: Baseline (BL), Working Memory (WM) and Semantic Control (SC). (n=8). $P < 0.001$.

Speech-specific activations were found bilaterally in the superior temporal gyrus, see Figure 4, reflecting a function that is specific to speech.

Analysis of results from the n=5 group showed similar results with the difference that the right hemisphere bias of the bilateral superior parietal activation for the WM task shifted to the left, possibly reflecting an age-of-acquisition effect.

Discussion

Rönnberg (2003) predicts similar neural networks for working memory for sign and speech, while the sensorimotor account (Wilson, 2001) predicts differences relating to the embodied nature of cognition. The general pattern of data in the present study shows that the neural organisation of working memory for sign and speech have some common and some modality-specific components (cf. Buchsbaum et al., in press). In particular, working memory for sign language shows net engagement of bilateral superior parietal and bilateral occipito-temporal regions.

Sign language is transmitted by means of a visual signal, and the spatial relations between the hands and the body bear meaning. Thus, visuospatial processing is central to sign-language processing. Visual processing activates the ventral stream while spatial processing activates the dorsal stream. Thus, the parietal activations found for sign language in the present study may represent sign storage through the activation of perceptual mechanisms (cf. Jonides et al., 2005).

Behavioural performance during the WM task was lower for sign than for speech (cf. Boutla et al., 2004). This discrepancy could not be explained in terms of response time or rate (cf. Marschark & Mayer, 1998) but it does indicate differing organisation for the two modalities. It seems likely that the parietal activation in our study, rather than reflecting sign language processing as such, reflects the implicit visuospatial processing involved in generating the virtual spatial array in order to complete working memory tasks in sign language.

No activation was found in Broca’s area, an area typically implicated in articulatory rehearsal (Smith & Jonides, 1997), in any of the contrasts between modalities. This finding ties in with previous work, suggesting common processes for language production across modalities (MacSweeney, Woll, Campbell, McGuire, et al., 2002). This is an important indication of a nonmodality-specific aspect of the data.

Paper I addressed the research question: Are differences in working memory storage for sign and speech reflected in neural representation? And provides strong evidence to answer in the affirmative. This raises the question of what happens to the representation of working memory when modalities are mixed. Paper II addresses this question.

Paper II

Speech-sign switching in working memory is supported by semantic networks

We investigated neural mechanisms involved in switching back and forth between spoken Swedish and SSL, while, at the same time, seeking to replicate the results of Paper I and pinpoint whether the components of the working memory systems involved were of a sustained or transient nature.

Method

Thirteen hearing native signers took part and fMRI technique was used to investigate neural mechanisms with better temporal and spatial resolution than in Paper I. As head movement must be avoided during fMRI, a working memory task was used that required yes/no responses only, which could be given by pressing a button, rather than by articulation of words and signs. This task was a two-back task which involved matching each new item to the item which had occurred two steps back in the list of presented items. This task was presented under three conditions: Swedish, SSL and Switching. In the Swedish condition all stimuli were spoken Swedish words, in the SSL condition all stimuli were signs in SSL, and in the Switching condition words and signs were mixed. All stimuli were presented audiovisually. A hybrid fMRI design was used to identify transient event-related and sustained block-related components of the working memory task. Transient components reflect on-line rehearsal and storage while sustained components reflect executive functions that are more stable throughout the task.

It was predicted that working memory systems for sign and speech would show the same pattern of shared and dedicated components as in Paper I, and that activation patterns for switching would indicate whether new items were being translated on-line in order to match them to old items with a modality-specific representation, or whether comparison of semantic representations was taking place.

Results

Behavioural data showed that performance accuracy was high throughout with no significant difference between the Swedish and SSL conditions but slightly lower for the Switching condition. Similarly, responses were given more slowly for Switching but there was no difference in response times for Swedish and SSL.

For both transient and sustained components, significant activation was found for the group of thirteen participants for all three conditions compared to rest. For the transient components, this activation was extensive and included the left hemisphere classical language areas, Broca and Wernicke, and the right cerebellum, as we had predicted. For the sustained components, activation was focused more anteriorly.

Comparisons between conditions revealed transient, but not sustained, components, indicating that whereas transient components differ between conditions, sustained components do not. Significant activation was found for the transient component of SSL > Swedish, Swedish > SSL and Switching > non-switching, but not for non-switching > Switching.

For SSL > Swedish there were three significant clusters of activation, one in each of the left and right inferior temporo-occipital regions and one in the right frontal lobe. The temporo-occipital activations probably reflect sign perception and visual aspects of sign storage while right frontal activation probably reflects visuospatial rehearsal mechanisms specific to sign language. See Figure 5a.

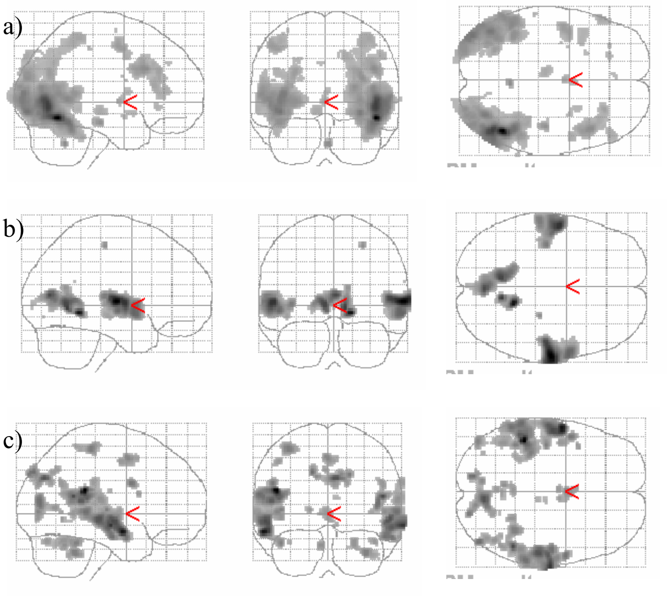

Figure 5. (Figure 3, Paper II). FDR-corrected maps ($p < 0.05$) for transient task components for a) SSL > Swedish, b) Swedish > SSL and c) Switching > non-switching.

For Swedish > SSL, there were four significant clusters with peaks of activation in the superior temporal lobes bilaterally and the lingual gyrus bilaterally probably reflecting integration of visual and auditory information in speech perception. See Figure 5b.

Switching > non-switching showed a number of large clusters of activation all concentrated in posterior regions with no prefrontal activity whatsoever, see Figure 5c. The two largest clusters covered the superior and middle temporal lobes bilaterally. There was also activation in the right cerebellum, the supplementary motor area, the left precentral gyrus, the right supramarginal gyrus, the right angular gyrus, the left superior parietal lobe and the left fusiform gyrus. This pattern of activation with no prefrontal component shows that modality switching relies on semantic storage rather than on-line executive control.

Conjunction analyses revealed extensive overlapping of neural networks involved in processing sign and speech. In particular, the conjunction of sustained components across tasks showed a main focus of activation in the right temporal lobe, which may be linked to a sustained aspect of working memory storage that is not language-modality specific. Further, the patterns of activation for conjunction analyses of sustained and transient components within conditions were relatively similar between conditions. Generally speaking, conjoined activation across transient and sustained components was organised anteriorly rather than posteriorly. The results of the conjunction analyses emphasise the key role of nonmodality-specific neural networks in working memory processing.

Discussion

The key finding in the present study is that language-modality switching is supported by semantic processes rather than on-line executive processing, providing an answer to research question 2: Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?

Structure-to-function induction (Henson, 2005) shows that working memory systems for sign and speech share nonmodality-specific processing networks engaging the left hemisphere language areas, and conjunction analysis confirms the extent of these (cf. Rönnberg, 2003). In contrast to the study reported in Paper I, there was no net parietal engagement for sign language, suggesting that the bilateral parietal sign-specific activation reported in Paper I, may relate to the task-specific storage demands of the immediate serial recall task. On the other hand, we found a new right prefrontal sign-specific rehearsal component. This may be specifically related to the two-back task used in the study reported in Paper II. Thus, using the logic of function-to-structure deduction (Henson, 2005), Papers I and II isolate task-specific components of working memory for sign language.

Together, these findings suggest that those components of working memory for language processing that are reliant on sensory systems may be generally language modality specific (cf. Wilson, 2001), whereas the language modality specificity of more abstractly defined components, such as rehearsal and storage, may be more paradigm dependent.

The cross-modal and language modality-free processing in the present study are not tied to executive functions and thus cannot be explained in terms of the central executive of working memory (Baddeley, 2000). Thus, an extended role is indicated for the other modality-free component of working memory, the episodic buffer. Theoretically, it seems plausible that the episodic buffer may be able to accommodate an explanation of cross-modal and modality-free aspects of working memory for sign and speech.

Paper III

Space for compensation – further support for a visuospatial array for temporary storage in working memory for deaf native signers

Working memory for sign language seems to have a spatial rather than a temporal organisation. This finding gave rise to the third research question: Is working memory for sign language enhanced by a spatial style of information presentation? In Paper III it was investigated whether a spatial style of presentation would enhance working memory performance in deaf native signers.

Method

We compared the performance of 12 deaf native signers, 12 hearing signers and 12 hearing non-signers on a working memory task using two different styles of presentation, spatial and temporal. With the spatial style of presentation, all items were presented simultaneously in a matrix. With the temporal style of presentation, stimulus items were presented serially.

In order to achieve even processing demands across groups, we used pictures of common objects as stimuli rather than words or signs. Previous work has shown that performance on serial recall tasks deteriorates when items share phonological features, for example if words rhyme with each other or signs share the same handshape. On the other hand, semantic similarity, for example, when items belong to the same category such as fruit or vegetables, does not affect working memory performance. However, it is not known whether phonological and semantic similarity affect performance with spatial presentation and thus inter-item similarity was included as a design variable with four list types: Distinct, Semantic, Swedish and SSL. In Distinct lists, neither the lexical labels of the pictures nor their semantic content bore any particular relation to each other. In Semantic lists all pictures represented objects that either belonged to the same semantic category or had a similar physical shape. In Swedish lists, the Swedish labels of all pictures were phonologically similar and in SSL lists, the SSL labels of all pictures were phonologically similar.

For each presentation style each list type was presented twice. With spatial presentation the nine items in each list were presented for nine seconds in a three-by-three matrix and with temporal presentation the nine items in each list were presented for one second each. Thus, total presentation time was the same for both presentation styles.

The task was to memorise the identity and order of all items and then, when the stimuli had been removed, either to write down their lexical labels or draw representations of them in the correct order in a response booklet. For the spatial style of presentation, the pages of the response booklet had a blank three-by-three matrix and for the temporal style, nine ruled lines. All participants performed the task with both styles of presentation, and order of presentation style was balanced.

Two different methods of scoring were used: item scoring and order scoring, reflecting maintenance of item and order information respectively. With item scoring, responses were deemed correct as long as they corresponded to list items, irrespective of order. With order scoring, responses were deemed correct only when they were recorded in the correct matrix cell for spatial presentation, or in the correct serial order for temporal presentation. ANOVAs were computed for presentation style, list type and group for both methods of scoring and, where appropriate, simple main effects were investigated. Serial position analyses were also performed.

Results

The mean score across list types and groups with item scoring was about five items per list, irrespective of presentation style, and with order scoring, about one item less. Scores on Semantic lists were generally higher then for other list types. There was no significant difference in level of performance between the three groups across styles of presentation and list types with either method of scoring. A significant three-way interaction between presentation style, list type and group for order scoring revealed that the spatial presentation style helped deaf native signers preserve order information in the case of distinct lists, see Figure 6. Further analysis showed that this effect was confined to educationally promoted signers who are younger native deaf signers who, unlike their older counterparts, have had the benefit of an accepting attitude to their native language.

With the temporal style of presentation, deaf native signers performed better when list items were semantically similar than when they were distinct, see Figure 7. This was not the case for the hearing groups. Further analysis showed that this effect was similar for older and younger signers.

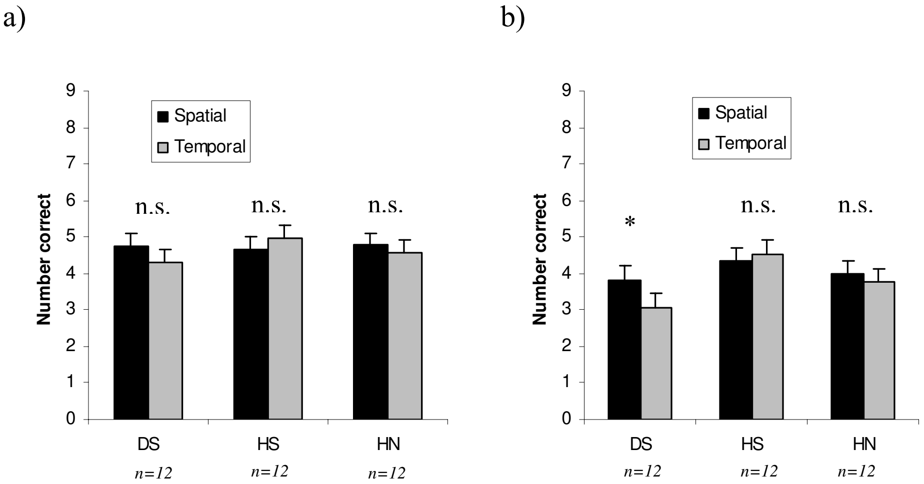

Figure 6. (Figure 1, Paper III). Effect of presentation style with Distinct lists. Deaf signers (DS), unlike the other two groups (hearing signers, HS and hearing non-signers, HN), performed significantly better with spatial presentation than temporal presentation with order b) but not item a) scoring.

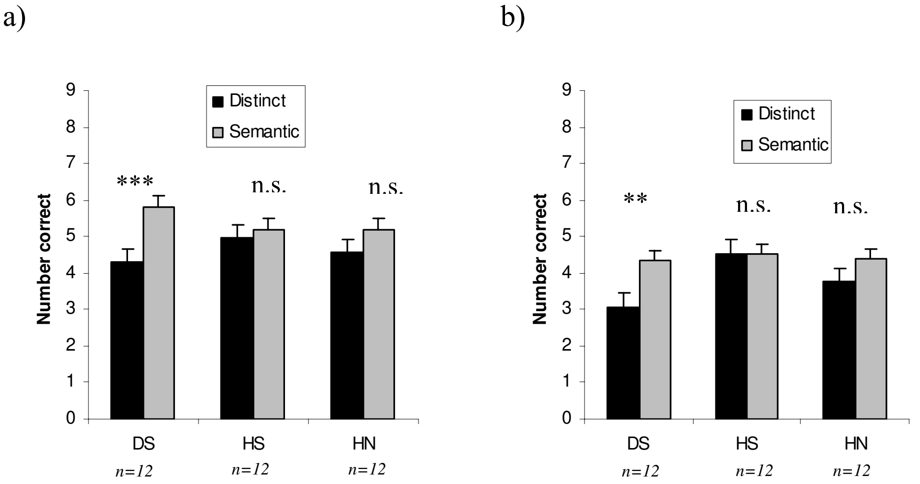

Figure 7. (Figure 4, Paper III). Effect of semantic similarity with temporal style of presentation. Deaf signers (DS), unlike the other two groups (hearing signers, HS and hearing non-signers, HN), performed significantly better on Semantic lists than Distinct lists with both item a) and order b) scoring.

An interaction between group and serial position with order scoring revealed that the deaf signers, unlike the hearing groups, did not show a primacy effect, see Figure 8. This indicates that they do not have the usual advantage for memorising the order or information at the beginning of lists. Thus, the advantage of the spatial style of presentation seen for deaf signers may be specifically linked to compensation for a poorer ability to effectively capture order information at the beginning of temporally ordered lists.

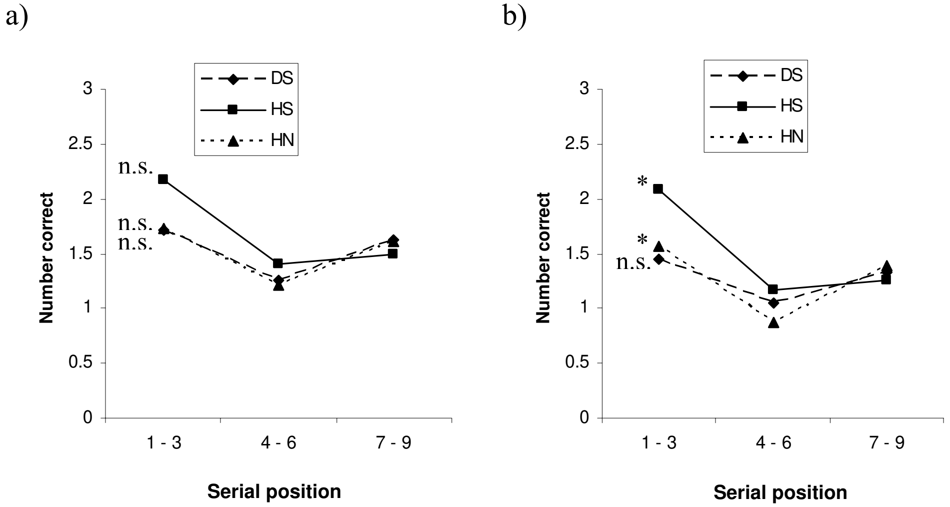

Figure 8. (Figure 8, Paper III). Effect of primacy. Hearing non-signers (HN) and the hearing signers (HS) but not deaf signers (DS) displayed a primacy effect with order b) but not item a) scoring.

All the deaf signers in the study were congenitally deaf and had started signing prelingually. However, the active promotion of sign language among deaf children in Sweden since the 1970s may have supported a compensatory process that exploits the inherently spatial characteristics of sign language in support of working memory (cf. Preisler & Ahlström, 1997). The younger deaf signers in the present study, unlike their older counterparts, have had the benefit of an accepting attitude to their native language, and are thus, educationally promoted signers.

There were no effects of presentation style for either of the hearing groups. We had expected that the hearing signers would also perform better with the spatial style of presentation but this was not the case. Furthermore, the hearing signers did not show the phonological similarity effect on Swedish lists shown by the hearing non-signers. Indeed the performance of the hearing signers showed no effects of any of the variables, unlike that of the other two groups. This indicates that working memory processing in hearing signers differs from that of deaf signers and hearing non-signers.

Discussion

These results show that the deficit in immediate serial recall typically displayed by deaf persons may be due to a poorer ability to preserve the order of information at the beginning of serially presented lists and that this deficit may be compensated for either by presenting items simultaneously in a spatial array, rather than serially, or by semantic similarity among list items. Spatial compensation seems to be limited to educationally promoted signers while semantic compensation seems to be general for deaf signers, irrespective of educational background. The finding of a spatial presentation effect for deaf signers is in line with our prediction and supports the notion that the storage component of working memory for deaf native signers is supported by a visuospatial array. Thus, research question 3: Is working memory for sign language enhanced by a spatial style of information presentation? Can be answered in the affirmative, at least as far as educationally promoted native deaf signers are concerned.

The further finding of a semantic similarity effect for the same group was not predicted as semantic similarity effects are not generally found for working memory tasks (Baddeley, 2003). However, semantic similarity does become a factor when longer lists are involved. It may be the case that the semantic similarity effect found for deaf signers with temporal presentation is related to recruitment of long-term memory processes when short-term memory span is exceeded.

Further work

Using the same three groups, deaf native signers, hearing native signers and hearing non-signers, a second working memory experiment is being performed to further investigate the effects revealed in Paper III. Materials in the new experiment are based on a standardised set of pictures (Snodgrass & Vanderwart, 1980). The design is 3 x 2 x 2 with three presentation styles, two response-cueing orders and two list types. The three presentation styles are spatial and temporal as in the study presented in Paper III, and the third is a hybrid, whereby items are presented one by one but in a spatial array. This third presentation style has been introduced to determine whether it is the spatial or the simultaneous nature of the spatial presentation style that offers deaf signers a compensatory effect. In the new study, cued response rather than recall is used. This obviates the need for written or drawn responses, eliminating a group-related nuisance variable, and at the same time improves accuracy of response recording. Items are cued either in order or randomly, to investigate potential between-group differences. The two list types are Distinct and Semantic, with semantically similar lists consisting of items that belong to the same category. Finally, the maintenance of item and order information is treated separately with the participants first being asked to indicate whether a particular item was present and then whether it occurred in the order indicated.

Initial results from a group of four hearing native signers do not indicate any effects of presentation style, cue order or list type. This is in keeping with the results of the experiment presented in Paper III, where there were no effects of presentation style or list type for this group.

Interim discussion of Papers I, II & III

Papers I, II and III investigate some of the implications of language modality for working memory processing. Together, the results presented in these papers demonstrate a range of language modality specific and language modality neutral effects in working memory. Results reported in Papers I and II indicate that while components of working memory for language processing that are more closely related to sensory systems seem to have a neural organisation that is generally language modality specific, more abstractly defined components, such as rehearsal and storage, may or may not be revealed to be supported by modality specific neural systems depending on the methods of investigation.

The neurocognitive findings of Papers I and II are supported by the cognitive findings of Paper III, which shows that the relative working memory performance of persons who are more or less dependent on sign or speech is task specific. Previous work has shown that working memory storage may be organised differently for sign and speech (e.g. Wilson & Emmorey, 2003) and the work reported in Papers I, II & III supports this notion.

The work reported in Papers I & II was based on studying working memory in native hearing signers using neuroimaging methods. This group was used in order to achieve an economical within-subjects design. However, care should be taken in generalising these results to deaf signers. Although some previous work has shown that it is the age of acquisition of sign language rather than absence of hearing that determines organisation of neural and cognitive systems (e.g. Emmorey et al., 1993; Newman et al., 2002), differences in brain structure relating to auditory experience have been found for deaf and hearing persons (Emmorey, Allen, Bruss, Schenker & Damasio, 2003), which may affect functional processing, and results of Paper III indicate that the working memory processes of hearing and deaf signers may differ.

Further work should investigate the neural correlates of working memory in deaf native signers compared to hearing native signers and hearing non-signers. At the same time, attention should be paid to choice of tasks used and how language modality is controlled. Results reported in Papers I and II indicate that different neural systems are involved in immediate serial recall and the two-back paradigm for working memory processing for sign language, probably reflecting differentiated involvement of rehearsal and storage processes. Thus, future work should focus on task analysis (cf. Rönnberg & Bäckman, 1995).

In Papers I and II stimulus material was presented audiovisually in either sign or speech. This functions well with a within-subjects design but is more problematic for comparisons between groups as it may be difficult to separate effects attributable to the stimulus material and those attributable to different cognitive processes. In Paper III, the stimulus material was based on easily nameable pictures to avoid the problem of different stimulus material for different groups. However, this approach has its own problems in that even though pretesting confirmed that all pictures were easy to name, there is no direct control over which language modality the two signing groups are using to encode items. This problem can be circumvented by using a task which focuses the participant's attention on phonological aspects of lexical items in respective language modalities. For example, the task may involve judging the phonological similarity of the sign or speech labels of pictures. We are using this technique in a current study (Gunnarsson, Rudner, Rönnberg, Elfgren, Larsson & Risberg, in preparation). Other techniques may be based on the fact that letters of the alphabet and digits have distinct phonological qualities in sign and speech.

Papers I, II and III represent a research thread which aims to reveal the similarities and differences in cognitive and neural mechanisms behind working memory for sign and speech. This research is important on two counts: first, it gives us knowledge that can inform deaf education and second, it furthers our understanding of cognitive systems in general. The results of Papers I, II & III show that there clearly are differences in the organisation of sign and speech that are not directly related to sensorimotor differences. These differences are related to both storage and rehearsal aspects of working memory processing and it seems that the inherently spatial organisation of working memory for sign language can be supported by presenting information items simultaneously in a spatial array.

Papers IV and V represent a parallel research thread that uses the findings of sign language cognition to generate new research questions of a more general nature. This research is important because it provides a new angle on theories developed on the basis of findings from speech-based cognition. Papers IV and V continue the theme of working memory from Papers I-III.

Paper IV

Perceptual saliency in the visual channel enhances explicit language processing

Paper V

Reversing spoken items – mind twisting not tongue twisting

Papers IV and V report a package of results from experiments designed to address the fourth research question posed in this thesis: Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

Paper IV reports results related to accuracy and reaction time measures from three experiments, referred to as Experiments 1, 2 and 3. Paper V reports an fMRI study that further investigates the findings of Experiment 1 in Paper IV. The behavioural results reported for Experiment 3 in Paper IV are those obtained for the fMRI study in Paper V. Owing to the intertwined nature of the results reported in these two papers they are discussed together here in the following order: Paper IV, Experiment 1; Paper V; Paper IV, Experiment 2.

Emmorey and colleagues (1993) showed that sign language users have superior abilities in some aspects of manipulating mental imagery that are crucial to the specific linguistic requirements of sign language. These aspects include image generation and the ability to detect mirror image reversals. Both deaf and hearing signers demonstrated this enhancement and it was also found that the earlier the age of sign language acquisition, the greater the enhancement. This shows that it is the demands of sign language use, rather than deafness, that drive enhancement of imagery abilities in signers and demonstrates a link between the characteristics of language in the visuospatial domain (sign language) and non-linguistic cognitive abilities in the same domain (manipulation of visual mental imagery). More recently, further evidence of this link has been provided by findings that show that signers, unlike non-signers, spontaneously use imagistic properties in making meaning similarity judgments (Vigliocco, 2005).

The work covered in Papers IV and V explores whether a corresponding phenomenon may be found within the auditory domain; in other words, whether there is a link between spoken language processing and manipulation of auditory mental imagery. This is achieved by investigating performance on the word reversal task, a taxing cognitive task which requires the active manipulation of auditory imagery, relative to the perceptual saliency of the words reversed. The word reversal task requires the participant to mentally reverse a speech stimulus and then match the result of this process to a second stimulus consisting of temporally reversed speech. Thus, the word reversal task is performed in working memory. The perceptual saliency of a word is defined in terms of its sonority profile. Sonority is the relative loudness of a speech sound compared to that of other sounds with the same length, stress and pitch and is correlated with the relative openness of the oral cavity in making that sound (Blevins, 1995). Syllables have a sonority profile that rises to a peak at the vowel and can thus be categorised according to degree of perceptual saliency at the syllable peak. In the present studies, spoken items (words and non-words) in which the stressed syllable has a low-sonority vowel [i, y, u], are categorised as having low perceptual saliency, while items in which the stressed syllable has a high-sonority vowel [a, ɑ], are categorised as having high perceptual saliency.

We hypothesised that performance on the word reversal task would be higher for words with high perceptual saliency, indicating a link between spoken language processing and manipulation of auditory mental imagery in working memory.

Paper IV, Experiment 1

Method

16 (eight women and eight men) hearing non-signers took part in Experiment 1. The stimuli were audiovisual recordings of common Swedish words and non-words, some of which were temporally reversed. The non-words had the same number of syllables as the words with which they were matched, and the same stress pattern, and were formed by replacing the onset (initial consonant cluster) of each constituent syllable of the corresponding word, for example, the word ‘betydelse’ [bəty:delsə](meaning) was matched with the non-word ‘gefypelte’ [gəpy:feltə]. All stimuli were based on natural speech produced by a male adult. Stimuli were presented in pairs. The first stimulus was always a word, and it was never temporally reversed. The second stimulus was always temporally reversed and it was either identical to the first stimulus or it was based on the matched non-word. The task was to mentally reverse the first stimulus and then determine whether the mentally reversed word matched the second stimulus. The task was performed under four different conditions with four different kinds of phonological profile of the stimulus material. The four conditions were long high sonority, short high sonority, long low sonority and short low sonority. In the long conditions, all stimuli contained three or four syllables, while in the short conditions all stimuli had one or two syllables. In the high sonority conditions all the stimuli had a low vowel [a, ɑ] in the stressed

syllable. In the low sonority conditions all the stimuli had a high vowel [i, y, u] in the stressed syllable.

Stimuli were presented on a computer screen and through loudspeakers and responses were given by pressing keys on a computer keyboard. Average accuracy and reaction time was calculated for each condition and ANOVAs were computed using SPSS software.

Results

Just as we had predicted, accuracy was higher for high-sonority words (F (1, 15) = 17.14, $MS_E = 0.03$, $p < 0.01$) and responses were made faster (F (1, 15) = 12.11, $MS_E = 0.07$, $p < 0.01$). There was no difference in accuracy for long and short words, although short words were processed faster (F (1, 15) = 42.84, $MS_E = 0.08$, $p < 0.001$), as one would expect. There were no gender differences.

Discussion

Results showed that the ability to perform the taxing cognitive task of word reversal is affected by the perceptual saliency of the items. This indicates that manipulating mental imagery in the auditory domain is linked to speech processing. In order to find out more about the cognitive mechanisms behind word reversal and perceptual salience we performed an fMRI study which is reported in Paper V.

Paper V

To separate neural processing relating to linguistic and cognitive aspects of the word reversal task, a phonological baseline task in the form of a rhyme judgment task was used along with the word reversal task.

Method

12 (6 women and 6 men) hearing non-signers whose native language was Norwegian took part in this study. Two tasks were used: a modified version of the word reversal task used in Paper IV, Experiment 1, and a rhyme judgment

task. The rhyme judgment task involved determining whether two words rhymed with each other. The auditory stimuli used in both tasks were based on Norwegian. Ideally, we would have liked to have used audiovisual presentation as in Paper IV, Experiment 1, but technical limitations did not allow this. Perceptual saliency was manipulated as described previously. As no effect of word length was obtained in Paper IV, Experiment 1, all stimuli used in the study in Paper V were monosyllabic. Even though no effect of gender was obtained in Paper IV, Experiment 1, the gender variable was retained to determine whether there were any gender-related differences in neural response.

Results

Performance accuracy was significantly higher for the phonological baseline task than for the word reversal task (F (1, 78) = 137.19, $MS_E = 0.02$, $p < 0.001$). This effect was especially prominent for women whose performance was higher than that of men on the baseline task but not the word reversal task, as evidenced by an interaction between task type and gender (F (1, 78) = 7.31, $MS_E = 0.02$, $p < 0.01$). Surprisingly, in contradiction of the results of Paper IV, Experiment 1, there was no difference in performance on either task relating to perceptual saliency.

Performance was significantly faster for the phonological baseline task (F (1, 78) = 336.52, $MS_E = 50435$, $p < 0.001$), especially for women (F (1, 78) = 21.48, $MS_E = 50435$, $p < 0.001$). Surprisingly, and again in contradiction of the results of Paper IV, Experiment 1, responses were given faster to stimuli with low perceptual saliency (F (1, 78) = 20.54, $MS_E = 48795$, $p < 0.001$).

Imaging results showed extensive activation for both word reversal and rhyme judgment. Word reversal collapsed across perceptual saliency and gender in relation to the rest baseline showed activation of an extensive network of regions bilaterally, including anterior and posterior regions both cortically and subcortically (see Figure 9).

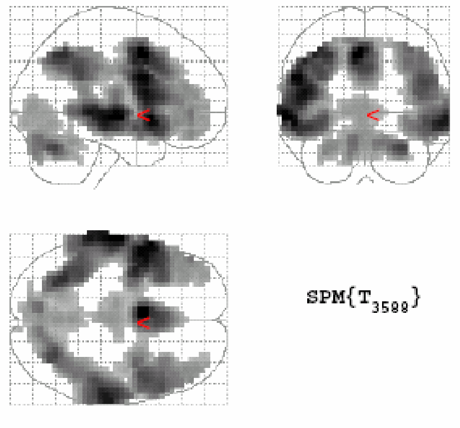

Figure 9. Word reversal collapsed across perceptual saliency and gender in relation to the rest baseline. P (corrected) < 0.05.

In order to identify those regions that were involved exclusively in the active manipulation of auditory imagery rather than phonological processing, activation obtained for the rhyme judgment task was subtracted. Word reversal minus rhyme judgment showed robust activation bilaterally in the inferior and superior parietal region, the left middle frontal gyrus, the right inferior frontal gyrus and the cerebellum (see Figure 10 a). This pattern of activation is very similar to that found in studies of mental rotation (Jordan et al, 2001; Podzebenko et al, 2002; Vanrie et al, 2002).

For the word reversal task, high saliency minus low saliency activated the occipital lobes bilaterally, see Figure 11 a. This suggests that primary visual processing was taking place. This result was surprising as there is no overt visual processing involved in the tasks used in this study.

High saliency word reversal minus high saliency rhyme judgment task showed activation in the parietal lobes bilaterally and the middle frontal gyrus bilaterally. In this high saliency contrast there was once again activation in the primary visual cortex and there was also activation in the right inferior frontal gyrus (see Figure 10 b).

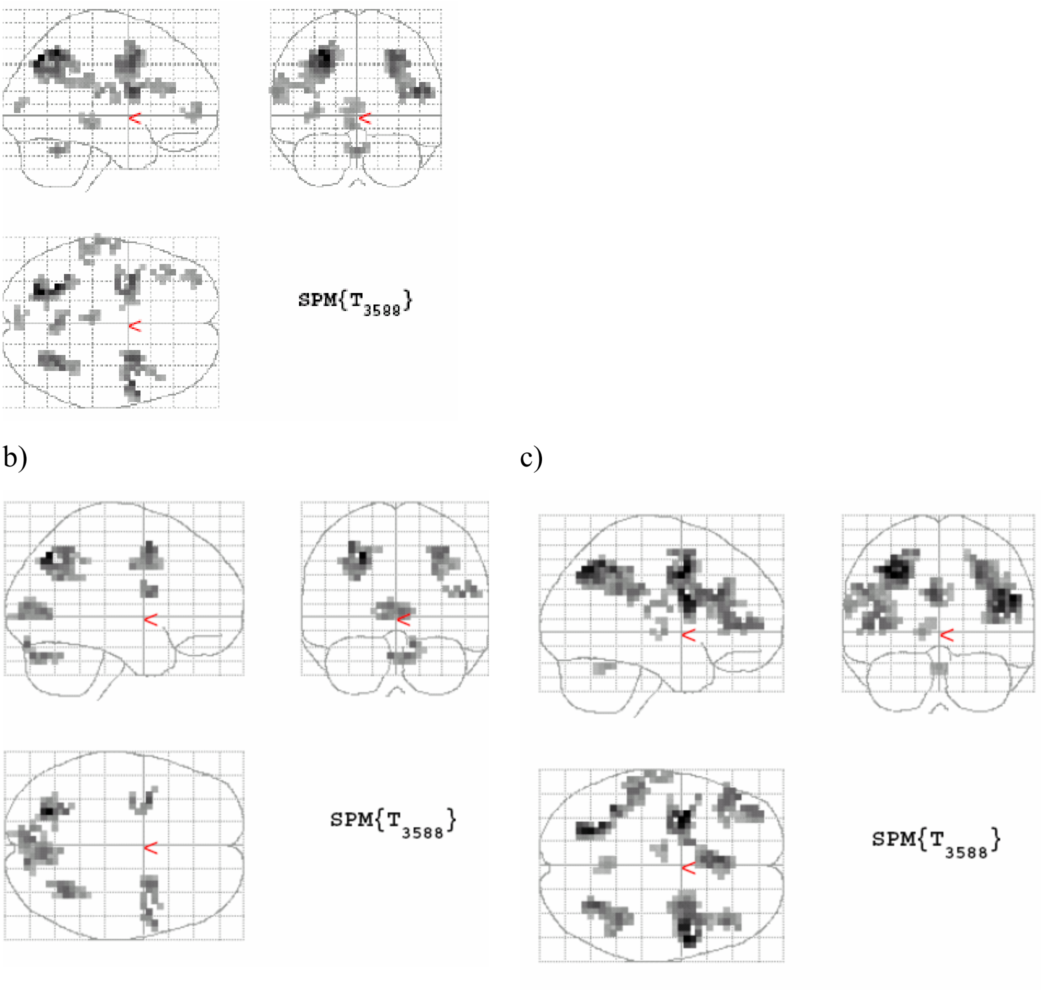

Figure 10. Word reversal > rhyme judgment. a) Collapsed across saliency, b) High saliency c) Low saliency. P (corrected) < 0.05.

Low saliency word reversal minus low saliency rhyme judgment showed activation in the parietal lobes bilaterally and the middle frontal gyrus bilaterally. Unlike the equivalent high saliency contrast, there was no activation in the visual cortex. On the other hand, there was activation in the anterior cingulate, which is known to be associated with executive mechanisms. There was also activation in the anterior portion of the left inferior frontal gyrus, which spread into the dorsolateral prefrontal cortex, and activation in the posterior portion of the right inferior frontal gyrus posteriorly on the right. See Figure 10 c.

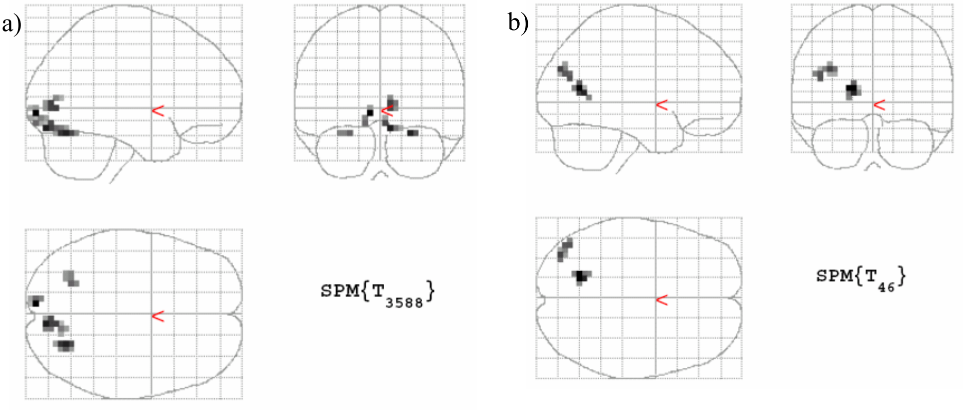

Figure 11. a) High saliency > low saliency, for the word reversal task. b) Women > men across all conditions. P (corrected) < 0.05.

Thus, by function-to-structure deduction, differences in patterns of cerebral activity for the word reversal and rhyme judgment tasks imply at least one different component between those tasks. Analytically, this is the non-phonological component of the word reversal task and it is supported by bilateral parietal and right inferior frontal regions, that are similar to those found for the manipulation of visual imagery such as during a mental rotation task.

With structure-to-function induction, activity in the same brain regions for the high and low saliency versions of these tasks implies a common component across these conditions. However, differences in patterning between the high and low saliency versions of these contrasts implies that further separate components are involved. The engagement of primary visual areas for the high saliency contrast, which was also found for high saliency collapsed across tasks, suggests the involvement of visual processing in performing the high saliency version of the word reversal task. More extensive frontal engagement for the low saliency version, particularly in the left inferior frontal gyrus and the dorsolateral prefrontal cortex, suggests the involvement of more executive mechanisms, possibly related to phonological processing.

Significant gender differences in activation were only found when a contrast was performed across all conditions. In this case net activation was found for women in the left superior occipital gyrus and the left middle temporal gyrus, see Figure 11 b. These areas are associated with different stages of visual processing. No net activation was found for men.

Discussion

The net bilateral parietal and right inferior frontal activation found for the word reversal task suggests that the dynamic manipulation of auditory imagery involved in mental reversal of words seems to engage mechanisms similar to those involved in manipulation of visual mental imagery, as for example, in mental rotation. This fits in with the proposal of a common supra-modal spatial processing component in working memory supported by occipito-parietal structures (Zimmer et al., in press). Activation of the visual cortex in the high saliency version of this task suggests that participants may be generating visual mental imagery to help solve the task, but only in the high saliency version. The temporo-occipital activation for women suggests that they may be relying more on imagery processes. High perceptual saliency is associated with both loudness and a more open mouth. It is possible that visual mental imagery in the form of an imagined open mouth or an imagined loudness curve may be being used here. Activation of left frontal areas in the low saliency version of the word reversal task suggests that more executive and possibly phonological processing was taking place.

Contrary to expectations, perceptual saliency did not affect performance accuracy and reaction times were actually faster on the low saliency conditions. The key difference between the word reversal task in Paper V and the equivalent task in Paper IV, Experiment 1, is that there was no visual component in

Paper V. Results of Paper V suggest that visual imagery may be generated during the high saliency version of the task. In order to investigate whether the visual component is the key to the perceptual saliency effect, Experiment 2 in Paper IV was conducted.

Paper IV, Experiment 2

The purpose of Experiment 2 was to investigate the relative contribution of visual and auditory information to the perceptual saliency effect in word reversal.

Method

Experiment 1 was repeated using the same stimulus material and procedure but with either sound only or vision only. Five new participants were recruited.

Results

Performance was more accurate for the auditory version of the task than the visual version, (F (1, 4) = 52.56, $MS_E = 0.01$, $p < 0.01$). There was no main effect of perceptual saliency but there was an interaction between version and saliency (F (1, 4) = 12.25, $MS_E = 0.00$, $p < 0.05$), revealing a simple main effect of sonority for visual presentation (F (1, 16) = 27.25, $MS_E = 0.00$, $p < 0.001$). This shows that performance was more accurate for high sonority items when they could only be seen but not when they could only be heard. There were no effects relating to reaction time.

Discussion

The results of Experiment 2 show that perceptual saliency information affects performance on the word reversal task, with visual-only presentation but not with sound-only presentation. This indicates that perceptual saliency information seems to be borne by the visual channel rather than the auditory channel.

Papers IV & V General discussion

Perceptual saliency transmitted by the visual channel enhances performance on the word reversal task. The word reversal task is a taxing cognitive task that requires the active manipulation of auditory imagery. Performance of this task seems to be supported by the same neural substrates as active manipulation of visual mental imagery as, for example, during mental rotation. When this task is performed without the support of a visual signal, there is evidence to suggest that visual imagery is generated for material with high perceptual saliency but not for material with low perceptual saliency. Moreover, women seem to engage imagery processes to a greater extent than men. The low saliency version of the task seems to rely more on executive and possibly phonological processing. These results provide evidence to indicate that in response to research question 4 that the neural networks supporting word reversal indicate that this task involves mind-twisting rather than just tongue-twisting.

General discussion of Papers I-V

The work covered in this thesis addresses four research questions:

1. Are differences in working memory storage for sign and speech reflected in neural representation?
2. Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?
3. Is working memory for sign language enhanced by a spatial style of information presentation?
4. Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

The following answers were obtained:

1. The results of Papers I and II indicate that rehearsal and storage components in working memory are supported by at least partially differentiated neural networks for sign and speech. Furthermore, these

networks seem to be dependent on the specific working memory task employed.

2. Paper II shows that switching between sign and speech during a working memory task is supported by semantic rather that executive neural processing networks.
3. Paper III shows that the working memory performance of educationally promoted native deaf signers is enhanced by a spatial style of presentation.
4. Paper IV shows that performance on the taxing cognitive task of reversing spoken items is enhanced by perceptual saliency information transmitted through the visual channel. This information may help in the generation of mental imagery to aid in solution of the task. Paper V shows that even when no perceptual saliency information is available in the visual channel, mental imagery still seems to be generated and manipulated in solution of this auditory-based task, indicating that word reversal is a matter of mind-twisting rather than tongue-twisting.

Thus, the work covered in this thesis has extended our knowledge of the neurocognition of working memory by exploring the relative organisation of working memory for sign and speech, and by using previous findings in the field of sign language cognition to generate new hypotheses about the interaction of language and cognition.

5

Theoretical implications, functional ontology and model

The work presented in this thesis shows that working memory for language processing has both modality-specific, and nonmodality-specific aspects. This has theoretical implications which can be interpreted in terms of a functional ontology and a model of working memory for sign and speech.

Modality-specific aspects

Working memory for sign language has been shown to have two kinds of modality-specific component: modality-specific components that reflect the sensory modality in which the stimulus material is delivered, and modality-specific components that are related to the higher-level cognitive functions of storage and rehearsal rather than directly to sensorimotor mechanisms. Components relating to sensory modality have been demonstrated neurally in the form of bilateral occipito-temporal engagement during both immediate serial recall (Paper I) and a two-back task (Paper II). These components are clearly related to sign perception. However, they may also be linked to sign storage. High-level components relating to rehearsal and storage in working memory have been demonstrated both neurally and behaviourally. Neural components were found in the form of bilateral superior parietal engagement for sign storage during immediate serial recall (Paper I), and right frontal engagement for sign rehearsal during a two-back task (Paper II). Behaviourally, native hearing signers showed inferior immediate serial recall performance when items were presented in sign language (Paper I), and educationally promoted deaf native signers showed that they could compensate for a deficit in immediate serial recall performance when items were presented simultaneously in a spatial array (Paper III).

Working memory for speech has been shown to have modality-specific components that reflect the sensory modality in which the stimulus material is delivered. These components have been demonstrated neurally in the form of bilateral superior temporal engagement during both immediate serial recall (Paper I) and a two-back task (Paper II). These components are related to speech perception but probably also to word storage.

Nonmodality-specific aspects

Nonmodality-specific aspects of working memory were found in the form of modality-free, cross-modal and extra-modal neural components. Modality-free neural components of working memory are those regions which are engaged in working memory processing *irrespective of whether it takes place in sign or speech*. These regions were revealed directly by conjunction analysis (Paper II) and indirectly by subtraction (Paper I). Modality-free neural networks for working memory were found to include the classical language areas (Papers I & II) as well as bilateral parietal and prefrontal areas (Paper II, conjunction analysis), reflecting executive processing.

Cross-modal neural components of working memory are those regions which are engaged when processing involves *switching between sign and speech*. These regions were revealed directly by subtraction (Paper II). Cross-modal neural networks were found to include the middle temporal gyrus bilaterally as well as the right cerebellum, the supplementary motor area, the left precentral gyrus, the right supramarginal gyrus, the right angular gyrus, the left superior parietal lobe and the left fusiform gyrus, reflecting semantic storage rather than on-line executive control.

Extra-modal neural components of working memory are those regions which are related to a sensory modality other than the modality of the stimuli. Extra-modal components relating to *vision and mental imagery* were shown to be engaged during a taxing speech-based task using *auditory* stimuli (Paper V), reflected in bilateral parietal and right frontal activation.

Theoretical interpretation

A number of different models of working memory have been proposed over the years and it is important to consider to what extent they can accommodate the results of the work in this thesis. Models of working memory fall into two general categories, capacity models and components models. Among capacity models, Rönnberg's (2003) model for cognitive involvement in language processing predicts that similar neural networks will be activated for working memory for sign and speech. Among component models, Wilson's (2001) sensorimotor model, predicts that working memory processing for sign and speech will reflect the sensorimotor processes involved in language comprehension and production in respective modalities. Thus, modality-specific aspects of the data are better explained in terms of the component model, while nonmodality-specific aspects are better explained by a capacity approach and harder to accommodate in terms of the current component model (Baddeley, 2000).

Modality-specific aspects of working memory for sign language can be accommodated by the visuospatial sketchpad in Baddeley's (2000) model, given that the functionality of the visuospatial sketchpad also includes language. Nonmodality-specific aspects, on the other hand are harder to explain in terms of the slave loops. Nonmodality-specific components of the model are the central executive and the episodic buffer. Some of the nonmodality-specific components of working memory found in this thesis are related to executive control, such as the modality-free bilateral parietal and prefrontal activations (Paper II) and thus can be explained in terms of the central executive. However, this does not apply to all nonmodality-specific components. For example, modality-free neural networks including the classical language areas (Papers I & II), cross-modal networks, reflecting semantic storage rather than on-line executive control during cross-modality switching (Paper II), and extra-modal components, relating to visual processing during a speech-based task (Papers IV

& V), cannot be explained in terms of the central executive. As all these aspects implicate processes involved in working memory for language processing that are not tied to a specific sensory modality, they could, theoretically, be taken care of by the episodic buffer, which has been defined as a limited-capacity temporary storage system that is capable of integrating information from a variety of sources (Baddeley, 2000).

Thus, the findings of this thesis can be interpreted in terms of the component model of working memory (Baddeley, 2000), *given that the visuospatial sketchpad can accommodate language and that the functionality of the episodic buffer is extended to include a number of functions*. These specific functions and their related neural regions are 1) modality-free aspects of language processing which engage the classical language areas, 2) cross-modal processing involved in switching between sign and speech, which engages a network including principally the middle temporal gyrus bilaterally, and 3) extra-modal integration of visual information in support of speech processing, supported by bilateral parietal areas.

Functional ontology

In the present thesis, behavioural and neuroimaging methods have been used to address the issues at hand. Traditional cognitive models do not explicitly take into account the neural correlates of individual processes. A new approach is to use functional ontologies to link cognitive functions to neural structures (Price & Friston, 2005). Functional ontologies have the advantage that they facilitate integration of cognitive and anatomical models and organise the cognitive components of diverse tasks into a single framework. According to Price and Friston (2005), a good ontology should have a hierarchical structure that predicts the coactivation of anatomical regions, where sets of coactivated regions should have demonstrable effective connections, and enable cognitive processing to be predicted given any distribution of activations, based on which area, or set of areas, is necessary for that processing. A new functional ontology relating to the components of working memory for sign and speech as discussed in this thesis is proposed and shown in Figure 12.

This ontology is based on a modification of Baddeley's (2000) model of working memory with its four key components, the central executive, the phonological loop, the episodic buffer and the visuospatial sketchpad. The neural correlates of three of these key working memory components are addressed in the functional ontology. Reading from left to right, these are the phonological loop, the episodic buffer and the visuospatial sketchpad.

The solid black arrows joining these four components indicate information flows at a cognitive level as defined in the model. The connections without arrows indicate fractionation of the phonological loop, the episodic buffer and the visuospatial sketchpad into subcomponents as suggested by previous work and the work presented in this thesis. The solid half-tone arrows indicate how these subcomponents are supported by neural structures as indicated by the experiments reported in this thesis. These arrows may be read as 'causes activation in'. The roman numerals labelling these arrows indicate the papers in the thesis that justify their existence. In the functional ontology, neural regions are arranged so that they correspond with the cognitive functions that cause their activation. Thus, their relative positions are determined by ease of reading and do not have any significance of themselves.

The phonological loop

The phonological loop is fractionated into storage and rehearsal subcomponents (Baddeley, 2000). In Papers I, II & V we found that the superior temporal cortex bilaterally is activated during speech-based working memory tasks and that this activation probably reflects temporary storage processes. Paper V showed that this area was equally engaged for two different speech-based working memory tasks, while Papers I & II showed that it was more heavily engaged for working memory for speech than sign. Papers II & V showed activations in Broca's area for speech-based working memory tasks, which probably reflect rehearsal processes. However, Paper I showed implicitly, and Paper II, explicitly that the same area is also engaged in similar processing in sign language.

The episodic buffer

In an attempt to explain the results of work presented in this thesis in terms of the component model, it is suggested that the only amodal component of the model that is not engaged in executive processing, the episodic buffer, might be redefined to accommodate three different species of nonmodality-specific processing: modality-free, cross-modal and extra-modal. The fact that Broca's area is engaged in rehearsal processes in both sign and speech means that it is involved in modality-free processing in working memory, and thus, that it is a neural correlate not only of the phonological loop for speech processing, but also of the modality-free subcomponent of the episodic buffer. In Paper II, it was shown that cross-modal processing during a working memory task engages bilateral middle temporal regions. Paper V provided evidence of extra-modal processing in bilateral parietal and right frontal regions.

The visuospatial sketchpad

Papers I & II showed that if the definition of the visuospatial sketchpad, with its previously described fractionation into a visual cache and an inner scribe (Logie, 1995), is extended to include language processing, then it can accommodate the data. The work presented in this thesis focuses on language processing in the speech and sign modalities, and thus no conclusions can be drawn regarding a fractionation of the sketchpad for linguistic and non-linguistic processing. However, data do motivate fractionation of the visual cache into two components: Visual cache 1, which is task-neutral, and visual cache 2, which is task-specific. The task-neutral visual cache seems to engage bilateral occipito-temporal regions, irrespective of the nature of the working memory task, while the task-specific visual cache comes into play when storage capacity demands are high, engaging bilateral parietal regions. Similar regions are also engaged by the postulated modality-free and cross-modal subcomponents of the episodic buffer, and may support a common supra-modal spatial processing component in working memory (Zimmer et al., in press). Paper II showed that when rehearsal demands are high, the inner scribe comes into play, engaging right frontal regions.

Common neural regions and effective connectivity

Price and Friston (2005) stipulate that a good ontology should enable cognitive processing to be predicted given any distribution of activations. However, the ontology presented here includes several instances where one and the same neural region is implicated in a number of cognitive functions. For example, the left inferior prefrontal area is engaged by the rehearsal component of the phonological loop and the postulated modality-free component of the episodic buffer. This indicates that these two cognitive components may share a common function and suggests that an investigation of potential functional commonalities may be an interesting area for further investigation.

Another stipulation for good ontologies (Price & Friston, 2005) is that they should have demonstrable effective connections at the neural level. In other words, it should be indicated which regions are coactivated in support of specific cognitive functions. The ontology presented here does not explicitly show effective connections between neural regions. This is because the focus is on the function-to-structure relationship and how it may illuminate fractionation of cognitive function.

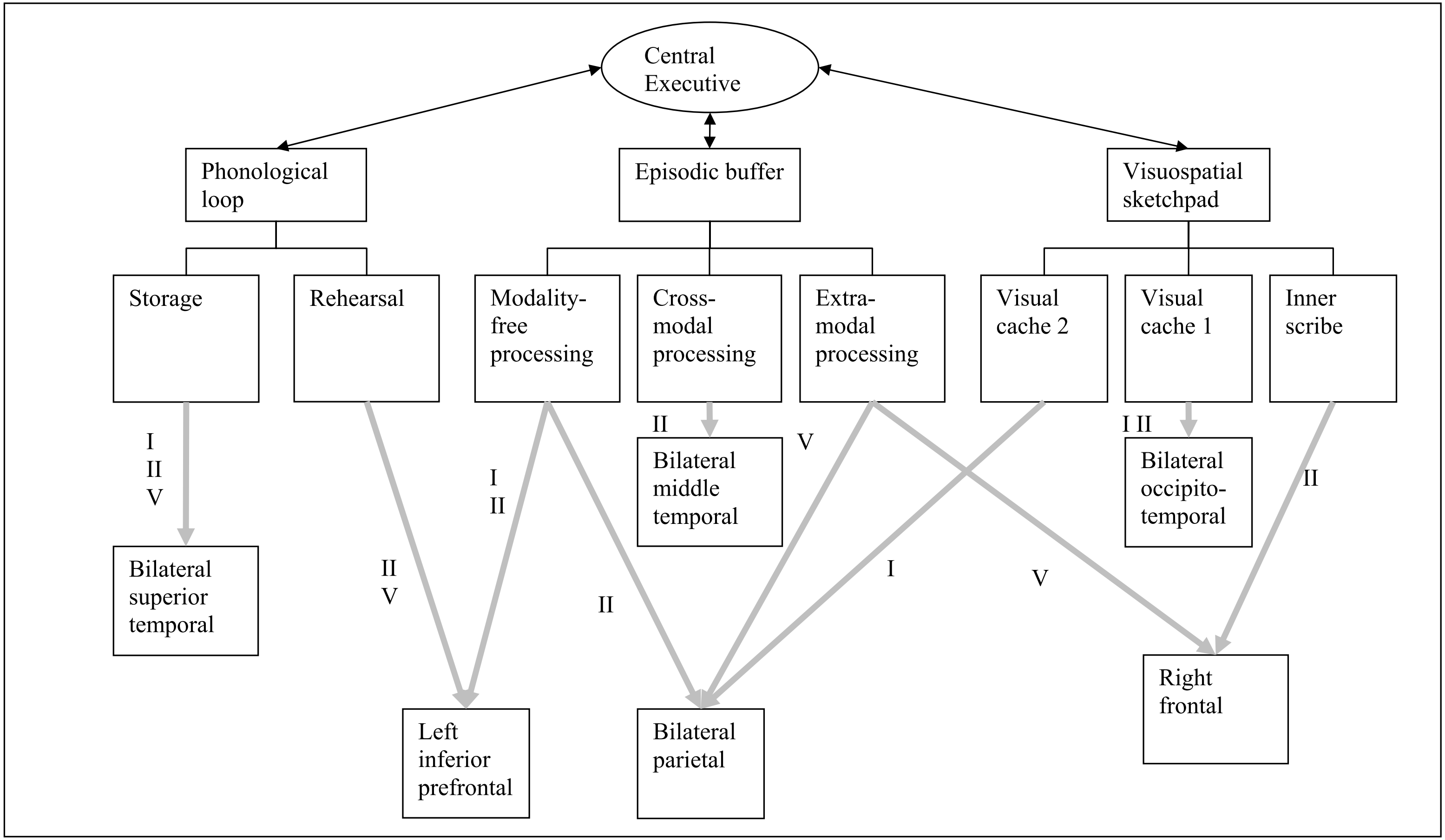

Figure 12. Functional ontology showing cognitive functions and their neural correlates as revealed by the empirical work presented in the thesis. The ontology is based on a modification of Baddeley's (2000) model of working memory and applies to language processing in the sign and speech modalities.

Wider theoretical implications

The functional ontology summarises findings of the studies presented in this thesis and provides a basis for further investigation of working memory for sign and speech. The strength of the ontology is that it ties cognitive constructs to a biological base and allows these two levels of explanation to inform each other. However, functional ontologies are less useful for summarising data at a more general theoretical level. The results of the Papers presented here together with other work, provide an empirical base for extending previous models of working memory and offer a solution to the conundrum of differing simple span lengths for sign and speech.

Span discrepancies

Marschark and Mayer (1998) suggested that the discrepancy in simple span lengths for sign and speech may be accounted for by differences in articulation rate. Paper I indicated that this factor was not the key, and Boutla and co-workers (2004) came to similar conclusions. They suggested that either inherent differences in echoic and iconic memory systems or a measuring problem may be responsible. In Paper III, we addressed both the sensory memory and measuring issues by using easily nameable pictures. We showed that although there were compensatory effects of spatial presentation and semantic similarity, deaf native signers still performed worse on immediate serial recall.

Sublexical, lexical and supralexical language processing

The studies presented in this thesis are based on working memory processing of isolated lexical items, rather than phrases or sentences, and thus, focus on the sublexical and lexical levels of language processing, rather than the supralexical level. However, further insight into the span problem may be obtained by considering the role of working memory in communication at the supralexical level. Working memory underpins language processing and is sensitive to phonological similarity (Baddeley, 2003) and a specialisation in the verbal working memory system for unravelling the syntactic structure of a sentence, and using that structure to determine sentence meaning, has been proposed by Caplan and Waters (1999).

Neuroimaging studies have shown that Broca's area plays a critical role in maintaining syntactic dependencies during sentence comprehension (Cooke et al., 2002; Fiebach et al., 2005) and at the same time shows a functional dissociation between semantic processing in the anterior portion and syntactic processing in the posterior portion (Newman et al., 2003). There is a similar functional dissociation in Broca's area, with semantic anterior to phonological processing. Thus, there seems to be a common neural representation of syntax and phonology.

Syntactic, semantic and phonological processing are also known to engage Broca's area in sign language (McGuire et al., 1997). Paper I shows common representation of semantic processing for sign and speech in the anterior regions, but there seem to be separate representations for sign and speech in the posterior regions (Horwitz et al., 2003). Cross-modality interactions of phonological and syntactic processing have not been tested.

From a linguistic point of view, phonology concerns sublexical organisation and syntax concerns supralexical organisation. From a neurocognitive point of view, it seems that phonology and syntax may engage similar mechanisms.

Syntax and span

In spoken languages, all phonological and syntactic information is carried by the individual words and their order. In signed languages, all phonological, and some syntactic information, is carried in a similar way by individual signs and their order. During communication, the phonological form, the semantic content and the relative order of lexical items are stored in working memory during language processing, to allow, among other things, phrase, sentence and discourse level processing. This applies to both sign and speech. In sign language, however, certain syntactic information is carried by spatial relationships (e.g. prepositional information) and facial expression (e.g. clausal structures) (Emmorey, 2002). This supralexical information is crucial to sentence and discourse level processing in sign language and it is also of a different nature to the information borne by the form, content and order of lexical items. It can be characterised in terms of spatial relations between lexical items and visual information that is not intrinsic to the signs themselves.

In cognitive terms, this means that, in spoken languages, all phonological and syntactic information is available from the form, content and order of items stored in working memory, while in sign languages, additional information relating to spatial relations between signs and facial expression has to be attended to. This means that attentional resources have to be devoted to perceiving spatial relations and facial expression, which, in turn, means that less general cognitive resources are available for memorising individual items. Thus, it is proposed that the shorter span length consistently found for sign language is due to cognitive resources being diverted to attentional processes for gleaning supralexical information.

Paper I shows that immediate serial recall performance is lower for sign then speech in hearing signers, suggesting that attentional processes for gleaning supralexical information are automatically engaged for signers when stimuli are presented in sign language. Paper III shows that serial recall performance is lower for deaf native signers, but not hearing signers, when items are presented as easily nameable pictures. We inferred that, as sign language was the primary language modality of the deaf native signers, they were using inner signing to encode the pictures, whereas the hearing participants were using inner speech. In Paper III, to-be-remembered items were presented not as signs but as pictures. Even so, the performance of deaf native signers was depressed on immediate serial recall. This suggests that attentional processes for gleaning supralexical information are automatically engaged for deaf native signers even when items are presented in a derived modality.

Visual attentional resource

Tasks used in the studies are based on the presentation of series of lexical items or pseudo-lexical items. In so far as these items represent any word class, they represent nouns, and so there is limited potential for assigning lexical items to phrases and building syntactic structures. This means that where a task involves recall of a list of nouns, as in Papers I and III, individual items cannot be combined into meaningful units. Thus, working memory capacity in these tasks represents the number of individual items than can be held in working memory without being organised in phrases, and as we have noted this number is lower for sign than speech. General working memory capacity, on the other hand, as measured by complex span tasks, is the same for sign and speech (Boutla, 2004) and it is proposed that syntactic processes may explain this anomaly.

Although signed lexical items generally take longer to articulate than their spoken equivalents, signed propositions do not take longer to articulate than their spoken counterparts (Bellugi & Fischer, 1972). This indicates that fewer signs than words are required to express the same meaning and, by the same token, that the organisation of working memory with a lower item capacity but with attentional resources set aside for syntactic processing is functional for sign language processing.

In Paper III we found compensatory effects of spatial presentation and semantic similarity for the deaf signers. We argued that ability to exploit spatial information to preserve order relations between items was a compensatory effect of having been encouraged to use sign language during childhood. Early encouragement to use sign language may lead to enhanced ability to exploit the spatial relations inherent in the grammar of sign language in other cognitive contexts. Thus, for educationally promoted signers, even non-linguistic spatial information may be attended to using the attentional resources postulated here to be set aside to perceive supralexical information.

Semantic content is item-specific, but in the special case of lists that comprise semantically similar items, semantic category information may be maintained at a supralexical level, in a way rather like grammatical information. Thus, some of the attentional capacity that we have argued is devoted to noting grammatical markers, not intrinsic to the signs themselves, may be available for exploiting semantic similarity.

Neural correlates of the visual attentional resource

Papers I & II showed sign-specific neural engagement in working memory tasks. It was proposed that the superior parietal engagement found in Paper I reflected the temporary storage component of working memory for sign language and that the right frontal engagement found in Paper II reflected the rehearsal component of working memory for sign language, while the occipito-temporal engagement found in both studies is related to sign identification. It has been argued that behavioural differences in performance on working memory tasks may be related to differences in syntactic processing mechanisms in sign and speech. Thus, there is reason to seek an explanation for differences in neural representation in terms of different syntactic mechanisms. Previous work has shown that perception of linguistically meaningful facial expressions engages left-lateralised temporal and occipital regions in signers (McCullough et al., 2005), while processing of propositional information in sign language engages right superior parietal areas (Emmorey et al. 2005). These areas found to be involved in sign-specific syntactic processing are partially similar to those revealed for sign-specific working memory. *Thus, the sign-specific activations found in the work presented here, and which we have associated with sign identification and temporary storage in working memory, may have aspects related to monitoring of facial expression and spatial relationships to glean grammatical information.*

The visual resource and speech phonology

In Paper IV we found that manipulation of phonology-based mental imagery in support of processing spoken items is enhanced by perceptual salience in the visual stream, but not the auditory stream. It was also found that irrelevant visual information may hamper processing (cf. the McGurk effect, McGurk & MacDonald, 1976) and that its absence seems to have a facilitating effect. These findings indicate that when facial information relating to phonology is available, it is hard to ignore, and that it can either enhance or impair cognitive processing, depending on whether it is relevant or not. Paper V showed that manipulation of auditory mental imagery related to phonology engages cortical regions known to be involved in visuospatial processing and that this effect is more pronounced for women than men. This suggests that visuospatial imagery may be involved in language processing, especially for women, even when stimulus material is delivered through the auditory channel only.

Thus, just as resources relating to visual processing of faces seem to be set aside for syntactic use in sign language processing, visual processing may be engaged to unravel speech-related phonology.

Linking phonology and syntax

Evidence indicates that visual processing mechanisms are involved in processes related to both phonology and syntax. Phonology and syntax are two fundamental linguistic processes which may be described as combining units into meaningful entities at the sublexical and supralexical levels respectively. Neuroimaging work has shown that these two processes may have a common representation in the posterior position of Broca's area, suggesting that they share neurocognitive mechanisms (cf. Hagoort, 2005). On the other hand there is evidence to suggest that these two processes may be neurally distinct for sign and speech within the same area (Horwitz et al., 2003).

Model

The purpose of the proposed model (see Figure 13) is to provide a framework for explaining some of the anomalies relating to working memory processing for sign and speech and generate testable predictions. In this model, both signed and spoken communication are automatically subjected to phonological and facial analysis of linguistic components. Primary phonological analysis takes place at the sublexical level, is analytically similar for sign and speech and may interact with gender. Facial analysis, on the other hand, has different functions for sign and speech. In terms of the model, processing capacity used for facial analysis is labelled as a visual attentional resource.

For speech, the results of facial analysis contribute to phonological analysis of individual speech items. For sign, facial expressions are analysed for grammatical meaning, and thus, the results of facial analysis for sign language users contribute to syntax building. If items can be identified as lexical items following phonological analysis they go to the temporary store. If they cannot be recognised as lexical items executive processes switch in to unravel sublexical form. When items reach the temporary store, they are still coded as either sign or speech.

As items accumulate in the temporary store they are sent for supralexical analysis, in which lexical items are assembled into larger meaningful units, at phrase, sentence or discourse level, with the help of grammatical markers. For speech, the grammatical markers are attached to the items themselves, or are inherent in item order. For sign, some grammatical markers are attached to items and their order, but other grammatical markers come from facial analysis. If a supralexical unit can be assembled from lexical items, it replaces the equivalent lexical items in the store. If no unit can be built, as is the case in a simple span task, executive processes switch in to determine which items will be retained in the limited capacity temporary store. Thus, all processing is implicit as long as items can be identified as lexical items and built into supralexical units. Explicit processes come into play when there is a hitch in implicit processing.

In relation to previous modelling of working memory functions, the present model introduces a visual attentional resource which plays different roles for sign and speech. For sign language processing, the visual attentional resource is postulated to directly influence processing at the supralexical level, while for speech processing, it directly influences processing at the sublexical level. The visual attentional resource is assumed to function implicitly, as long as communication proceeds smoothly.

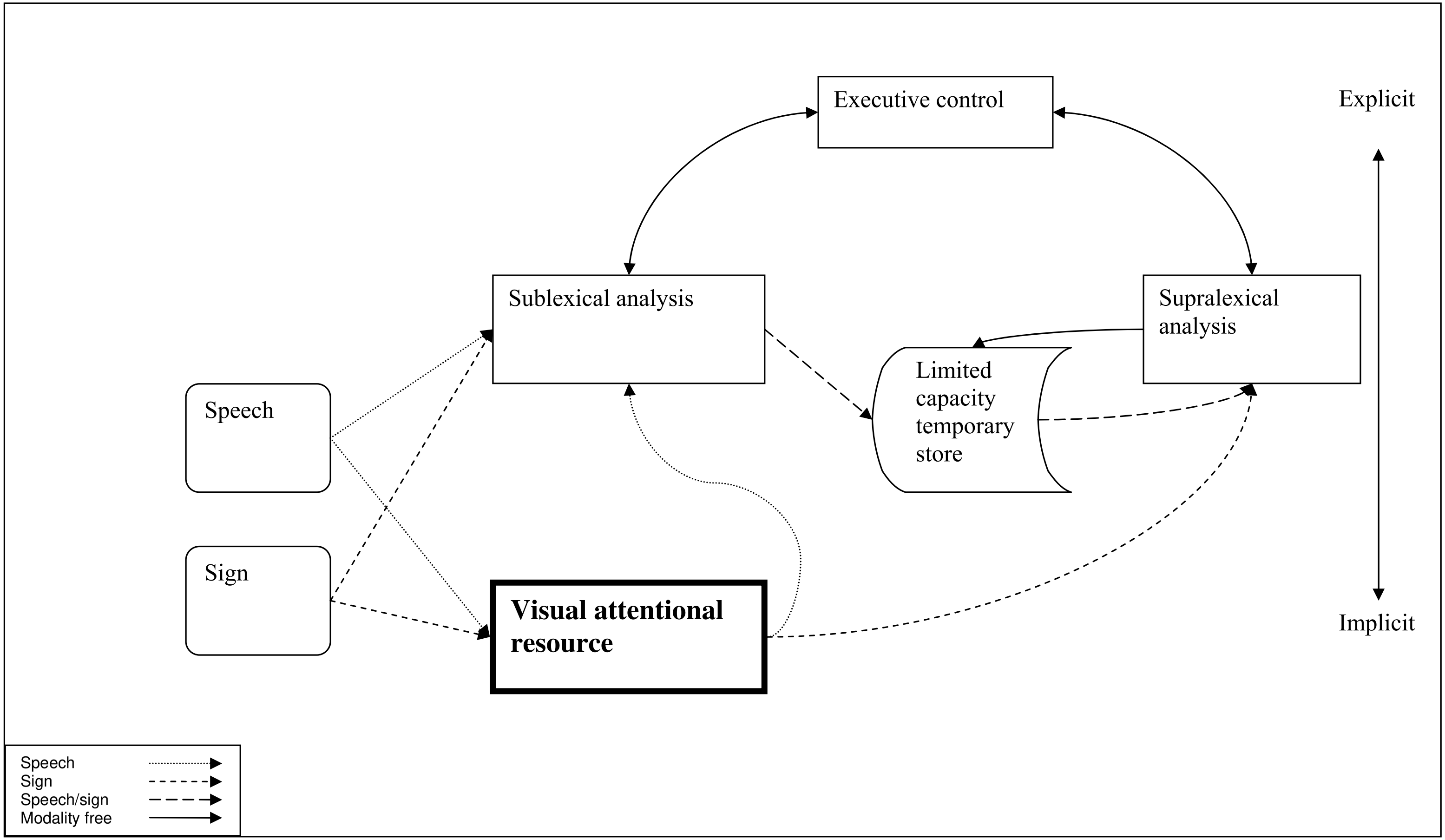

Figure 13. A model of working memory for sign and speech with the visual attentional resource as key component.

Predictions and further research

The proposed functional ontology and model of working memory for sign and speech generate a number of predictions which should be tested.

Some predictions of the functional ontology

On the basis of empirical results presented in this thesis, the functional ontology suggests a fractionation of the visual cache of the visuospatial sketchpad into task-specific and task-neutral components, and a fractionation of the episodic buffer into modality-free, cross-modal and extra-modal components. The validity of these fractionations should be tested along with the functional split between the three key model components, the phonological loop, the episodic buffer and the visuospatial sketchpad.

In particular, the ontology pinpoints a number of specific areas of investigation. First, the modality-specificity of the phonological loop should be investigated further by investigating the neural substrates of phonological decision-making in sign and speech. We are addressing this issue in a current study (Gunnarsson, Rudner, Rönnberg, Elfgren, Larsson & Risberg, in preparation). Second, the postulated fractionation of the visual cache should be investigated further by manipulating the relative contribution of rehearsal and storage processes in working memory for sign and speech. Third, the neural substrates of modality switching should be investigated by introducing a third modality, for example, easily nameable pictures, and examining the relative effects on neural activity of switching between the three modality pairs. Fourth, the postulated extra-modal function of the episodic buffer should be examined by comparing neural activity during speech-based working memory under audiovisual, visual-only and auditory-only conditions.

Some predictions of the model

On the basis of empirical results presented in this thesis and elsewhere, the model suggests the importance of a visual attentional resource that has different functions for sign and speech and may interact with gender. The validity of this theoretical construct should be tested. The work in this thesis suggests that when the resource is not utilised for facial analysis by deaf native signers, it can be exploited for semantic information and, by educationally promoted signers, for spatial information. The model predicts that signers will not be able to exploit non-facial visual information when facial information is available, but that hearing speakers will be able to do so, as long as facial information is not required to unravel the auditory speech signal. Work should be done to test this prediction and to determine exactly what forms of supralexical visuospatial information can be processed by the attentional resource. The model also predicts that, if facial information is not available, grammatical processing in signers, but not hearing speakers, will be impaired and at the same time that phonological processing of a degraded articulatory signal will be impaired in hearing speakers, but not signers.

The model distinguishes different phonological and syntactic processes in signers and speakers. However, on the basis of theoretical analysis and empirical results from the field of neurocognition, it seems that it may be possible to collapse phonological and syntactic processes into a common combinatorial linguistic processor. It should be investigated whether the differences between phonological and syntactic processes for signers and speakers can be explained in terms of the combinatorial linguistic processor or whether it is useful retain the distinction. If a cognitive distinction is to be retained, further work should be done to identify structural differences at the neural level.

Finally, data indicate that there may be gender differences in working memory processes at different linguistic levels. These potential differences should be looked into, along with their possible interactions with language modality.

Further issues

The work presented in this thesis addresses four research questions:

1. Are differences in working memory storage for sign and speech reflected in neural representation?
2. Do the neural networks supporting speech-sign switching during a working memory task reflect executive or semantic processes?
3. Is working memory for sign language enhanced by a spatial style of information presentation?
4. Do the neural networks supporting word reversal indicate tongue-twisting or mind-twisting?

Horizontal and vertical dimensions were applied in order to achieve greater theoretical depth. The first three questions specifically address differences in working memory processing in the two different language modalities of sign and speech, while the fourth question addresses a potential link between speech processing and mental imagery suggested by findings from sign language cognition.

Questions one and two were investigated using native hearing signers who are bilingual in SSL and Swedish. This approach was used to obtain the closest possible comparison between cognitive processes in the two language modalities. However, care should be taken in generalising our findings horizontally to deaf signers. On the one hand it has been found in many cases that cognitive functions are similarly organised in deaf and hearing signers (e.g. Boutla, 2004), on the other hand, congenital deafness in itself leads to differences in cognitive organisation (e.g. Cattani & Clibbens, 2005).

Question three is addressed in the study presented in Paper III which gave positive results. However, this study was based on a relatively small number of subjects, due to the difficulty in finding suitable participants in the signing groups. The effects identified in this study are being investigated further.

Question four is addressed in Papers IV and V, again with positive results. However, the effects of manipulating perceptual saliency need to be investigated further to determine whether they can be generalised horizontally beyond the specific task used in these studies and the neural correlates of word reversal should be directly compared to those of mental rotation to establish how similar they actually are.

Conclusion

This thesis shows that working memory for language processing has both modality-specific, and nonmodality-specific aspects. Working memory for sign language has modality-specific aspects relating to both the visuospatial sensory modality and to higher-level cognition. Working memory for speech has modality-specific aspects relating to the auditory sensory modality.

Modality-specific aspects can be explained in terms of Wilson's (2001) component-based sensorimotor account, given that the functionality of the visuospatial sketchpad is extended to include language processing. Nonmodality-specific working memory processing is predicted by Rönnberg's (2003) model of cognitive involvement in language processing. However, nonmodality-specific aspects of working memory processing revealed in the present work can be explained in terms of the component model (Baddeley, 2000), providing the functionality of the episodic buffer and its neural representation are extended.

A functional ontology presents results within a common neurocognitive framework that links cognitive function to neural structure, and a new model of working memory for sign and speech with a key visual attentional resource is proposed. The ontology and the model suggest directions for future work and demonstrate the fruitfulness of applying horizontal and vertical dimensions within the field of disability research (cf. Rönnberg & Melinder, in press).

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Acknowledgements

Thanks are due to many who in one way and another have contributed to the scientific journey of which this thesis is a milestone. First and foremost, I would like to thank Professor Jerker Rönnberg for giving me the opportunity to pursue my interest in neurocognitive aspects of language in such a stimulating environment, introducing me to the field of sign language cognition and teaching me the art of research.

I would also like to thank my co-authors on the papers for stimulating collaboration. I am particularly grateful to Dr Peter Fransson who has been so generous with his time and expertise. Professor Lars Nyberg has my thanks for contributing research ideas and for thoughtful comments on an earlier version of this thesis.

The creative environment generated by my colleagues at the Department of Behavioural Sciences, Linköping University and at the Institute for Disability Research at the Universities of Linköping and Örebro has been invaluable. In particular, I would like to thank Professor Björn Lyxell for his interest in my work and broadening my understanding of language and cognition. I would also like to say a special thank you to my student colleagues for discussion of all aspects of the research process, especially Anna Levén, Janna Ferreira and Catharina Karlsson.

I am indebted to Ulla Remius Eriksson, Tolkcentralen Linköping, who sadly passed away recently. Ulla had a driving interest in cognitive aspects of sign language use and her knowledge, experience and practical help have been invaluable to me in my research.

I would also like to thank Rolf Ericsson, Valla folkhögskola; Ingvar Edvall, Västanviks folkhögskola; Michael Karlsson, Mo Gård folkhögskola; Susanna Norsell, Tolkcentralen Jönköping and Irene Söderlind, Härnösands folkhögskola

for showing interest in my research, welcoming me to their workplaces and allowing me to gather data there.

Thanks are also due to Dr Birgitta Larsby who adapted SWIPs software for use in Experiments 1 & 2 in Paper IV.

Finally, I would like to thank my family and friends on both sides of the North Sea for support and encouragement. In particular, I would like to thank Stefan Roth, Mikael Rudner and Lucy Roth for leading your own lives and inspiring me to do the same; I am proud of you all. Thanks also to Lucy for drawing the illustrations for this thesis. Finally, my deepest gratitude to Staffan Rudner for showing me that it was possible and never letting me forget it.