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Working memory (WM) for sign language has an architecture similar to that for speech-based languages at both functional and neural levels. However, there are some processing differences between language modalities that are not yet fully explained, although a number of hypotheses have been mooted. This article reviews some of the literature on differences in sensory, perceptual and cognitive processing systems induced by auditory deprivation and sign language use and discusses how these differences may contribute to differences in WM architecture for signed and speech-based languages. In conclusion, it is suggested that left-hemisphere reorganization of the motion-processing system as a result of native sign-language use may interfere with the development of the order processing system in WM.

WM is the limited cognitive capacity available for storing and manipulating information. This concept has been thoroughly investigated over the past thirty years and more since the ground-breaking work by Baddeley and Hitch (1974). These investigations have focused primarily on the cognitive functions of people for whom speech based language is the primary mode of communication. In order to determine how closely WM architecture is tied to mode of communication, it is important to study cognitive function in people with other types of communicative experience. This paper considers findings relating to the specific cognitive function in people who are native sign language users, either because they were born deaf or because their parents were deaf signers.

Sign languages are the natural languages of people who are born with a severe auditory deficit or who acquire such a deficit at an early age. In an environment where language is spoken, deaf infants do not have access to the auditory language signal and the visual signal related to spoken language does not provide sufficient information for adequate language development unless supplemented by other information such as purposefully generated manual cues (Leybaert & D'hondt, 2003) or tactile information from the larynx (Rönnberg, 1993). For deaf children, access to sign language communication from an early age does, however, provide a satisfactory basis for development of language skills (Mayberry & Lock, 2003) as well as cognitive and social skills (Meristo et al., 2007; Peterson & Siegal, 2000).

Sign languages are manual languages that are transmitted visually, in contrast to oral languages that are transmitted audio-acoustically. Work in the field of sign language linguistics over the past few decades has demonstrated that sign language can be analysed at, for example, phonological, syntactic and prosodic levels in much the same way as speech-based language (Emmorey, 2002). For speech-based languages, phonology refers to the way in which sounds are combined to form utterances while for sign languages it refers to the way in which the components of lexical signs (handshape, position, movement and orientation) are combined simultaneously and consecutively (Liddell & Johnson, 1986; Stokoe, 1960). Thus, the Swedish Sign Language (SSL) signs for dog and hat

3

(see figure 1) are phonologically similar, because they share both a handshape and a movement, although one common feature is sufficient to constitute phonological similarity (Klima & Bellugi, 1976). Functionally, poetry and nursery rhymes in sign language build on rhythmic use of phonology in much the same way as poetry in the oral tradition (Sutton-Spence, 2001). This means that both theoretically and functionally there is a good basis for comparing speech-based and sign languages at the phonological level.

/Insert Figure 1 about here/

The manual-visual nature of sign language, as a primary mode of communication makes it an important key to investigating core issues in the fields of language and cognition that cannot be addressed in any other way. Such issues include the extent to which linguistic and cognitive mechanisms are bootstrapped onto processing mechanisms at the sensory and perceptual levels or completely independent of the sensory modality the language exploits. Neuropsychological studies of signers with acquired brain damage provide firm evidence for a left lateralized organization of sign language with an anterior production region and a posterior comprehension region similar to that of spoken language (for review see Corina & Knapp, 2006). This literature also documents a relative dissociation between basic sign language skills and spatial ability (for review see Rönnberg, Söderfeldt & Risberg, 2000), although recent studies show that spatial systems may be recruited for certain aspects of sign language processing (Campbell, MacSweeney, & Waters, 2008). Neuroimaging studies confirm that the neural systems supporting signed and spoken languages are very similar at several levels of language processing, involving a predominantly left-lateralized perisylvian network (MacSweeney, Capek, Campbell & Woll, 2008). However, there is also evidence of a special role for the right hemisphere (Neville et al., 1997; 1998) and the parietal lobes (Corina & Knapp, 2006) in sign language processing, which may be linked to the specific sensorimotor demands of the modality.

Deafness, sign language and neurocognition

There is a popular belief that deprivation in one sensory modality may lead to enhanced performance in another, although there is little evidence to support this hypothesis (Rönnberg, 1995): auditory deprivation does not generally seem to enhance visual perception (Armstrong, Neville, Hillyard & Mitchell, 2002; Bavelier et al., 2001; Bavelier, Dye & Hauser, 2006; Bosworth & Dobkins, 1999; Bross, 1979; Bross & Sauerwein, 1980; Brozinsky & Bavelier, 2004; Finney & Dobkins, 2001). It does, however, alter the morphology of the brain (Emmorey, Allen, Bruss, Schenker & Damasio, 2003), as well as its functional organization (Finney, Fine & Dobkins, 2001) and speed of response to visual stimuli (Finney, Clementz, Hickok & Dobkins, 2003). Congenital deafness enhances motion processing in the visual periphery (Armstrong et al., 2002; Bavelier et al., 2001; Bosworth & Dobkins, 2002; Fine, Finney, Boynton & Dobkins, 2005) and some aspects of attention in the visual periphery (Bavelier et al., 2001; Colmernero, Catena, Fuentes & Ramos, 2004; Dye, Baril & Bavelier, 2007; Hauser, Dye, Boutla, Green & Bavelier, 2007; Proksch & Bavelier, 2002) and these phenomena are detectable at both behavioural and neural levels (Neville & Lawson, 1987). In particular, persons who are congenitally deaf display a relative left-hemisphere bias in cerebral lateralization for motion processing (Bosworth & Dobkins, 1999). Thus, although auditory deprivation does not lead to general visual enhancement, it does affect the structural and functional organization of the brain and some aspects of motion processing and these aspects must be taken into account when attributing cognitive differences to the effects of sign language use. This can be achieved by comparing the performance of deaf native signers with that of hearing native signers who are hearing individuals brought up in a signing environment to become bimodal bilinguals (Emmorey & McCullough, 2008). Studies addressing this group have shown that while some aspects of the cognitive enhancement found in deaf native signers is attributable to lack of auditory stimulation, other aspects must be attributed to sign language use. For example, the left-hemisphere bias in cerebral lateralization for motion processing found for deaf native signers (Bosworth & Dobkins, 1999) is also found for hearing

native signers (Bosworth & Dobkins, 2002), possibly due to the perceptual processes required for the acquisition and comprehension of language (ie motion processing in the case of sign language) being recruited by the left, language-dominant hemisphere (Bosworth & Dobkins, 2002), demonstrating that this phenomenon is related to early sign language use rather than congenital deafness.

Taking the effects of auditory deprivation into account, it has been shown that preferred mode of communication exerts developmental force on perceptual and cognitive processes and their neural organization (Emmorey, 2002). The mirror neuron system processes motion in the form of action, either observed or executed (Rizzolatti, Fogassi & Gallese, 2001; Villarreal et al., 2008) and includes the left inferior frontal lobe, superior temporal sulcus and the parietal lobe. It is involved in both speech (Arbib & Lee, 2008) and sign language processing (MacSweeney, Waters, Brammer, Woll & Goswami, 2008). The mirror neuron system is engaged when deaf signers observe signs or perform semantic monitoring of TicTac (a manual code used for communication between bookmakers at racecourses) but not when they observe non-linguistic actions (Corina et al., 2007; Emmorey, 2008). These findings suggest that experience with sign language impacts the neural systems that are recruited during the perception of different kinds of motion, including, but not limited to action in the form of linguistic and non-linguistic gestures (Willems & Hagoort, 2007). As regards non-linguistic cognitive processing, native signers show superior cognitive abilities in a number of domains including categorization of motion (Poizner, 1983), face recognition (Bettger, Emmorey, McCullough & Bellugi, 1997), discrimination of facial features (McCullough & Emmorey, 1997), identification of emotional facial expressions (Goldstein & Feldman, 1996), mental rotation (Emmorey, Kosslyn & Bellugi, 1993) and image generation (Emmorey & Kosslyn, 1996).

Working memory

WM is a cognitive function that encompasses temporary storage and processing of information from sensory sources or from other more long-term memory (LTM) stores. This includes manipulation of

both non-linguistic and linguistic information at all levels of language processing (Baddeley, 2003; Daneman & Carpenter, 1980), including segmentation and generation of the phonological stream, parsing of sentences and dialogue processing (Caplan & Waters, 1999; Daneman & Carpenter, 1983). Baddeley and Hitch (1974) proposed a model of WM with separate modular components or slave systems for processing linguistic speech-based information (the articulatory loop) and non-linguistic visual information (the visuospatial sketchpad or VSSP), controlled by a central executive. This model emphasized the distinction between processing modalities as well as the functional separation from LTM, and was an advance on earlier models of short-term memory (STM) which simply focus on storage aspects (e.g. Atkinson & Shiffrin, 1968). The articulatory loop (renamed the phonological loop when its role in processing abstract linguistic representations that are more closely related to form than production was discovered; Baddeley, 1986) is characterized by the classical effects of phonological similarity and word length -- when to-be-remembered items are phonologically similar (e.g. rhyme with each other) or long – serial recall performance is poorer than if items are distinct and short. Another classic effect, articulatory suppression, (repetition of an irrelevant lexical item during item encoding) compromises performance by disrupting rehearsal, and obliterates the word length effect. Disruption of rehearsal affects the recoding of items from secondary (e.g. text) to primary (e.g. word) format and thus obliterates the phonological similarity effect for written materials (Baddeley, 2000).

WM is characterized by its limited capacity, which is sometimes considered to be 7 items +/- 2 (Miller, 1956), but under certain circumstances may be either higher or lower (Cowan et al., 2005). Information may fade from WM or be overwritten by new information. These effects can be studied by analyzing relative recall performance for supraspan lists. Superior performance is found for the last item which has not yet faded or become overwritten, in contrast to earlier words in the list. The obvious role of order in WM has led to proposals that separate mechanisms deal with processing of item and order information and that serial order is supported by a timing signal (Brown, Preece &

7

Hulme, 2000; Henson, Hartley, Burgess, Hitch & Flude, 2003; Burgess & Hitch, 1999). It has also been suggested that the inferior parietal sulcus might play a key role in maintenance of serial order, although the evidence for this is not clearcut (Majerus et al., 2007).

Other models of WM emphasize its capacity rather than features distinguishing it from other memory functions (Daneman & Carpenter, 1980). WM capacity is characteristically limited in terms of the amount of information that can be retained and for how long (Baddeley, 2000) and may vary considerably between individuals (Daneman & Hannon, 2001; Hannon & Daneman, 2001). An accumulation of evidence of integration across sensory modalities in WM (e.g. Logie, Della Sala, Wynn & Baddeley, 2000) and between WM and LTM on the other hand (Baddeley & Wilson 2002) has led Baddeley (2000) to propose a fractionation from the central executive of a separate module known as the episodic buffer, to deal with these integratory functions.

More recently a WM model for Ease of Language Understanding (ELU, Rönnberg, Rudner, Foo & Lunner, 2008) has been proposed that focuses on the communicative function of WM. This model includes implicit and explicit processing components. The implicit component comprises an episodic buffer known as RAMBPHO, whose function is the Rapid, Automatic, Multimodal Binding of PHOnology. Under optimum conditions, the RAMBPHO function mediates rapid access to appropriate representations in LTM for effortless, implicit, language understanding. Under less advantageous conditions, due to a degraded signal or sensory or language impairment, it is less likely that appropriate representations can be accessed without difficulty. In such a mismatch situation, explicit WM capacity is needed to infer meaning (Hannon & Daneman, 2001) and the explicit processing component comes into play. Accumulated evidence suggests that whereas RAMBPHO is not modality-specific (Rönnberg, 2003), the explicit component of the ELU model is (Rönnberg, Rudner & Ingvar, 2004; Rudner, Fransson, Ingvar, Nyberg & Rönnberg, 2007; Rudner & Rönnberg, 2008 a,b).

Neural correlates of working memory

Neuroimaging studies suggest that WM storage is mediated by the same posterior brain structures that process perceptual information and that rehearsal engages fronto-parietal networks that also control attention to external stimuli (Jonides, Lacey & Nee, 2005). It was recognized early on that these storage and rehearsal networks were fractionated according to the type of material: e.g. verbal, object and spatial (Wickelgren, 1997). There is some evidence of a left-hemisphere bias for verbal WM and a right hemisphere bias for spatial WM (Smith & Jonides, 1997; Wager & Smith, 2003) and a distinction between a ventral pathway for object processing in WM and a dorsal pathway for spatial processing (Cabeza & Nyberg, 2000; Wager & Smith, 2003). These rather coarse distinctions are most apparent in the posterior part of the WM network and do not apply consistently to fronto-parietal rehearsal systems (Cabeza & Nyberg, 2000; Wager & Smith, 2003). Within the prefrontal cortex, evidence suggests that ventral-lateral regions are involved in updating and maintenance of information, while dorsolateral regions are involved in the selection, manipulation and monitoring of that information and anterior regions in the selection and processing of subgoals (Fletcher & Henson, 2001). Evidence suggests that the anterior portion of the left ventrolateral region supports controlled access to stored conceptual representations, whereas the posterior portion supports a higher-order post-retrieval selection process (Badre, 2008; Badre & Wagner, 2007). Comparison of verbal WM in auditory and visual modalities reveals largely consistent fronto-parietal networks but with some modality-specific differences (Crottaz-Herbette, Anagnoson & Menon, 2004).

Deafness, sign language and higher cognitive functions

Deafness and short-term memory

Both deafness and sign language use shape short-term and WM function. Older work consistently showed poorer STM performance for deaf people than for hearing people (Conrad, 1972; Hanson,

1982; Logan, Mayberry & Fletcher, 1996; Pintner & Patterson, 1917; Ross, 1969; Wallace & Corballis, 1973) and better performance for deaf signers with greater access to speech-based phonological or articulatory information (Conrad, 1970; 1972; Dornic, Hagdahl & Hanson, 1973; Hanson, 1990; Locke & Locke, 1971; Wallace & Corballis, 1973). Some studies showed that memory performance is related to linguistic experience (sign or speech), that stimuli may be encoded in either modality (Campbell & Wright, 1990; Hamilton & Holzman (1989); MacSweeney, Campbell & Donlan, 1996) and that sign language structure interacts with STM (Locke & Locke, 1971; Poizner, Bellugi & Tweney, 1981). Whereas hearing subjects prefer a temporal mode of recall in STM, deaf people do not (O'Connor & Hermelin, 1973; 1976; Wilson, Bettger, Niculae, & Klima, 1997).

Sign language and short-term storage and processing capacity

With an increasing understanding of the educational needs of deaf people and the rise in the status of sign languages as fully fledged natural languages with all the communicative potential of speech-based languages, the research community began to refocus attention from WM function in deaf people to WM function in sign language users (Bebko & Metcalfe-Haggert, 1997; Marschark, 1998; MacSweeney et al., 1996).

It has been shown that both deaf and hearing native signers have a reduced STM span for signs (Boutla, Supalla, Newport, & Bavelier, 2004; Geraci, Gozzi, Papagno, & Cecchetto, 2008; Marschark & Mayer, 1998) but that general WM span is equivalent in speakers and signers (Boutla et al., 2004; Rudner & Rönnberg, 2008 a). There is still no consensus on the full explanation of differences in STM capacity for sign and speech. Proposed explanations include intermodality differences in articulation rate (Marschark & Mayer, 1998); phonological properties (Emmorey & Wilson, 2004; Wilson & Emmorey 2006a; b); retention of auditory and visual information (Boutla et al., 2004); and retention of temporal order information (Boutla et al., 2004).

Signs take longer to articulate than words (Bellugi & Fischer, 1972) and this characteristic is retained in WM representations (Wilson & Emmorey, 1998). An articulatory loop of 2 seconds in length (Baddeley, Thomson & Buchanan, 1975) can therefore accommodate fewer signs than words (Marschark & Meyer, 1998). However, differences in articulation rate do not provide a full explanation of discrepancies in STM capacity (Rönnberg et al., 2004).

There are inherent difficulties in matching stimuli for phonological similarity across modalities which may confound results (Bavelier, Newport, Hall, Supalla & Boutla, 2006; Boutla et al., 2004; Emmorey & Wilson, 2004; Wilson & Emmorey 2006a; b). For example, the paradigmatic STM test is the digit-span test which requires immediate serial recall of digits. In speech-based languages such as English and Swedish, digits are phonologically distinct, whereas in sign languages such American Sign Language (ASL) and Swedish Sign Language (SSL) some digits are phonologically similar, see figure 2.

/Insert Figure 2 about here/

The phonological store in STM is reliant on early sensory memory stores and thus the inherent modality-specific differences between these stores (auditory sensory memory traces persist for 2–4 s, whereas visual memory traces last at most 1 s) may at least partially account for span differences (Bavelier et al., 2006; Boutla et al., 2004).

Short-term retention of temporal and spatial information

A further suggested explanation of intermodality span differences concerns potential differences in the retention of temporal order information across modalities (Boutla et al., 2004). The auditory system is adept in retaining sound order, whereas the visual system may be less efficient in this respect, but see Smyth, Hay, Hitch & Horton, (2005). On the basis of this, it should be easier to retain the order of sound-based representations in WM than their vision-based counterparts. This hypothesis is supported by the work of O'Connor and Hermelin (1973) showing a preference for temporal coding in hearing subjects but not in deaf subjects. Other works shows that deaf subjects,

11

unlike hearing subjects, show no preference for forward over backward recall (Andin, Rudner & Rönnberg, 2008; O'Connor & Hermelin, 1976; Wilson et al., 1997). In a review of the literature on the effects of auditory deprivation on successive processing, Cumming and Rodda (1985) came to the conclusion that the spatial bias of deaf individuals resulting from sign language use seems to result in a decreased emphasis on temporal ordering. Thus, it is well established that deafness leads to differences in temporal processes and as temporal coding plays a key role in working memory processing, these differences may to a certain degree account for intermodality span differences.

In a series of experiments addressing WM processes in signers and speakers (Rudner & Rönnberg, 2008 a) the relative role of temporal and spatial information during encoding was assessed. In order to obtain comparable encoding and storage conditions for deaf and hearing groups, easily nameable pictures were used as stimuli, with the rationale that the stimuli would be recoded into the preferred language modality of the subjects, sign language for deaf signers and speech for hearing speakers. Similar levels of performance were found for deaf signers, hearing signers and hearing non-signers, as well as modality-specific phonological similarity effects when explicit processing requirements were low at a presentation rate of one item every two seconds (cf. Wilson & Emmorey, 1997) but not when they were moderately increased to a presentation rate of one item per second. However, when explicit processing requirements were further increased by introduction of a distracter task, although there was no difference between groups in item recall performance, the order recall performance of deaf signers (unlike that of hearing non-signers) was not sensitive to the temporal order in which recognition cues were presented. This supports the idea of separate item and order processing mechanisms in WM and suggests that the order processing mechanism differs for deaf signers and hearing speakers. This notion is supported by the finding that irrelevant visuospatial material disrupts recall of ASL signs by deaf signers but not recall of words by hearing nonsigners (Wilson & Emmorey, 2003).

Neural organisation of working memory for sign and speech

The neuropsychological and neuroimaging literature supports the idea that WM systems for sign and speech are largely similar with some sign-specific differences (Bavelier et al., 2008; Buchsbaum et al., 2005; Pa, Wilson, Pickell, Bellugi & Hickok, 2008; Rönnberg et al., 2004; Rudner et al., 2007; Rudner & Rönnberg, 2007). In a PET study (Rönnberg et al., 2004) with eight hearing bilinguals who had acquired sign language before primary school age, it was found that similar neural networks were engaged for sign and speech both on a WM task and on two analogous tasks which had similar encoding demands but different storage and recall demands, see figure 3. All tasks required the encoding of six items (words or signs) presented audiovisually and generation of six items in the appropriate language modality. In the WM task, immediate serial recall of all items was required. In the semantic control task generation of six items belonging to the category represented by the last presented item was required and in the baseline task, the last presented item was to be repeated six times. Ceiling performance was recorded for the baseline task for both sign and speech but whereas similar levels of performance were obtained for the semantic control task in both sign and speech, performance was higher on the WM task in spoken Swedish than in Swedish sign language.

/Insert Figure 3 about here/

Comparison of activation patterns for sign and speech showed net activity bilaterally in auditory cortex for speech compared to sign in all three tasks, suggesting that it is related to auditory processing (cf. Pa et al., 2008). For sign compared to speech net activation was found in the superior parietal lobes and the temporo-occipital region bilaterally. It was argued that this sign-specific activation may reflect a more spatially-oriented mode of order processing in WM for sign language compared to WM for speech.

Neural mechanisms for order processing in working memory

Activation of spatial processing regions in working memory tasks based on sign language fits in with other work showing activation of a dorsal processing stream for spatial WM (Cabeza & Nyberg, 2000; Jonides, Lacey & Nee, 2005; Olson & Berryhill, 2008; Smith & Jonides, 1997; Wager & Smith, 2003) that is more prominent in posterior than in anterior regions (Cabeza & Nyberg, 2000; Wager & Smith, 2003) and with the notion of different order processing mechanisms in WM for sign and speech. In an fMRI study (Rudner et al., 2007), using a 2-back task rather than immediate serial recall and a group of 13 hearing bilinguals who had acquired sign language from birth similar patterns of net activation were found for WM for sign and speech, generalizing results across imaging methods and experimental paradigm, see Figure 4.

/Insert Figure 4 about here/

The engagement of a fronto-parietal network for WM for sign language has also been found for deaf signers (Bavelier et al., 2008; Buchsbaum et al. 2005), generalising results across hearing and deaf signing groups. Bavelier et al. (2008) showed that net parietal activation for deaf signers was related to the recall phase but not to encoding and maintenance. It is in connection with recall that the effects of different order processing mechanisms become apparent. Thus, these findings also support the notion of separate order processing mechanisms for sign and speech as indicated by behavioural data (Andin, Rudner & Rönnberg, 2008; O'Connor & Hermelin, 1973; 1976; Rudner & Rönnberg, 2008 a; Wilson et al., 1997) and the notion of an explicit processing buffer that is at least partially modality-specific (Rönnberg et al., 2008).

Neural mechanisms for semantic binding in working memory

In a study of neural mechanisms underlying semantic binding in WM of lexical signs and words, Rudner et al. (2007) showed that the right middle temporal lobe is implicated in this role and that prefrontal areas previously proposed to support cross-modal binding of information (Prabhakaran,

14

Narayanan, Zhao & Gabrielli, 2000) do not play a key role when both formation and maintenance of bound representations of lexical information across language modalities are involved. It was suggested that the right middle temporal involvement may be related to the binding of phonological information in WM to semantic representations in LTM, which has been proposed as one of the key functions of the episodic buffer of WM (Baddeley, 2000; Repovs & Baddeley, 2006). This proposal is based on neuropsychological evidence from two patients who despite dense amnesia were able to integrate semantic information retrieved from long-term memory in a working memory representation, thanks to intact episodic buffer function (Baddeley & Wilson, 2002). Other evidence suggests a common semantic store for lexical signs and words (Damasio, Grabowski, Tranel, Hichwa, Damasio 1996; Emmorey, Grabowski et al, 2003; McEvoy, Marschark & Nelson, 1999; Rönnberg et al., 2004) and that semantic processing in WM for both sign and speech taps similar mechanisms supported by the anterior portion of the left inferior frontal gyrus (McDermott, Petersen, Watson & Ojeman, 2003; Rönnberg et al., 2004; Rudner & Rönnberg, 2008 a). Together, these findings support the notion of a modality-neutral episodic buffer (Baddeley & Larsen, 2007; Rönnberg et al., 2008; Rudner & Rönnberg, 2008 b).

Modality-specificity in working memory for sign language

The literature on working memory for deafness and sign language indicates largely similar systems irrespective of access to auditory information and preferred language modality (Baddeley & Larsen, 2007; Bavelier et al., 2008; Boutla et al., 2004; Buchsbaum et al., 2005; Pa et al., 2008; Rönnberg et al., 2004; Rönnberg et al., 2008; Rudner et al., 2007; Rudner & Rönnberg, 2007; Rudner & Rönnberg 2008 a, b; Wilson & Emmorey, 1997). The behavioural and neurological differences that do exist seem to be related to language modality rather than sensory modality. This means that established functional and neural differences at lower cognitive and linguistic levels attributable to sign language experience may make a contribution to the language modality-specific architecture of WM. On the other hand, differences attributable to auditory deprivation probably do not contribute to the

15

language modality-specific architecture of WM. However, functional and neural differences at lower cognitive levels, attributable to auditory deprivation, for example those relating to processing in the visual periphery, may interact with WM function when they are specifically brought into play; this warrants investigation.

Key differences in WM architecture relating to language modality include behavioural differences concerning the processing of temporal information and neural differences relating to net bilateral engagement of the temporo-occipital region and the superior parietal cortex in WM for sign language. It has been argued that this pattern of neural activation reflects differences in the processing of order information in WM for sign language (Rönnberg et al., 2004). Order processing plays a prominent role in models of WM (Baddeley, 1986; 2000; Baddeley & Hitch, 1974; Daneman & Carpenter, 1980; Rönnberg et al., 2008) and some have singled out this feature for special attention (Brown et al., 2000; Henson et al., 2003; Burgess & Hitch, 1999) and suggested that left hemisphere regions may been implicated in the processing of temporal order in WM (Majerus et al., 2007).

Native sign language use leads to functional reorganization of the brain (Bosworth & Dobkins, 1999; 2002); in particular, a left-lateralization of motion processing, possibly in the service of sign language processing (Bosworth & Dobkins, 2002). This may interfere with the development of left-lateralized order processing mechanisms in WM (Majerus et al., 2007). Thus, the characteristic bilateral posterior neural signature of WM for sign language may reflect a modality-specific order processing mechanism in WM for sign language operating bilaterally in response to reorganisation of the left hemisphere for lower level functions. Stenfelt and Rönnberg (this issue) have argued that temporal order processing is one of the functions of RAMBPHO, the episodic buffer in the ELU model (Rönnberg et al., 2008), and the findings reviewed in the present article do not contradict such a notion. However, what they do suggest is that temporal order processing apart from being a function of RAMBPHO may also be one of the modality-specific functions of the explicit processing buffer in the ELU model, see figure 5.

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Figure 1

a)   b)
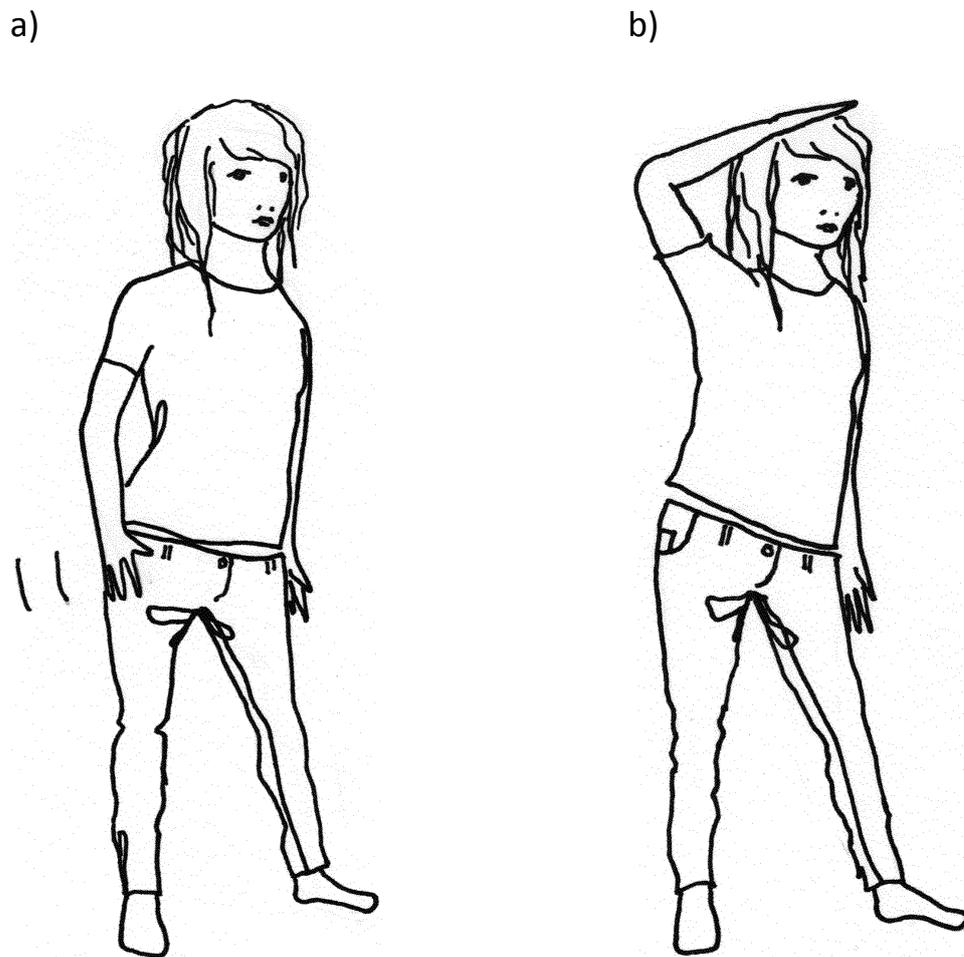
SSL signs for a) *dog* and b) *hat* share handshape and movement but are distinguished by hand position.
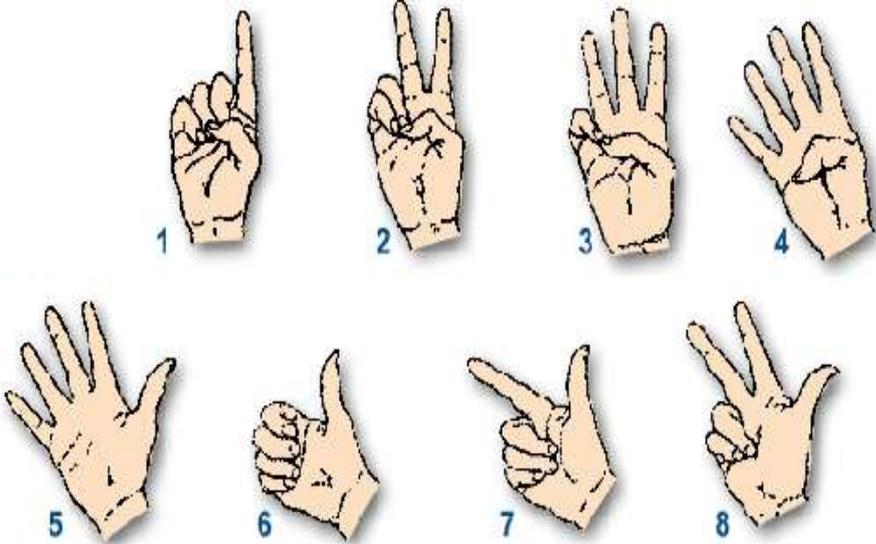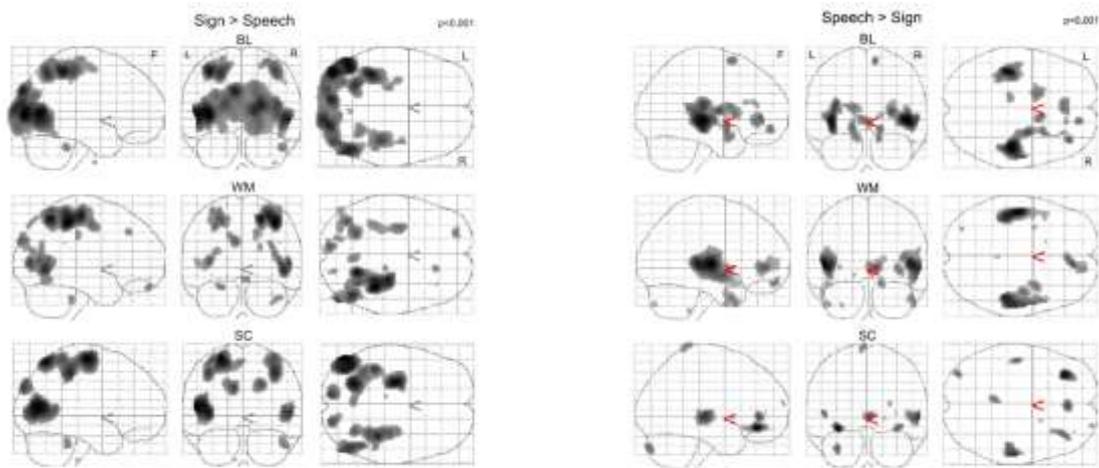
Figure 2. Digits 1-8 in Swedish Sign Language.

Figure 3.

A working memory task (WM) and two analogous tasks (BL, SC) performed by hearing sign/speech bilinguals generated greater net activity in the superior parietal lobes and the temporo-occipital region bilaterally for the signed tasks than the spoken tasks and greater activity bilaterally in auditory cortex for spoken compared to signed tasks. Reprinted from *Cognitive Brain Research, 20*, Rönnberg, J., Rudner, M. & Ingvar, M., Neural Correlates of Working Memory for Sign Language, 165-182, (2004), with permission from Elsevier.

Figure 4.
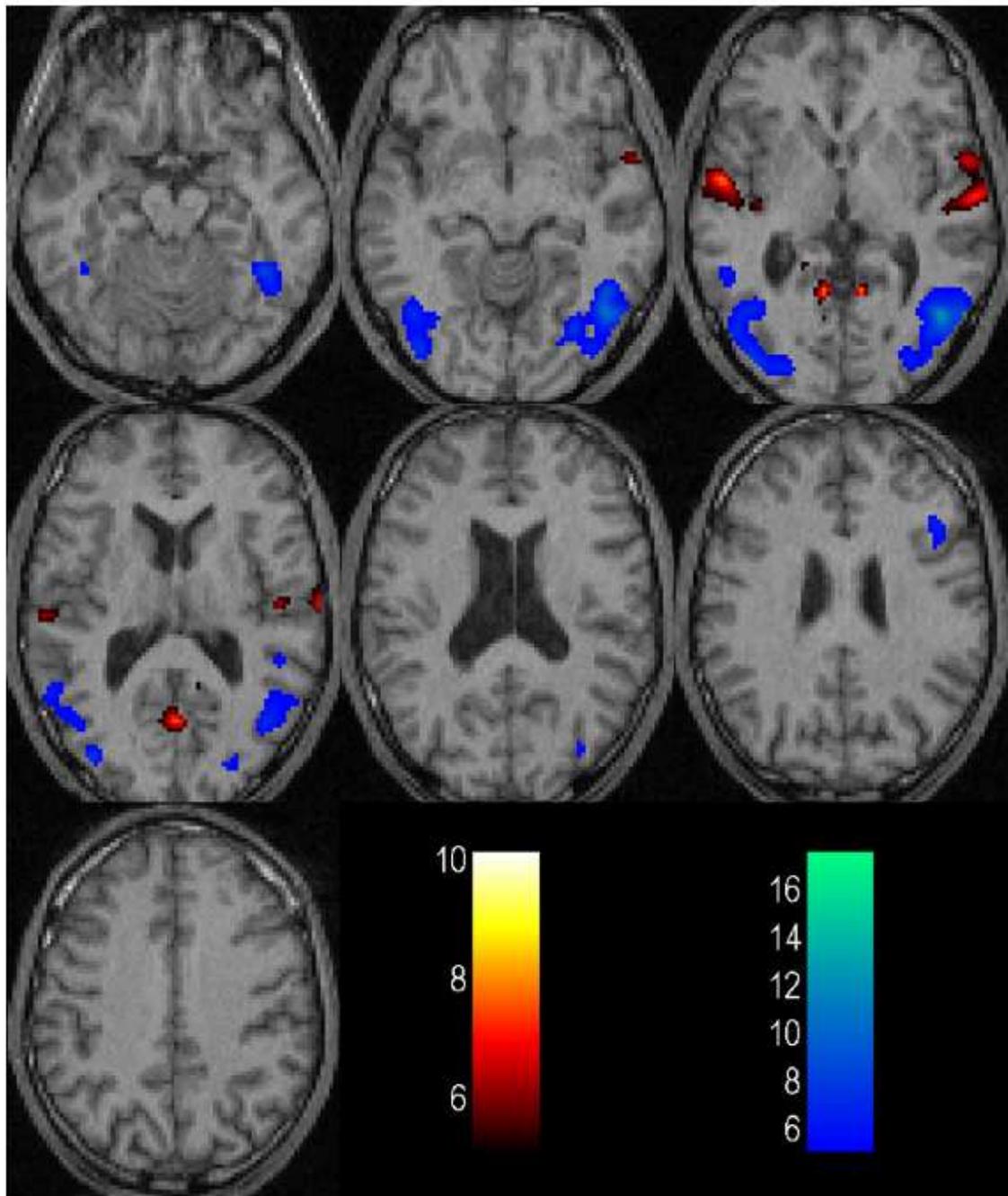
Blue areas show net activation for sign compared to speech in a 2-back task and red show net activation for speech compared to sign. Reprinted from *Neuropsychologia, 45(10),* Rudner, M., Fransson, P., Ingvar, M., Nyberg, L. & Rönnberg, J., Neural representation of binding lexical signs and words in the episodic buffer of working memory, 2258-2276, (2007), with permission from Elsevier.

Figure 5
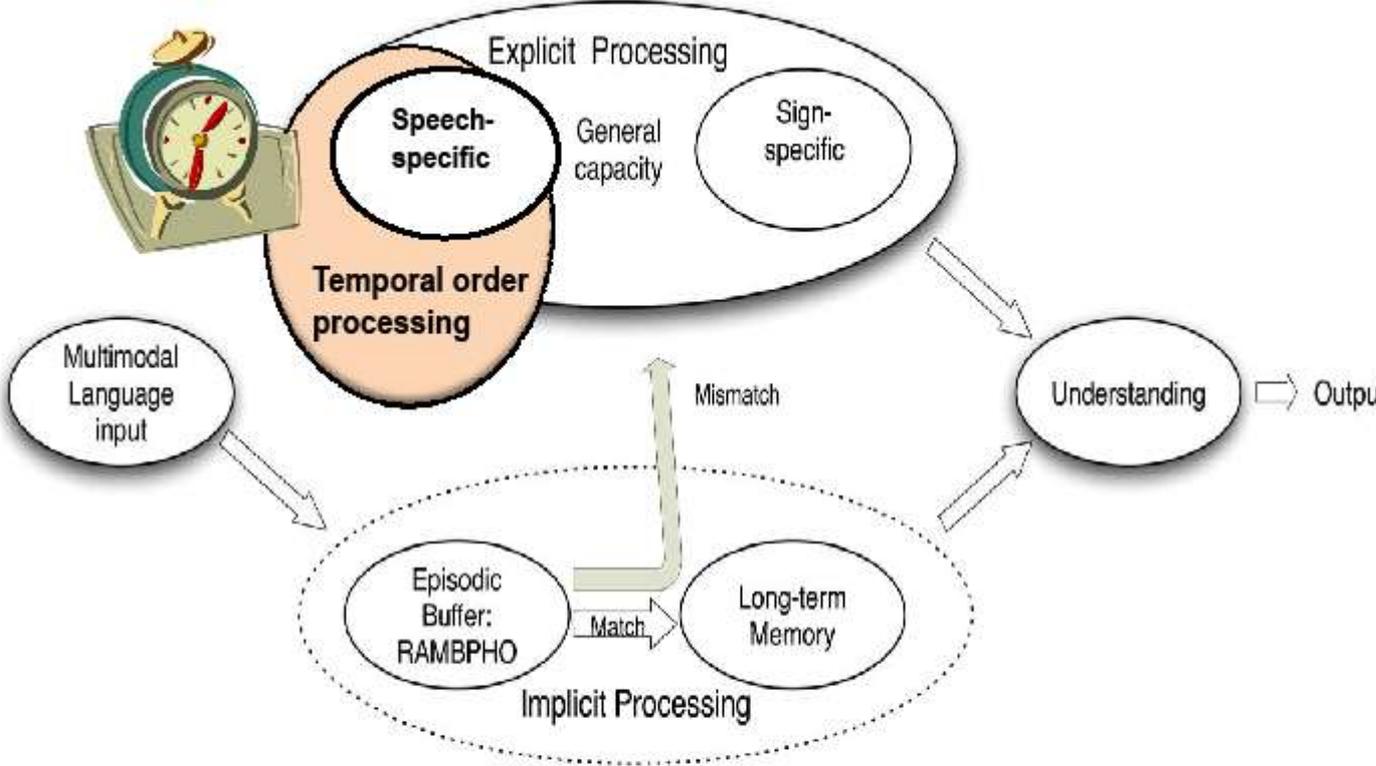
The role of temporal order processing in the ELU model.