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Levels of processing and language modality specificity in working memory

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ABSTRACT

Neural networks underpinning working memory demonstrate sign language specific components possibly related to differences in temporary storage mechanisms. A processing approach to memory systems suggests that the organisation of memory storage is related to type of memory processing as well. In the present study, we investigated for the first time semantic, phonological and orthographic processing in working memory for sign- and speech-based language. During fMRI we administered a picture-based 2-back working memory task with Semantic, Phonological, Orthographic and Baseline conditions to 11 deaf signers and 20 hearing non-signers. Behavioural data showed poorer and slower performance for both groups in Phonological and Orthographic conditions than in the Semantic condition, in line with depth-of-processing theory. An exclusive masking procedure revealed distinct sign-specific neural networks supporting working memory components at all three levels of processing. The overall pattern of sign-specific activations may reflect a relative intermodality difference in the relationship between phonology and semantics influencing working memory storage and processing.

1. Introduction

Working memory is the cognitive function that allows on-line processing and storage of information and is thus vital for everyday functioning and communication (e.g. Baddeley and Hitch (1974), Daneman and Carpenter (1980), Postle (2006), Ruchkin, Grafman, Cameron and Berndt (2003)). Studies investigating the language modality specificity of working memory have revealed that although behavioural performance is similar across signed and speech-based languages (Boutla, Supalla, Newport & Bavelier, 2004; Rudner, Fransson, Ingvar, Nyberg & Rönnberg, 2007), the neural networks that support them, despite significant overlap, show clear evidence of language modality specificity, possibly related to differential organisation of storage mechanisms (Bavelier et al., 2008; Buchsbaum et al., 2005; Pa, Wilson, Pickell, Bellugi & Hickok, 2008; Rönnberg, Rudner & Ingvar, 2004; Rudner et al., 2007).

A processing approach to memory systems suggests that the organisation of memory storage is related to type of memory processing and includes both general and specific mechanisms (Nyberg, Forkstam, Petersson, Cabeza, & Ingvar, 2002). In the present study we investigate for the first time the specificity of semantic, phonological and orthographic processing in working memory and whether the neural representation of these processes is language modality specific.

1.1. Signed language

Signed languages are the preferred mode of communication for people who are born deaf (Emmorey, 2002). In signed languages, communication takes place in the visual mode as opposed to audiovisually, or simply auditorily, in speech communication. This means that cognitive processes mediated by sign language may bootstrap onto visual processes but also onto sign language-specific processes that are not primarily related to visual processing. This is analogous to speech-based cognition which is dependent on both lower-level auditory processes and higher cognitive processes (Davis & Johnsrude, 2003). However, signed language is predominantly left-lateralized in the brain (Rönnberg, Söderfeldt & Risberg, 2000; Söderfeldt, Rönnberg & Risberg, 1994), as demonstrated by both lesion data (reviewed in Corina and Knapp (2006)) and imaging data (reviewed in MacSweeney, Capek, Campbell and Woll (2008)). Further, thinking in sign language or "inner signing" is mediated by similar regions to inner speech (McGuire et al., 1997).

There is no longer any doubt about the linguistic status of sign language (Campbell, MacSweeney, & Waters, 2008; Rönnberg, Söderfelt & Risberg, 2000) and similar levels of linguistic analysis (phonological, semantic, syntactic; Siple, 1997) across language

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modalities allow an analytic approach to the investigation of the modality specificity of cognition.

The representation of semantics appears to be similar across language modalities (Bosworth & Emmorey, 2010; McEvoy, Marschark & Nelson, 1999). For example, retrieval of lexical signs from different semantic categories activates regions of the left temporal lobe similar to those activated by the retrieval of words (Emmorey et al., 2003, 2004). Further, semantic violations in sign language generate a classic N400 effect (Capek et al., 2009).

Phonology may be defined as the level of linguistic analysis that organises the medium through which language is transmitted (Sandler & Lillo-Martin, 2006, p. 114). In speech-based languages, this refers to the patterning of sounds, at segmental as well as suprasegmental levels; in sign languages, it refers to the patterning of the position, shape and movement of the signing hands. Phonological processing in sign language has been shown to engage the same left perisylvian regions in the inferior frontal lobe, superior temporal sulcus and the parietal lobe as speech-based language (MacSweeney, Waters, Brammer, Woll & Goswami, 2008). This suggests that the neural network supporting phonological processing is to some extent supramodal. However, activation within this network is modulated by both language modality and hearing status, indicating a measure of modality specificity (MacSweeney, Waters et al., 2008).

Orthography refers to the mapping between speech sounds and written letters. Deaf people have limited access to speech sounds due to their sensory impairment and although a certain amount of phonological information is available from lip reading (or speechreading), this information typically underdetermines the phonological variation of spoken language. Signed languages have their own code for representing the orthography of spoken language and this code is known as finger-spelling. The Swedish finger-spelled alphabet is a set of signs for the Swedish alphabet. It is not a representation of the sounds of Swedish but a manual representation of the orthographic representation of Swedish. Finger-spelling is used by signers to fill lexical gaps in a signed language (Sutton-Spence & Woll, 1999). Thus, although sign language users have a way of representing orthography in their own language modality, it remains irreducibly linked to speech-based language. Despite this, it has been shown that orthographic processing activates common regions including the mid fusiform gyrus across the language modalities of sign and speech (Waters et al., 2007).

Thus, there is evidence to suggest that language modality-general neural networks are engaged in all three kinds of processing addressed in this study. As regards semantics, there is little theoretical reason and, to our knowledge, no empirical evidence of modality-specific representation. Phonology can be described at an abstract supramodal level and there is empirical evidence that its neural underpinnings reflect this. At a surface level, the phonologies of sign and speech are very different which is likely to drive some modality specificity. Orthography is by definition speech-based and thus modality specific although it is functionally represented in sign language by finger-spelling and finger-spelling seems to be supported by neural networks similar to those underlying speech-based spelling. Consequently, we expect to find modality neutral networks for all three types of processing with some modality-specific components for phonological and orthographic but not semantic processing.

1.2. Working memory

Working memory refers to the mechanisms involved in the processing and short-term maintenance of information. One influential model proposes separate phonological and visuospatial processing buffers and an episodic buffer that maintains integrated information from other cognitive systems and combines information in different codes into unitary multidimensional representations (Baddeley, 2000, 2012; Repovs & Baddeley, 2006). At an abstract level, the function of these buffers can be described in the same way for signed and speech-based language (Rudner, Davidsson & Rönnberg, 2010; Rudner & Rönnberg, 2008a, 2008b; Wilson & Emmorey, 1997; 1998; 2003) but at a surface level the phonological processing buffer seems to be modality specific (Wilson, 2001) while the episodic buffer is modality independent (Rudner et al., 2010; Rudner & Rönnberg, 2008a, 2008b). Wilson (2001) made the case for sensorimotor coding in working memory and it has been argued that working memory, rather than being a distinct cognitive mechanism, can be parsimoniously described in terms of general purpose sensorimotor and representational systems (Buchsbaum and D'Esposito, 2008; Hickok, Buchsbaum, Humphries, & Muftuler, 2003; Postle, 2006) whose capacity is determined by attentional resources (Ruchkin et al., 2003).

Working memory has a characteristic neural organisation involving a load-sensitive frontoparietal network (Cabeza & Nyberg, 2000; Smith & Jonides, 1997; Wager & Smith, 2003). Work from our lab (Rönnberg et al., 2004; Rudner et al., 2007) showed that despite the fact that sign language processing engages similar networks to speech processing (Emmorey et al., 2003, 2004; McGuire et al., 1997; MacSweeney, Waters, et al., 2008; Waters et al., 2007), and that working memory has a similar capacity for signed and speech-based language (Boutla et al., 2004; Rudner et al., 2007), working memory for sign language engages some parts of the brain to a greater extent than working memory for spoken language. In other words, there are modality specific neural networks that support working memory for sign language.

In two studies, one using PET and one using fMRI, we showed that hearing individuals who are bilingual in Swedish and Swedish Sign Language (SSL) engage working memory networks to a similar extent using sign and speech but that they in addition engage bilateral parietal and temporal regions significantly more for sign-based than speech-based working memory. We interpreted this sign-specific activation as indexing a modality-specific short-term store of signs. This is in line with the extensive behavioural evidence indicating that short-term storage of words has a more prominent serial organisation than short-term storage of signs which may be more spatial (O'Connor & Hermelin, 1973; 1976; Rudner & Rönnberg, 2008a; Rudner et al., 2010; Wilson, Bettger, Niculae & Klima, 1997). This evidence supports a partly language modality specific view of working memory. Our PET study (Rönnberg et al., 2004) showed similar patterns of results for both episodic and semantic retrieval in working memory, suggesting that the modality specificity of working memory generalises across types of processing.

Work by the Hickok group studied the neural correlates of working memory for pseudosigns in deaf native signers (Buchsbaum, et al., 2005) and compared working memory for pseudosigns and pseudowords in hearing native users of American Sign Language (ASL, Pa et al., 2008). Like our own work, these studies showed modality specificity for working memory for sign language. In particular, working memory for pseudosigns activated more posterior regions, including parietal cortex, than working memory for pseudowords, during both encoding and maintenance phases of the task, while frontal regions showed similar activation across modalities. In a study from the Bavelier group (Bavelier et al., 2008) deaf native users of ASL and hearing non-signers memorised series of letters that were presented either as speech for the hearing participants or by finger-spelling for the deaf group. The deaf group showed greater activation than the hearing group in bilateral parietal regions during the recall phase of the task and more bilateral frontal activation during the encoding phase of the task.