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Keywords:	working memory, visuospatial, sign language, deafness, semantic

Pre-existing semantic representation improves working memory performance in the visuospatial domain

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Abstract

Working memory (WM) for spoken language improves when to-be-remembered items correspond to pre-existing representations in long-term memory. We investigated whether this effect generalizes to the visuospatial domain by administering a visual n-back WM task to deaf signers and hearing signers as well as hearing non-signers. There were four different kinds of stimuli: British Sign Language (BSL, familiar to the signers); Swedish Sign Language (unfamiliar); non-signs; non-linguistic manual actions. The hearing signers performed better with BSL than SSL, demonstrating a facilitatory effect of pre-existing semantic representation. The deaf signers also performed better with BSL than SSL, but only when WM load was high. No effect of pre-existing phonological representation was detected. The deaf signers performed better than the hearing non-signers with all sign-based materials, but this effect did not generalize to non-linguistic manual actions. We argue that deaf signers who are highly reliant on visual information for communication develop expertise in processing sign-based items, even when those items do not have pre-existing semantic or phonological representations. Pre-existing semantic representation, however, enhances the quality of the gesture-based representations temporarily maintained in WM by this group, thereby releasing WM resources to deal with increased load. Hearing signers, on the other hand, may make strategic use of their speech-based representations for mnemonic purposes. The overall pattern of results is in line with flexible resource models of working memory.

Keywords: working memory; visuospatial; sign language; deafness; semantic

Introduction

Working memory (WM) is the cognitive capacity available for on-line processing and short-term storage of information (Baddeley, 2012; Ma, Husain & Bays, 2014). It is limited to three or four items (Cowan, 2001), except when encoding can take place in relation to representations that are already established in long term memory (Hulme, Maughan, & Brown, 1991). Indeed, the short-term store can accommodate as many as nine familiar words (Miller, 1956), that is, items with pre-existing representations in the mental lexicon, but considerably fewer non-words (Hulme et al., 1991) or items that cannot be verbalized (Luck & Vogel, 1997). Long-term representations also influence short-term storage of non-words, such that non-words with a common phonological structure are more robustly represented than those which are more unusual (Gathercole, Frankish, Pickering & Peaker, 1999). However, it is not known whether these semantic and phonological effects pertain exclusively to speech-based representations in the auditory domain or whether they can be generalized to sign-based representations in the visuospatial domain. The main purpose of the present study is to investigate this.

Sign languages are natural languages in the visuospatial domain used by deaf communities (Sutton-Spence & Woll, 1999). They develop independently of the spoken languages that surround them and have a different grammatical structure (Emmorey, 2002). However, the sublexical structure of signed languages can be understood in terms similar to those used to describe the phonology of spoken languages (Sandler & Lillo-Martin, 2006). Spoken language phonology relates to a largely sequential set of contrasts, manifest in the notion of minimal pairs – where two words contrast in a single phonological element, such as the final consonants in words like bag and bad, or in rhyme. In signed languages, the less sequential phonological elements comprising the shape, movement and location of the signing hands (Sandler & Lillo-Martin, 2006) give rise to minimal pairs consisting of two signs differing e.g. in location only, such as British Sign Language (BSL) NAME and AFTERNOON , see Figure 1. Phonological processing tasks generate similar patterns of performance across the language modalities of sign and speech (Andin, Rönnberg & Rudner, 2014) and activate similar neural networks, suggesting at least some degree of amodal representation of phonology (Macsweeney, Waters, Brammer, Woll & Goswami, 2008).

Figure 1. BSL minimal pair. The BSL minimal pair NAME (left panel) and AFTERNOON (right panel) share handshape and movement but differ in location.

The Ease of Language Understanding (ELU) model of WM (Rönnberg et al., 2013) proposes that WM in the service of communication is multimodal. Input to the system can be in any language modality, transmitted by any or several sensory modalities, and enters an episodic buffer (Rudner & Rönnberg, 2008b) whose function is Rapid Automatic Multimodal Binding of PHOnology (RAMBPHO). When the input can be smoothly matched to existing representations in long-term memory, language understanding is implicit and experienced as effortless. However, when there is a mismatch, language understanding becomes explicit and, depending on individual cognitive capacity, may be experienced as effortful. Mismatch may arise either due to a range of problems with input to the cognitive system including structural distortion and semantic distraction (Mattys et al., 2012; Rudner & Lunner, 2014; Zekveld et al., 2011) or to non-existent or degraded representations (Classon, Rudner & Rönnberg, 2013; Molander et al., 2013) in long-term memory. When explicit processing is brought into play, limited cognitive resources are devoted to processing, and thus storage limits become critical. This means that pre-existing representation improves performance in two ways, by avoiding mismatch and by reducing the load involved in maintaining items without pre-existing representation in WM. Evidence is accumulating to support the ELU model in the auditory/speech domain, and because the ELU model accepts multimodal input, it is likely that similar phenomena may be observable for sign language (for discussion see, Rudner, Toscano & Holmer, 2015).

Indeed, previous research has shown, in support of the multimodal nature of the ELU model, that signers and speakers perform at similar levels on WM tasks presented either in their preferred language modality or in a format that is language modality neutral (Andin et al., 2013; Boutla, Supalla, Newport & Bavelier, 2004; Rudner, Fransson, Ingvar, Nyberg & Rönnberg, 2007). However, there are differences in the neural organization of WM for sign and speech suggesting that at least partially different underlying mechanisms come into play when explicit WM processing is engendered, for example when executive functions are engaged (Rudner et al., 2007) or load is high (Rönnberg, Rudner & Ingvar, 2004; for a review see Rudner, Andin & Rönnberg, 2009). The main goal of the present study was to determine whether preexisting semantic and phonological representation in the sign-based mental lexicon improves WM performance in the visuospatial domain and whether such representation mitigates the effect of increasing memory load, in line with the prediction of the ELU model (Rönnberg et al., 2013).

In order to achieve this goal we manipulated pre-existing representation using different materials and groups. Three groups took part in the experiment: two groups who were native users of BSL: deaf and hearing, and one hearing sign-naïve group. We recruited both deaf and hearing signers to control for the effect of auditory deprivation, which has been shown to influence neural organization (Bavelier, Dye & Hauser, 2006; Cardin et al., 2013). Because BSL users were recruited to the present study, the signs of British Sign Language (BSL) served as familiar signs. Swedish Sign Language (SSL) is another well-documented European sign language that is mutually unintelligible with BSL. Thus, SSL signs were used as unfamiliar signs. Non-signs were created by combining sign components in a manner that contravenes the principles of signed language phonology. Because there is evidence that non-signers are sensitive to regularities in non-signs (Wilson & Fox, 2007) we included a fourth kind of material that consisted of meaningless non-linguistic manual actions in the form of ball-catching events. Other work has shown that such items can be successfully processed in WM by hearing non-signers, despite limited diversity in the motoric gestures involved (Rudner, 2015).

Because we wished to test WM for items with and without pre-existing representation we chose to use an n-back paradigm (Rudner, 2015). The n-back procedure avoids the need for articulation which is likely to be better for items with pre-existing representation compared to those without, and it has previous been used successfully to study WM for sign language (Rudner et al,. 2007; 2013) and gestures (Rudner, 2015). The n-back paradigm also allows parametric manipulation of WM load (Barch et al., 1997), enabling investigation of potential interactions between load, material and group.

We reasoned that sign language users have pre-existing representations comprising semantic and phonological information relating to their own sign language which may bear phonological similarity to an unfamiliar sign language. Non-signers, on the other hand, have no existing representations, with or without semantic or phonological information, relating to sign language. Thus, by comparing WM for familiar and unfamiliar sign languages in sign language users, we can isolate the effect of semantic information in preexisting representations, while no such effect should be found for non-signers. Similarly, by comparing WM for unfamiliar signs and non-signs in signers we can isolate the potential effect of the phonological information in preexisting representations, and again no such effect should be found for non-signers. Indeed, in non-signers there should be no difference in WM performance between the two categories of lexical signs (familiar and unfamiliar) or between signs and non-signs, since they have no preexisting representations with information concerning either semantics or phonology for any of these categories of items. However, we also reasoned that the differences in motoric diversity relating to handshape, position and movement between non-signs and non-linguistic manual actions would lead to differences in WM performance for all three groups of participants based on differences in the richness of representation and mutual salience. Further, by definition, signers are expert at processing signs and thus we expect them to have better WM performance than non-signers with all three sign-related materials (Ericsson & Kintsch, 1995). On the basis of previous work showing better performance by deaf signers than hearing non-signers on a non-verbal visuospatial task (Corsi Block: Geraci, Gozzi, Papagno & Cecchetto, 2008; Orsini, Grossi, Capitani, Laiacona, Papagno & Vallar, 1987) we expected this effect, attributed to experience of sign language, to generalize in the present study to non-linguistic manual actions.

The main aim of the current study was to test whether the enhancement of WM capacity due to semantic and phonological representation in the mental lexicon in long term memory can be generalized to sign-based representations in the visuospatial domain. We also investigated whether sign language experience generally improves WM for manual gestures, irrespective of semantic content or phonological structure. Further, we studied whether sign language experience mitigates the effect of increasing WM load, as predicted by the ELU model and, if so, whether any such interaction is influenced by pre-existing semantic or phonological representation.

Specifically, we predicted that signers would perform better on the n-back task with familiar than unfamiliar signs (semantic representation) and better with unfamiliar signs than with non-signs (phonological representation) as well as better with non-signs than non-linguistic manual actions (motoric diversity). We predicted no difference in performance between different sign-based materials for non-signers but we did predict that they would perform better with sign-based materials than with non-linguistic manual actions (motoric diversity). At the same time, we predicted better performance for signers compared to non-signers on all materials due to experience with visuospatial information. We did not predict differences in performance between the two signing groups. Further, we predicted that increasing memory load would reduce n-back performance for all groups but that this effect would be mitigated by sign language experience, pre-existing representation and motoric diversity.

Method

Participants

Sixty-eight participants belonged to three groups: deaf signers (DS), hearing signers (HS) and hearing non-signers (HN). Hearing and deaf signers were included to control for any effect of auditory deprivation. Group size was estimated on the basis of previous experience with mixed repeated-measures designs, e.g. Rudner, Davidsson and Rönnberg (2010). Details of the groups are shown in Table 1. The three groups did not differ in terms of age and non-verbal intelligence measured using the t score of the block design scale from the WASI battery (Wechsler, 1999). All participants had completed secondary education. All HS had at least one deaf parent with whom they communicated in sign language and had been exposed to BSL before the age of three years. All but two DS had at least one deaf parent. One deaf signer with hearing parents was exposed to BSL before the age of three and the other before the age of five. The sign language fluency of the two signing groups was assessed using the BSL Grammaticality Judgment Test (Cormier, Schembri, Vinson, & Orfanidou, 2012). The signers had native or near-native proficiency in BSL, see Table 1. Because we used SSL materials as semantically inaccessible but phonologically well-formed items (see below) we ensured that none of the participants was familiar with SSL. All participants gave their written informed consent. This study was approved by the UCL Ethical committee.

Table 1. Participant information (standard deviations in parentheses)

	Native signers of British Sign Language (BSL)				Non-signers	
	Deaf		Hearing			
	DS		HS		HN	
	N=24, 10 women		N=20, 16 women		N=24, 17 women	
	M	SD	M	SD	M	SD
Age (years)	38	(13)	38	(14)	36	(13)
Non-verbal IQ (t)	62	(6)	61	(7)	61	(8)
BSL fluency (% correct)	83	(13)	80	(6)		

Materials

The stimulus set included four different types of material. There were three types of sign-based material: lexical signs in BSL, lexical signs in SSL and non-signs. The fourth type of material consisted of the model catching a ball (non-linguistic manual actions). They were constructed as follows.

BSL. An initial set of about 100 signs that potentially fulfilled the criteria for BSL stimuli were selected from Vinson, Cormier, Denmark, Schembri and Vigliocco (2008), which provides an inventory of BSL signs ranked with respect to age of acquisition (AoA), familiarity, and iconicity on the basis of average ratings obtained from 30 deaf signers of BSL. Rankings were used for stimulus matching. In addition, complexity ratings were obtained from two deaf native BSL signers. The raters were asked to look at videos of the candidate signs, concentrating on the movements of the model's hands, and then rate complexity on a scale of 0 to 4 based on first impressions. Each sign was viewed twice. Pearson's correlation was computed to determine inter-rater reliability (IRR), $r = .49$, $p < .001$. Thus, the BSL material consisted of items which we have every reason to believe should correspond to existing semantic and phonological representations stored in the long term memory of DS and HS, but not HN.

SSL. An initial set of about 100 SSL signs was selected from the Swedish Sign Language Dictionary (Hedberg et al., 2005; Institutionen för Lingvistik, 2010). The inventory of contrastive handshapes and locations differs somewhat between signed languages. However, only a small number of BSL handshapes are not found in SSL and vice versa and these tend to be rarely occurring handshapes only found in a small number of signs. For example, there is a BSL handshape with the index and little fingers extended from the fist, which does not occur in SSL. However, there are only three signs with this handshape in Brien's (1992) dictionary of BSL. This can be compared to 292 entries for the fist handshape in BSL and 213 in SSL. SSL was chosen for this study as although the inventories of contrastive handshapes, locations and movements in SSL are highly similar to those of BSL, SSL is not generally familiar to BSL users and lexical similarity between the two sign languages is only 35 % (Mesch, 2006), a figure indicating two historically unrelated sign languages (Woll, 1984).

Two deaf native signers of SSL ranked all items for AoA, IRR: $r = .80$, $p < .001$; familiarity, IRR: $r = .81$, $p < .001$; iconicity, IRR: $r = .89$, $p < .001$, and complexity, IRR: $r = .75$, $p < .001$, according to the principles used for the BSL sign ratings; two deaf native signers of BSL provided additional complexity ratings, IRR: $r = .77$, $p < .001$, and were asked if any of the signs could be considered as BSL signs. If a sign was considered to be a BSL sign by any of the judges, it was removed from the set. The remaining SSL signs were not lexical signs in BSL and their semantic content was not transparent. Thus, the SSL material consisted of items which we have every reason to believe should correspond to existing phonological but not semantic representations stored in the long term memory of DS and HS, but not HN (i.e. they were possible signs of BSL).

Non-signs. About 100 non-signs were generated by deaf native BSL signers. Most of these non-signs had previously been used in behavioural studies (Orfanidou, Adam, McQueen & Morgan, 2009; Orfanidou, Adam, Morgan & McQueen, 2010), but additional non-signs were created specifically for the current study. The non-signs were constructed so as to violate phonological rules in BSL, and therefore were not phonologically well-formed (i.e. impossible signs). For example, some non-signs had movement of both hands, but the hands had different handshapes, or there was a change of location on the body with movement from a lower to a higher location (well-formed BSL signs which involve a change of location height must move from a higher to a lower location). Other non-signs included those with an unusual place of contact on the signer's body: for example the non-sign occluded the signer's eye; or with an unusual place of contact on the signer's hand: for example, a handshape with the index and middle finger extended but contact only between the tip of the middle finger and a location on the body. Complexity ratings were obtained from native BSL signers as above, IRR: $r = .32$, $p = .03$. Although statistically significant, the IRR coefficient for non-sign complexity is low. This may reflect the fact that characteristics of the non-signs were unusual. Thus, the non-sign material consisted of items which we have every reason to believe include existing phonological components, although they have neither semantic representations nor phonologically permissible combinations of components (i.e. they are without a phonological representation), stored in the long term memory of DS and HS, but not HN.

Non-linguistic manual actions. This type of material consisted of the model catching a soft, bright green ball about 15 cm in diameter, thrown by an assistant to different locations proximal to the model's torso. This provided a control condition that included movements of the hands and arms to a range of locations but with limited variation in handshape. These stimuli were non sign-based and non-linguistic, being generated in a bottom-up manner in response to an external stimulus. Thus, we have no reason to believe that any of these items would correspond to linguistic representations stored in the long term memory of any of the participants.

A final set of 45 unique items was selected for each of the four types of material, that is, 180 items in all. The three categories of sign-based material were selected for similar AoA, familiarity, iconicity (lexical signs only) and complexity (based on the BSL signers ratings). A univariate analysis of variance, in which stimulus type (BSL, SSL, non-signs only for the complexity analysis) was entered as the fixed factor, and familiarity, iconicity, AoA and complexity were entered as the dependent variables, showed no significant differences between the different materials (Familiarity $F(1,88) = 2.9$, $p = 0.09$, Iconicity $F(1,88) = 3.1$, $p = 0.08$, AoA $F < 1$, Complexity $F < 1$). Importantly, there was no difference in rated complexity, despite low IRR for non-signs. Table 2 summarizes the characteristics of the sign-based materials and Appendix 1 lists the BSL and SSL signs and Appendix 2 lists the non-signs. It was ensured that a wide range of handshapes, movements and locations were represented in a balanced manner over sign-based categories and that there was a broad range of locations for the non-linguistic manual actions.

The final set of stimulus items was recorded in a studio environment using a digital High Definition camera. Signing was produced by a male deaf native signer of German Sign Language who was unfamiliar with either BSL or SSL. He was dressed in black and visible from the hips to above the head, against a blue background. All items were signed with comparable ease, speed, and fluency; no mouthing was used. The items were modelled individually and thus there was no transitional movement between forms. The videos of the individual items were between two and three seconds long. The mean duration of the stimuli was as follows: BSL, 2.77 s; SSL, 2.68 s; non-signs, 2.75 s; non-linguistic manual actions, 2.55 s. A univariate analysis of variance in which material was entered as fixed factor and duration as the dependent variable showed a significant effect of material on duration, $F(3,180) = 4.481$, $p = .005$. Pairwise comparisons showed that the duration of the non-linguistic manual actions was significantly shorter than the duration of both BSL, $p = .001$, and non-signs, $p = .004$ and tended to be shorter than SSL, $p = .053$. There were no other significant differences in duration between the material types, all ps > .16. As the model was not a native user of either BSL or SSL, all the sign-based material was equally ‘accented’.

Table 2. Material information (mean ratings and standard deviations in parentheses). Familiarity and Iconicity ratings are based on a scale from 1 to 7, AoA is based on a scale from 0 to 17 years or older and complexity ratings are based on a scale of 1 to 4.

Material	Familiarity		AoA		Iconicity		Complexity	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
BSL	5.5	(0.8)	8.9	(2.9)	2.9	(1.4)	2.1	(0.9)
SSL	5.9	(1.3)	8.9	(3.4)	3.6	(2.1)	2.1	(0.9)
Non-Signs	n.a.		n.a.		n.a.		2.4	(0.7)

Task and Design

We used an n-back task, in which WM load was systematically varied by manipulating n (1, 2, 3). All tasks were administered using DMDX software (Forster & Forster, 2003). Two different lists of each type of material were constructed for each of the three versions of the task (1-back, 2-back, 3-back). There were 45 items in each list which were arranged so that there would be 16 or 17 correct “yes” responses in accordance with the task description, but no more than four correct “yes” responses or six correct “no” responses in a row. Each item could be repeated up to three times and there were five lures in each of the lists.

The participants were instructed to make a ”yes” response when the video currently being shown exactly matched the last video in the sequence (1-back), the last-but-one video in the sequence (2-back) or the video three steps back in the sequence (3-back). Otherwise a “no” response was required. The responses were given by pressing the appropriate button on a two-button box. The “yes” responses were given with the participant’s preferred hand. All the participants performed the three versions of the task (n back 1, 2, 3) with one list of each of the materials. Lists were balanced across participants within groups. Task order was balanced across participants within groups and material order was randomized within task. Responses were collected by button press and d’ (Stanislaw & Todorov, 1999) calculated. Because of near ceiling performance for the 1-back task with sign-based stimuli, these d’ scores were arcsin transformed into radians to provide for a more normal distribution (Studebaker, 1985). The arcsin transformed scores are used in all analyses. The time between stimulus onsets was four seconds and the participants were given 3.5 seconds to respond.

Results

The overall pattern of performance on the n-back task is shown in Table 3.

Table 3. Mean d' scores and arcsin transformed scores and standard deviation for all groups under all conditions.

		BSL				SSL				Non-signs				Non-linguistic			
		d'		Arcsin		d'		arcsin		d'		arcsin		d'		arcsin	
Group	n	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DS	24	3.48	0.54	1.14	0.3	3.63	0.49	1.26	0.31	3.67	0.36	1.26	0.27	2.36	0.56	0.64	0.18
HS	20	3.76	0.32	1.33	0.26	3.57	0.39	1.17	0.25	3.74	0.3	1.3	0.25	2.49	0.55	0.68	0.18
HN	24	3.22	0.9	1.05	0.39	3.15	0.9	1.03	0.41	3.4	0.82	1.16	0.4	2.29	0.73	0.63	0.24
Total	68	3.47	0.67	1.16	0.34	3.44	0.67	1.15	0.35	3.59	0.57	1.23	0.31	2.37	0.62	0.65	0.2
DS	24	3.44	0.76	1.15	0.35	3.53	0.41	1.15	0.26	3.48	0.46	1.14	0.29	1.71	0.73	0.45	0.21
HS	20	3.36	0.51	1.08	0.31	3.1	0.71	0.98	0.36	3.26	0.54	1.02	0.29	1.63	0.75	0.43	0.21
HN	24	2.8	0.86	0.83	0.33	2.76	0.91	0.85	0.4	2.95	0.89	0.88	0.32	1.7	0.97	0.46	0.29
Total	68	3.19	0.78	1.02	0.36	3.13	0.77	0.99	0.36	3.23	0.69	1.01	0.32	1.68	0.82	0.45	0.23
DS	24	3.21	0.63	1.01	0.32	2.82	0.59	0.81	0.22	2.98	0.58	0.87	0.22	1.51	0.63	0.39	0.18
HS	20	3.03	0.53	0.89	0.23	2.77	0.53	0.78	0.19	2.82	0.58	0.8	0.2	1.18	0.47	0.3	0.13
HN	24	2.39	0.92	0.69	0.33	2.4	0.8	0.66	0.24	2.55	0.68	0.72	0.23	1.11	0.62	0.28	0.16
Total	68	2.87	0.8	0.86	0.33	2.66	0.67	0.75	0.23	2.78	0.63	0.8	0.23	1.27	0.6	0.33	0.16

Effect of semantic representation and interaction with load

The effect of semantic representation and its interaction with load were determined by computing a 2 x 3 x 3 mixed repeated-measures ANOVA, with two within-participant factors: type of material (BSL, SSL) and load (1-back, 2-back, 3-back); and one between-participant factor: Group (DS, HS, HN). The analysis revealed main effects of all three factors: material, $F(1,65) = 6.07$, $MSE = .05$, $p = .016$, partial $\eta 2 = .09$; load, $F(2,130) = 49.43$, $MSE = .09$, $p < .001$, partial $\eta 2 = .43$ and group, $F(2,65) = 9.97$, $MSE = .22$, $p < .001$, partial $\eta 2 = .24$. The predicted two-way interaction between material and group was marginally significant, $F(2,65) = 2.87$, $p = .06$, see Figure 2, as was the predicted three-way interaction, $F(4,130) = 1.55$, $p = .19$. None of the interactions was statistically significant.

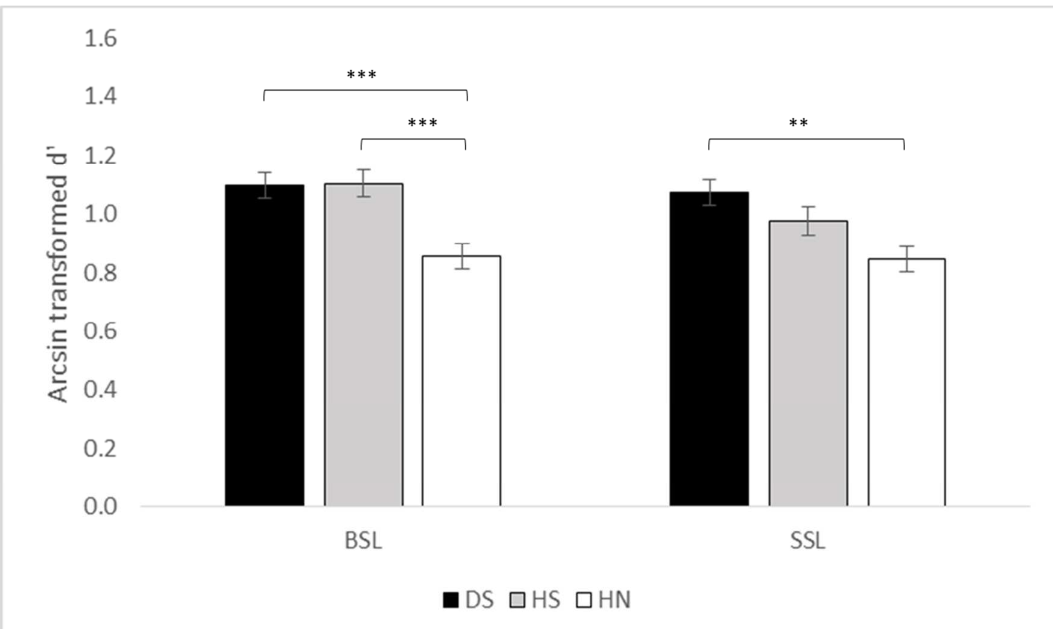

Figure 2. Interaction between Material (BSL, SSL) and Group (DS, HS, HN). Error bars show standard error for individual conditions and groups. ** and *** indicate p < .01 and .001 respectively.

The predicted interactions were investigated by computing separate ANOVAs for each of the groups. Contrary to our prediction, there was no statistically significant main effect of material for DS, $F(1,23) = .57$, $MSE = .04$, $p = .46$. However, there was a statistically significant main effect of load for this group, $F(2,46) = 13.27$, $MSE = .09$, $p < .001$, as well as a statistically significant interaction between material and load $F(2,46) = 3.52$, $MSE = .09$, $p = .04$. Separate ANOVAs for each of the materials showed a significant main effect of load with SSL, $F(2,46) = 23.41$, $MSE = .06$, $p < .001$, partial $\eta2 = .50$, but not BSL, $F(2,46) = 1.23$, $MSE = .12$, $p = .30$, partial $\eta2 = .05$. Further investigation of the material by load interaction using paired samples 2-tailed t-tests adjusted for multiple comparisons showed significantly better performance with BSL than SSL when WM load was high at n=3, $t(23) = 3.03$, $p = .02$, but no difference at n=1, $t(23) = 1.47$, $p = .46$, or n=2, $t(23) = .08$, $p = 1$, see Figure 3.

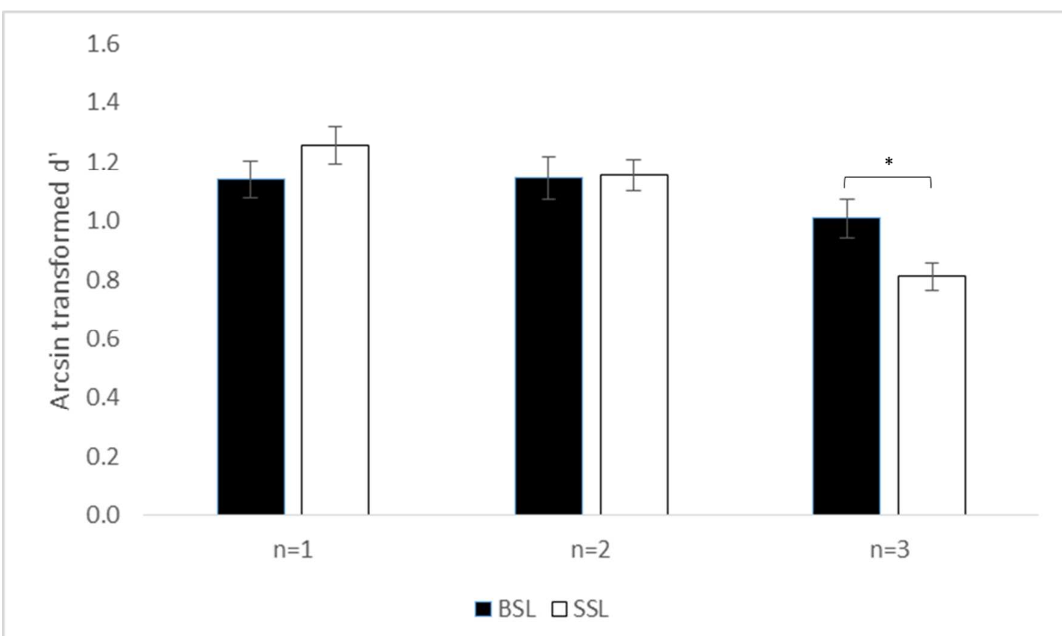

Figure 3. Statistically significant interaction between load and material (BSL, SSL) for DS. The error bars show standard error for the individual conditions. * indicates p < .05.

For HS there was a statistically significant main effect of material, revealing significantly better performance with BSL than SSL, $F(1,19) = 11.38$, $MSE = .04$, $p = .003$, in line with our prediction. There was also a statistically significant main effect of load, $F(2,38) = 27.05$, $MSE = .06$, $p < .001$ but no statistically significant interaction, $F(2,38) = 0.16$, $MSE = .05$, $p = .85$. For HN, there was no statistically significant main effect of material, $F(1,23) = .03$, $MSE = .06$, $p = .87$. This was in line with our prediction. There was a statistically significant main effect of load, $F(2,46) = 15.00$, $MSE = .11$, $p < .001$, for HN, but no statistically significant interaction with material , $F(2,46) = 0.08$, $MSE = .08$, $p = .92$.

Further investigation of the predicted two-way interaction between material and group, computing separate ANOVAs for BSL and SSL, revealed significant main effects of group both with BSL $F(2,65) = 10.77$, $MSE = .13$, $p < .001$ and with SSL $F(2,65) = 6.79$, $MSE = .14$, $p = .002$. With BSL, the performance of DS was significantly higher than that of HN, Mean difference (MD) = .25, $p < .001$, and the performance of HS was also significantly higher than that of HN, MD = .25, $p < .001$, while there was no difference in performance between DS and HS, MD = .01, $p = 1$. This pattern of between group differences was as predicted. With SSL, the performance of DS was significantly higher than that of HN, MD = .23, $p = .001$, as predicted. However, while there was no difference in performance between DS and HS, MD = .10, $p = .41$, the difference in performance between HS and HN, MD = .13, $p =.15$, did not reach significance.

Effect of phonological representation and interaction with load

The effect of phonological representation and its interaction with load were determined by computing a 2 x 3 x 3 mixed repeated-measures ANOVA, with two within-participant factors: material (SSL, non-signs) and load (1-back, 2-back, 3-back); and one between-participant factor: Group (DS, HS, HN). The analysis revealed main effects of all three factors: material, $F(1,65) = 4.71$, MSE = .06, $p = .034$, partial $\eta 2 = .07$; load, $F(2,130) = 77.07$, MSE = .08, $p < .001$, partial $\eta 2 = .54$ and group, $F(2,65) = 7.04$, MSE = .20, $p = .002$, partial $\eta 2 = .18$. The predicted two-way interaction between material and group was not significant, $F(2,65) = 0.61$, $p = .55$, neither was the predicted three-way interaction, $F(4,130) = 0.48$, $p = .75$.

The predicted two-way interaction between material and group was investigated by computing separate ANOVAs for each of the groups. Contrary to our prediction, there was no statistically significant main effect of material for DS, $F(1,23) = 0.19$, $p = .67$, or HS, $F(1,19) = 2.15$, $p = .16$, and the tendency observed for HN, $F(1,23) = 2.95$, $p = .10$, showed marginally better performance with non-signs than SSL. Further investigation of the interaction, computing a separate ANOVA for non-signs, revealed a statistically significant main effect of group, $F(2,65) = 4.44$, MSE = .55, $p = .016$. Bonferroni adjusted pairwise comparisons showed a statistically significant difference in performance with non-signs between DS and HN, MD = 0.17, $p = .015$, but not between HS and HN, MD = 0.12, $p = .16$, or between DS and HS, MD = 0.05, $p = 1$. Investigation of the threeway interaction computing separate ANOVAs for non-signs for each of the three groups showed a significant main effect of load for all three groups ($p < .001$ for all tests).

Effect of motoric diversity and interaction with load

Effect of motoric diversity and its interaction with load were determined by computing a 2 x 3 x 3 mixed repeated-measures ANOVA, with two within-participant factors: material (non-signs, non-linguistic manual actions) and load (1-back, 2-back, 3-back); and one between-participant factor: Group (DS, HS, HN). The analysis revealed statistically significant main effects of material, $F(1,65) = 511.69$, $MSE = .06$, $p < .001$, partial $\eta2 = .89$ and load, $F(2,130) = 102.40$, $MSE = .05$, $p < .001$, partial $\eta2 = .61$, but the effect of group was only marginal, $F(2,65) = 2.97$, $MSE = .13$, $p = .059$, partial $\eta2 = .18$. The two-way interaction between material and load was significant, $F(2,130) = 3.81$, $p = .03$, reflecting the fact that the negative effect on performance of increasing load was greater for non-signs than for non-linguistic manual actions, probably due to a floor effect at high load with non-linguistic manual actions, despite significant differences between all levels of load (all ps < .001) see Figure 4.

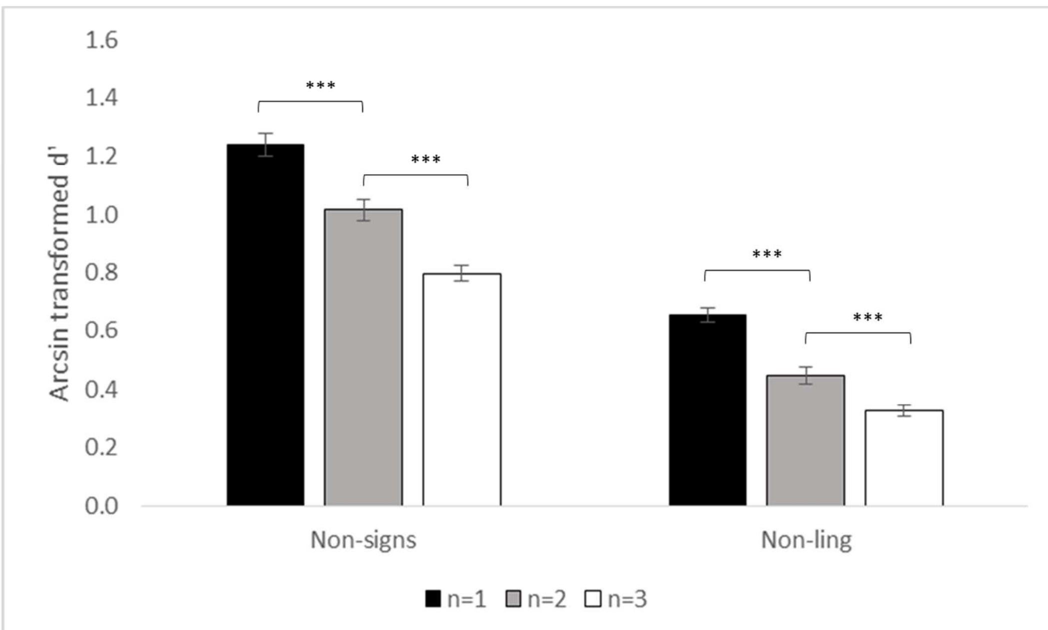

Figure 4. Two-way interaction between material (non-signs, non-linguistic manual actions) and load. Error bars show standard error for individual conditions. *** indicates p < .001.

The predicted two-way interaction between material and group was marginally significant, $F(2,65) = 3.02$, $p = .06$. Investigation of this interaction with an ANOVA including non-linguistic manual actions only, showed no significant main effect of group, $F(2,65) = 0.39$, p =

.68, reflecting the fact that the effect of group found for non-signs did not generalize to non-linguistic manual actions. The two-way interaction between group and load was not significant, F(4,130) = 1.08, p = .37 and neither was the three-way interaction, F(4,130) = 1.20, p = .32.

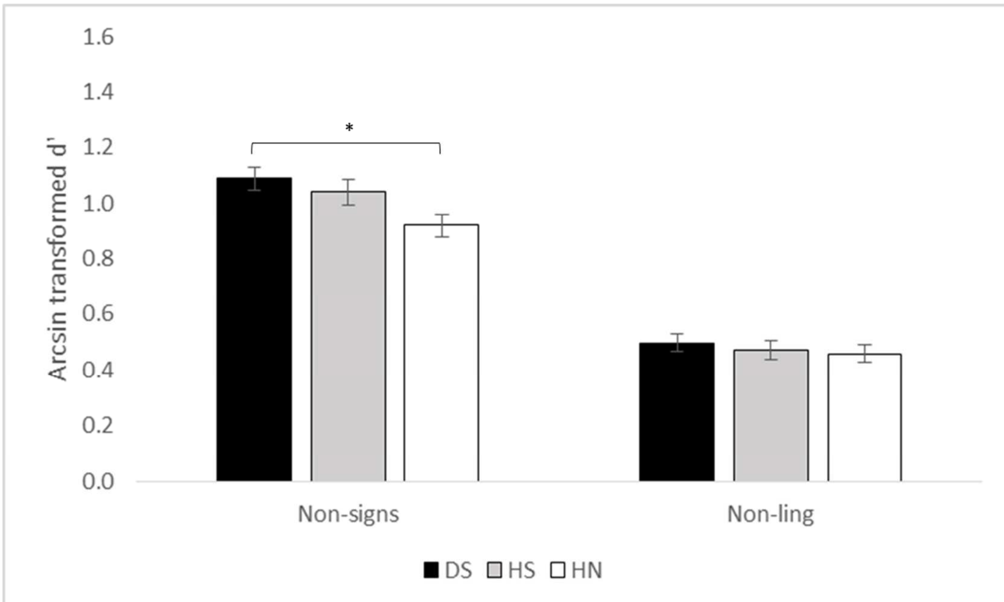

Figure 5. Interaction between material (non-signs, non-linguistic manual actions) and group. Error bars show standard error for individual conditions and groups. * indicates p < .05.

Discussion

The main aim of the current study was to investigate whether WM in the visuospatial domain is improved by pre-existing semantic and phonological representation in long-term memory in a manner similar to WM for speech-based language (Gathercole et al., 1999; Hulme et al., 1991). We also investigated whether differences in motoric diversity influence WM for manual gestures. Further, we investigated whether sign language experience generally improves WM for manual gestures and whether sign language experience, pre-existing representation and motoric diversity mitigate the effect of increasing WM load, as predicted by the ELU model.

Effect of pre-existing semantic representation

HS performed better with BSL than with SSL stimuli, in line with our prediction, supporting the notion that pre-existing semantic representation improves WM performance in the visuospatial domain. There was evidence of a similar effect for DS, but only when WM load was high. Thus, the effect of pre-existing semantic representation seems to play out differently for the two signing groups, possibly indicating the use of different strategies. Hearing signers have access to representations in two language modalities, sign and speech. Hall and Bavelier (2011) showed that the short-term recall performance of sign-speech bilinguals increases when they are instructed to silently mouth the spoken equivalents of to-be-remembered items presented in sign language. This applied even with signed recall. Thus, for individuals who have well-established speech-based representations, it may be more efficient to recode signs they know into their spoken equivalents in order to retain them in WM than to process sign-based representations. However, it is possible that this strategy is less effective, or even counterproductive, for unfamiliar signs that do not have an existing semantic representation.

Deafness restricts access to spoken language and makes it hard to develop speech-based representations. Thus, deaf signers compared to hearing signers are likely to be more reliant on sign-based representations during WM processing. The results of the present study indicate that deaf signers process familiar and unfamiliar signs just as successfully in WM when load is low or moderate, but also suggest that when load is high, pre-existing semantic representation facilitates WM processing for DS. This finding is in line with flexible resource models of WM which propose that the quality rather than quantity of WM representations determine performance (Ma, Husain & Bays, 2014). We suggest that for deaf signers pre-existing semantic representation enhances the quality of the representations temporarily maintained in WM, thus releasing WM resources to deal with increased load. This may become particularly important when the quantity of items is large. Such an interpretation is in agreement with the ELU model (Rönnberg et al., 2013) which states that when pre-existing representations cannot be activated due to a mismatch with input, explicit processing demands increase. Here we see the opposite effect: when the matching process is enhanced because pre-existing semantic representations are available, the effect of load is decreased. This supports the notion that the ELU model can explain phenomena related to sign-language processing and thus has cross-modal validity. Because DS performed relatively well even at the highest load level tested in the present study, future work should investigate the effect of pre-existing semantic representation at even higher levels of WM load.

We found no significant difference in performance between deaf and hearing signers with any of the materials, suggesting that even if different strategies were used, they did not differ in efficiency. However, the findings of the present study also suggest that the representational benefit of recoding familiar signs as words identified by Hall and Bavelier (2011) is restricted to the population they tested, hearing signers, but can be generalized across speech-sign pairs from American English-American Sign Language, tested in their study, to British English-British Sign Language, tested here.

No effect of pre-existing phonological representation

Because the forms of signs are sometimes visually motivated (iconic) in sign language (Thompson, Vinson, Woll & Vigliocco, 2012), the formally contrastive elements in phonology often carry meaning. For example, signs may depict perceptual features of an object, such as an airplane's wings; action-based features, such as drinking; or action location, such as the head for thinking (BSL examples, Thompson et al., 2012). This means that the signs of an unfamiliar sign language that are not lexicalized in a particular signer's own language, or even non-signs, may nonetheless bear semantic information. Thus, the comparison of WM for familiar versus unfamiliar signs in the present study is a conservative test of the influence of semantic information on WM processing. By the same token, any semantic influence at play during phonological processing would have tended to enhance performance with unfamiliar signs compared to non-signs, rendering the comparison of SSL to non-signs a liberal test of the effect of pre-existing phonological representation. Because there was no difference in performance between SSL and non-signs for either of the signing groups in the present study, we found no evidence of an effect of pre-existing phonological representation. The absence of a phonology-related effect in the present results was all the more surprising as there is a wealth of evidence suggesting that phonological representation is an important factor in WM processing. Indeed, WM capacity has been shown to be influenced by a range of factors relating to phonology. These include not only phonological similarity, but also the length of to-be-remembered items as well as articulatory suppression (Baddeley, 2012), and there is evidence to suggest similar effects for sign language (for a review see Wilson, 2001). Effects of formational similarity have also been found for non-signs (Wilson & Fox, 2007) and meaningless gestures (Rudner, 2015).

However, other work has shown that effects of phonological similarity on WM for sign language can be elusive (Rudner & Rönnberg, 2008a) despite effects of semantic category

(Rudner et al., 2010; Rudner & Rönnberg, 2008a). Indeed in a recent study, it was shown that although deaf users of SSL displayed an effect of phonological similarity on the short term store, as measured by digit span, this effect did not generalize to digit-based WM, as measured by operation span, and when the same experiment was performed with deaf users of BSL, no clear effect of phonological similarity was discernible for either the short-term store or WM (Andin et al., 2013). As the versions of both digit span and operation span used in the study by Andin et al. (2013) required recoding of printed stimuli to preferred language modality, it was argued that the difference in the pattern of effects between users of these two sign languages could be explained by a greater emphasis on sign-based deaf education in Sweden compared to a bias towards oral education for deaf children in the UK. This explanation is supported by evidence that speech-based phonology influences memory performance in British deaf individuals (Conrad, 1972; MacSweeney, Campbell & Donlan, 1996), while we know of no evidence of phonological similarity relating to BSL influencing recall.

Despite the lack of any previous evidence of a sign-phonology effect on memory performance in BSL users, this group has been shown to display an awareness of the phonological structure of their language (MacSweeney et al., 2008) and because all items were presented as manual actions in the present study, the phonological structure of the SSL signs was clearly visible. It is possible that in the present study the non-signs were more perceptually salient than the SSL signs, supporting WM encoding and thus counteracting any phonological benefit. This interpretation receives some support from the tendency for NS to perform better with non-signs than SSL. However, because there was no statistically significant difference in the rated complexity of the different sign-based manual gestures, this is not our preferred interpretation. Instead, we suggest that a parsimonious explanation of the significant effect of semantic representation on n-back WM performance with no effect of phonological representation, is that semantic, but not phonological information, is used in determining the n-back match. Although previous work has shown an effect of speech-based phonological similarity on performance on an n-back task, imaging results suggested that phonological similarity among items presented during an n-back task led to strategic disengagement of executive and language functions in the face of distracting information (Sweet et al., 2008), possibly leading to a less distinct representation of items in terms of their phonological content (Rudner, 2015) when this information is not explicitly required for solving the task (Rudner et al., 2013). It is possible that phonological information is systematically suppressed during n-back processing when it does not specifically contribute to task solution, which in this case requires determining whether items are identical. Another possible explanation that should be entertained is that there is a specific lack of a form-based effect for sign language processing. Future work should investigate this by manipulating the type of task and phonological demands.

Effect of sign language experience

We predicted better performance overall for signers compared to non-signers due to experience with visuospatial information. We found that DS performed better than HN with all the sign-based materials. HS only performed better than HN with BSL. The relatively high performance of NS overall is in line with other recent work showing that individuals with no experience of sign language can successfully perform an n-back WM task based on lexical signs (Rudner et al., 2015). This could be explained by an ad hoc quasi-phonological processing strategy capitalizing on existing motor representations. Indeed, such an interpretation is in line with results showing an effect of formational similarity on working memory for non-signs (Wilson & Fox, 2007). At any rate, the pattern of results in the present study does not support the notion that sign language experience alone facilitates WM processing of sign-based materials. However, it does indicate that reliance on visual information due to deafness combined with sign language experience facilitates WM processing of sign-based materials. It also suggests that when hearing signers have pre-existing semantic representations of sign-based items, they may be able to adopt a mnemonic strategy that allows them to outperform hearing non-signers. This further supports the notion that hearing signers, who have ready access to speech-based representations, may use these strategically during WM processing (Hall & Bavelier, 2011).

Sign language experience does not enhance WM for non-linguistic manual actions

Results showed the predicted poorer n-back performance with non-linguistic manual actions compared to the non-signs across groups. Our prediction was based on motoric diversity in relation to handshape, position and movement allowing richer and better differentiated manual representations. The shorter duration of the non-linguistic stimuli possibly also reflects the reduced information in these items. However, it should be noted that stimulus length did not influence timing of the WM task and thus did not confound the effect of load. We predicted that the effect of load would be smaller for non-signs compared to non-linguistic manual actions but this was not the case.

Further, we did not find the predicted effect that sign language experience would facilitate WM performance with non-linguistic manual actions for either of the signing groups. This finding suggests that better visuospatial processing for deaf signers than hearing non-signers (Geraci et al., 2008) with the Corsi blocks task does not generalize to non-linguistic manual actions when there is no requirement for spatial processing. However, it does support the notion that non-signers capitalize on existing motor representations during a gesture-based WM task, even when the to-be-remembered items are non-linguistic manual actions, in line with the findings of Rudner (2015). We suggest that WM is adapted to storage and processing of linguistic items, even when those items are gesture based and in the visuospatial modality. This may be due to systematic rhythmic motor patterns inherent in those items activating aspects of existing phonological representations at an abstract level that transcends modality or simply to the mutual distinctiveness between the motor patterns of linguistic items, but nonetheless supports the notion of multimodal models of WM such as ELU (Rönnberg et al., 2013).

Conclusion

We found evidence that pre-existing semantic representation enhances WM in the visuospatial domain. However, the underlying mechanisms appear to be different for deaf and hearing signers, possibly reflecting reliance on visuo-spatial processing in deaf signers and automatic access to speech-based representations in hearing signers. Pre-existing semantic representation mitigated the effect of increasing WM load for deaf signers, suggesting, in line with the ELU model (Rönnberg et al., 2013), that it enhances the quality of the gesture-based representations temporarily maintained in WM, thereby releasing WM resources to deal with increased load.

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Appendix 1. Signs – BSL and SSL.

BSL			SSL			
sign	type	parts	sign	English name	type	parts
amazed	2S	1	äcklig	disgusting	1L	1
argue	2S	1	afton	evening	1L	1
bank	2AS	1	ambitiös	ambitious	2S	1
believe	1L/2AS	2	anställd	employee	2S	1
biscuit	1L	1	april	April	1L	1
can't-be-bothered	1L	1	avundssjuk	envious	1L	1
castle	2S	1	bakelse	fancy pastry	2AS	1
cheese	2AS	1	bättre	better	1L	1
cherry	1L	1	bedrägeri	fraud	1L	1
chocolate	1L	1	beröm	praise	1L/2AS	2
church	2S	1	bevara	keep	2S	1
cook	2S	1	billig	cheap	1O	1
copy	2AS	1	blyg	shy	1L	1
cruel	1L	1	böter	fine	2AS	1
decide	1L/2AS	2	bräk	trouble	2S	1
dog	1O	1	broms	brake	2S	1
drill	2AS	1	cognac	brandy	1O	1
DVD	2AS	1	farfar	grandfather	1L	1
easy	1L	1	filt	rug	2AS	2
evening	1L	1	final	final	2AS	1
February	2S/2S	2	historia	history	1O	1
finally	2S	1	Indien	India	1L	2
finish	2S	1	kakao	cocoa	1L/1O	2
fire	2S	1	kalkon	turkey(bird)	1L	1
flower	1L	2	korv	sausage	2AS	1
give-it-a-try	1L	1	kväll	evening	2AS	1
helicopter	2AS	1	lördag	Saturday	1O	1
horrible	1L	1	modig	brave	2S	1
house	2S	2	modig	brave	1L	2
ice-skate	2S	1	partner	partner	2S	1
luck	1L	1	pommes frites	French fries	2S	1
responsibility	2S	1	rektor	headmaster	1L	2
silver	2S	1	rövare	robber	2AS	1
sing	2S	1	sambo	cohabitant	1L/2AS	2
strawberry	1L	1	service	service	2AS	1
strict	1L	1	soldat	soldier	2S	1
subtitles	2S	1	strut	cone	2AS	1
theatre	2AS	1	svamp	mushroom	2AS	1
Thursday	2AS	2	sylt	jam	1L	1
tree	2AS	1	tända	ignite	2AS	1
trophy	2S	1	välling	gruel	1L	1
wait	2S	1	varmare	hotter	1L	1
Wales	1O	1	verkstad	workshop	1O/2AS	2
work	2AS	1	yngre	younger	1L	1
worried	2S	1	yoghurt	yoghurt	1L	1

BSL: British Sign Language signs not lexicalised in SSL. **SSL:** Swedish Sigh Language signs not lexicalised in BSL. **Type of sign:** 1O – one handed sign not in contact with the body; 1L – one handed sign in contact with the body (including the non-dominant arm); 2S – symmetrical 2-handed sign, both hands active and with the same handshape; 2AS – asymmetrical 2-handed sign , one hand acts on the other hand; handshapes may be the same or different. **Parts:** 1 = 1 -part/1 syllable; 2 = 2-part /2 syllables.

Appendix 2. Non-signs.

Non-signs			
ID	**type**	**parts**	**odd feature(s)**
1	2AS	1	point of contact
4	1L	2	handshape change + higher second location
5	2AS	1	location
6	2S	1	2 different handshapes
7	2AS	1	point of contact
8	2S	1	orientation
9	2AS	1	location
12	2S	1	location
13	2S	1	handshape
14	1L	1	point of contact
15	2AS	1	handshape
17	1L	1	handshape, location + upward movement
21	1L	1	point of contact
23	1L	1	orientation change
24	1L	1	contralateral location
27	2S	1	location change
30	1L/1L/10	3	contralateral location, 3 distinct parts
34	2AS	1	point of contact + 2 different handshapes
36	1L	1	contralateral location on head
37	2AS	1	point of contact
39	1L	1	contralateral location on shoulder + orientation change
41	1L	1	location + handshape change
43	1L	1	location change
47	1L	1	point of contact
50	1L	1	low location, handshape change
51	1L	1	point of contact
52	1L	2	location + handshape change
53	1L	1	upward movement
54	1L	1	location
55	2S	1	point of contact
58	1L	1	point of contact
61	2S	1	two different handshapes + point of contact
62	1L	1	point of contact
64	2AS	1	point of contact
68	1L	2	handshape change
71	1L	2	location change, handshape change
73	1L	2	point of contact
81	1L	1	point of contact
83	1L	1	handshape change
85	1L	1	movement
89	2S	2	location change + upward movement
93	2S	1	change to different handshapes
96	2S	2	location change
98	1L	2	2 handshape changes
99	1L	2	handshape change + location change
102	1L	2	location change + upward movement
103	1L	2	location change + handshape change

Non-signs: sign-like items that are neither signs of BSL nor SSL, and violate phonotactic rules of both languages. **Type of sign:** 10 – one handed sign not in contact with the body; 1L – one handed sign in contact with the body (including the non-dominant arm); 2S – symmetrical 2-handed sign, both hands active and with the same handshape; 2AS – asymmetrical 2-handed sign , one hand acts on the other hand; handshapes may be same or different. **Parts:** 1 = 1 -part/1 syllable; 2 = 2-part /2 syllables; ; 3 = 3-part /3 syllables.