Short-Term Memory and Sign Languages. Sign Span and its Linguistic Implications*

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ABSTRACT: In this paper we discuss two distinct, although related questions. The first question is what explains the well-known fact that short-term memory (span) is lower for signs than for words. We review some explanations that have been proposed for this fact at the light of the results of a novel experiment involving gating of signs. The second question is how signers can process fully-fledged grammatical systems like sign languages even if they rely on a limited short-term memory. In order to deal with this issue, we discuss the distribution in sign languages of the configuration that is most challenging for short-term memory, namely center embedding. The conclusion is that center embedding is possible only if special strategies based on the use of space are used that are likely to reduce the short-term memory burden.

KEY-WORDS: Short-Term Memory, Sign Languages, Gating, Center Embedding, Relative Clauses, Role Shift.

1. Introduction

In the early days of generative grammar a very fruitful interaction developed between formal linguists and cognitive psychologists. A clear example of this interaction is the joint work by two founding figures in these two fields, namely Noam Chomsky and George Miller (cf. Miller & Chomsky, 1963).

This joint work was motivated by the observation that a distinguishing (possibly, a defining) property of natural languages is that they involve long distance dependencies, even if these are hard to process. One long distance dependency which we will explore, and that Miller & Chomsky (1963) first identified and studied, is center embedding, illustrated in (1):

(1) The politician who the journalist attacked is dishonest

Sentences like (1) are demanding for the syntactic parser (Gibson, 1998 for review), since the processing of the main sentence is interrupted by the intervening embedded clause (a relative clause in the case at hand). Intuitively, in order to successfully parse a sentence like (1), the listener (or the reader) has to maintain the information about the matrix subject (for example the fact that the NP 'the politician' is singular) in his/her memory buffer until (s)he meets the matrix verb. Crucially, this information must be retained while the parser is busy processing the embedded clause. While sentences like (1) are not too complex for healthy people in normal circumstances, they are much harder for special populations (crucially including patients with intact grammar but with short-term memory impairment, cf. Papagno et al. 2007) or even for healthy people if a virtual lesion is created in an area of the frontal cortex which is known to be recruited for short-term memory tasks (Romero Lauro et al., 2010, who applied repetitive Transcranial Magnetic Stimulation to left Brodmann area 44).

(1) is a sentence with a single level of center embedding. (2), which exemplifies a sentence with a double level of center embedding, shows that they are impossible or very hard to process even by healthy speakers under normal circumstances.

(2) The politician who the journalist who the judge met attacked is dishonest

A common view, which goes back to Miller & Chomsky (1963), is that a sentence like (2) is *not* ungrammatical, since the syntactic operation necessary to create it (roughly speaking, modification of the NP by a relative clause) is the same syntactic operation that is needed in (1), a fully grammatical (although somewhat difficult) sentence. What makes (2) impossible to parse is the overload on short-term memory. This is so because the matrix subject 'the politician' must be kept in the memory buffer until the matrix verb is met but this involves processing two embedded clauses, one nested into the other.

Processing factors interact with purely grammatical factors. For example, if object relatives, that are known to be syntactically complex structures, are replaced by subject relatives, which are easier, two levels of center embedding are more tolerable (although still challenging). (3) is an example.

(3) The politician who met the journalist who attacked the judge is dishonest

Two levels of center embedding become even more acceptable if certain conditions that alleviate the overload on short-term memory are met. For example, Gibson (1998) involved participants in a complexity rating task and found that (4a) is judged easier than (4b). According to Gibson, this is due to the fact the referent of the indexical pronoun 'I' is always present in the context of utterance, which includes speaker and hearer by definition. Therefore this pronoun never adds a discourse referent to be maintained in the memory buffer while the sentence is processed.

(4) a. The student who the professor who I collaborated with had advised copied the article

b. The student who the professor who Jen collaborated with had advised copied the article (from Gibson, 1998: 17-18)

In languages like English the main syntactic configuration where center embedding is observed is relativization, as shown in the examples considered up to now. However in languages with SOV order also complement clauses can be center embedded in the medial position between the matrix subject and the matrix verb. Also in this case while a single level of center embedding is easily tolerated by the general population, two levels become very hard to process.

An issue that we will thoroughly discuss in this paper is center embedding in sign languages, especially those with a preferential SOV order. The reason to investigate this issue is the following. It is known that there is a close equivalence of structure between short-term memory for signed and spoken languages (cf. Wilson & Emmorey, 1997a, 1998). However, everything else being equal, short-term memory for signs is lower than short-term memory for words, a result replicated by now by many research groups for several sign language / spoken language pairs. Given this scenario, two questions arise. First: why is short-term memory for signs lower? Second: how can signers process sign languages, which are fully-fledged grammatical systems (as 40 years of research have indisputably shown), given that they rely on a limited short-term memory?

As for the first question, after reviewing some answers that have been given in the literature, we will discuss some new findings from a gating study which contribute some interesting (yet indirect) evidence. Our temporary conclusion is that signs are harder to retain because they are units of information denser and heavier than words.

As for the second question, we will critically re-examine Cecchetto, Geraci & Zucchi's (2006) claim that sign languages are creatively responding to the challenge induced by a limited short-term memory capacity by building on those grammatical options that are allowed by Universal Grammar and impose little memory overload. To sustain this claim they discussed the two configurations that are typically associated with center embedding in SOV languages, namely relativization and complement clauses. They focused on LIS (Italian Sign Language), a language with a SOV order, and showed that LIS has both complementation and relativization structures but crucially they never involve center embedding (see below for some qualification, though). Given this scenario they conjectured that center embedding (even a single level of center embedding, which is usually easily tolerated in spoken languages) might be altogether banned in sign languages.

In this paper we will reconsider this hypothesis in the light of several papers that have been published in the meantime on this topic. Our conclusion will be that, although the strong version of this hypothesis is wrong (there are indeed cases of center embedding in sign languages, including LIS), the underlying intuition was on the right track, since in the few attested cases when center embedding is possible there are special strategies based on the use of space that do reduce the short-term memory burden.

This paper is organized as follows: section 2 briefly summarizes the literature on short-term memory for signs. In section 3 we report a new gating study and comment on its relevance for the debate about the low sign span. Section 4 focuses on center embedding and more generally on the strategies used by sign languages to deal with short-term memory limitation. Section 5 concludes the paper.

2. Short-term memory for signs and words

In this section we briefly review the existing body of knowledge on short-term memory for signs. We start from words because this allows us to make a comparison between language in the two modalities.

2.1 Short-term memory for words

Much work on short-term memory adopts the well-established framework of working memory proposed by Baddeley & Hitch (1974, 1994). In Baddeley & Hitch's model three components are involved: two separate sub-systems that are devoted to retain information in the acoustic and visual modalities (the phonological short-term memory and the visuo-spatial sketchpad, respectively) and a control system (the central executive). Here we focus on the phonological short-term memory system, which includes two components: a phonological store, where phonological information is retained, and a mechanism of rehearsal, capable of refreshing the phonological trace in the store, preventing or delaying its decay. The role of rehearsal can be informally illustrated by a typical task involving phonological short-term memory, namely remembering a phone number or a shopping list: continuous repetition is a common strategy to maintain in memory these items which would otherwise be lost.

The capacity of the phonological short-term memory is measured by asking participants to repeat lists of unrelated items (e.g. digits, words, pseudo-words, letters, nameable pictures) in the same order as they were presented. The number of items increases progressively and span is defined as the longest sequence in which recall is correct. The span is influenced (among others) by the following effects:

- Phonological similarity effect: lists of words that are phonologically similar ('man', 'mad', 'cap', 'tap') elicit a lower span than lists of phonologically different words ('bit', 'cue', 'bus', 'day'). The phonological similarity effect is due to the fact that two similar words may become indistinguishable when their phonological trace decays.
- Word length effect: lists of long words ('telephone', 'protocol', 'library') elicit a lower span than lists of short words ('spy', 'dog', 'cap'). The word length effect is due to the longer amount of time needed to rehearse polysyllabic words.
- Articulatory suppression effect: the span is reduced when participants are asked to articulate an irrelevant syllable (e.g. ba, ba, ba) during stimulus presentation. The articulatory suppression effect is due to the fact that rehearsal of the items to be remembered is impossible because the articulatory system is involved in producing the irrelevant syllable.

Interesting discoveries about the phonological short-term memory system come from the interaction between the previous effects. For example, if the stimuli to be repeated presented in written form, articulatory suppression eliminates the phonological similarity effect, meaning that under articulatory suppression similar and dissimilar words are remembered equally bad. However, if the stimuli are auditorily presented, articulatory suppression does *not* eliminate the phonological similarity effect, meaning that even under articulatory suppression lists of similar words remain harder to remember than lists of dissimilar words. On the other hand, articulatory suppression disrupts the length effect regardless of whether the stimuli are presented orally or in a written form.

We cannot discuss here the source of the interactions between the three effects (cf. the literature quoted above). Suffice it to say that these effects and their interaction have steadily been replicated and are considered a hallmark of the short-term memory system for words.

2.2 When short-term memory for signs and words is alike

Since sign languages are encoded in the visuo-gestural modality, one might expect retention of sign material *not* to involve the phonological short-term memory. If so, phenomena observed for spoken languages might not find a direct correspondence in sign languages and sign retention might show properties typical of visuo-spatial short-term memory. However, clear evidence has accumulated showing that that the architecture of short-term memory for signs closely resembles the architecture proposed for spoken languages. In particular, a number of studies on American Sign Language (ASL) found systematic evidence for the phonological similarity effect (Wilson & Emmorey, 1997b and Klima & Bellugi, 1979 for an early report) and the word length effect (Wilson & Emmorey, 1998). Furthermore, the length effect interacts with articulatory suppression in a way similar to that observed for spoken language, namely under articulatory suppression lists of long and of short signs are remembered at the same (low) level. Another similarity is that the phonological similarity effect is not eliminated by articulatory suppression when the stimuli are lists of signs but it is cancelled when the stimuli are lists of namable pictures (Wilson and Emmorey induced articulatory suppression by asking participants to open and close their fists during visual presentation of the signs). This finding is parallel to the one mentioned for spoken languages, with the difference that written words are replaced by nameable pictures, as sign languages do not have a written form.

Capitalizing on these findings, Wilson & Emmorey (1997b) argue that the same short-term memory mechanism (storage and rehearsal) underlies retention of auditory and signed linguistic items. They conclude that phonological short-term memory is not an exclusive domain of the auditory modality but emerges as an a-modal mechanism, triggered by language in any modality.

2.3 When short-term memory for signs and words is different

Despite striking similarities in phonological short-term memory for words and signs, an important difference remains, namely the sign span is smaller than the word span. The difference has been replicated many times with different stimuli (digits, finger spelled letters and words/signs) and with different populations (deaf signers compared to hearing speakers and hearing bilinguals tested with both sign and spoken language material) and with several sign languages (ASL: Bellugi, Klima & Siple, 1975, Boutla et al., 2004, Bavelier et al., 2008; Auslan: Logan, Mayberry & Fletcher, 1996; Swedish Sign Language: Rönnberg, Rudner & Ingvar, 2004; LIS: Geraci et al., 2008).

As an example we report here the figures emerging from Geraci et al.'s experiment. Hearing Italians naive to LIS were tested with the sequences of words that were the translation of the sequences of signs used with Deaf LIS signers. LIS signs and Italian words were matched for length (measured as time of articulation). The mean span for auditorily presented words was 4.94 (SD = 1.06, range 4-7) while the mean sign span for deaf participants was 3.31 (SD = 0.48, range 3-4). This difference is very robust even if signs and words were equally long.

Of course results like this one raise the interesting question of why it is so. What makes lists of signs more difficult to repeat than lists of words? Pinpointing the relevant factors is not easy and a number of non-mutually incompatible explanations have been proposed. Some possibilities that have been proposed over the years do not seem very promising now in the light of current knowledge. We mention three.

A first hypothesis is that deafness per se is the cause of a lower memory performance. However, we can exclude this, since hearing signers pattern with deaf signers when they are tested with signs, while they pattern with hearing non-signers when they are tested with words. Furthermore, deaf signers outperform hearing non-signers in other memory tasks, like the Corsi span task (Geraci et al., 2008). Therefore deafness per se does not have a general detrimental effect on short-term memory.

Another hypothesis that has been advanced (Klima & Bellugi 1979) is that the sign span is lower because on average signs take longer to be articulated than words. If so, the low sign span would be due to a generalized length effect. This hypothesis is made unlikely by the fact that the sign span remains low even if time of articulation is matched between signs and words (cf. Geraci et al., 2008).

A third hypothesis is that the sign span is low because the information about the four formational parameters of the sign (handshape, location, movement and palm orientation) is presented simultaneously and simultaneous information might not well suited for a *serial* recall task. This hypothesis makes the prediction that free recall of signs should be as good as free recall of words. However, Alba (2016) replicates the word advantage in a free recall task. Therefore, it is unlikely that this explanation suffices to explain the low sign span.

We mention now three possible explanations that seem to be more promising.

The first one is that auditory and visual information decays at different rates: while echoic (auditory) memory lasts 2-4s (Darwin, Turvey & Crowder, 1972), iconic (visual) memory lasts 1s at the most (Sperling, 1960). Although the decaying can be compensated by articulatory rehearsal, this basic difference might still play a role.

The second explanation, advanced by Marshall, Mann & Morgan (2011), is that signs are harder to retain because there are very few restrictions on the constructions of signs. For example, in principle each handshape can occur with each location. This makes the inventory of phonological components that can be combined in a single sign larger than the inventory of phonological components that can be combined in a single word. This bigger freedom comes with a cost when signs have to be retained.

The third explanation is that signs are harder to retain because they are intrinsically heavier, since even the simplest syllable requires the signer to process information about the four formational parameters of a sign, while the syllable in a spoken languages can be light (cf. Brentari 2012).

In the next section we describe an experiment that gives (admittedly indirect) evidence in favor of the third explanation over the second one and hints at a further possible cause for the low sign span.

3. A gating study

The gating technique consists in presenting a word or a sign not from the onset to the end, but at different intermediary stages. A word or sign is stopped several times during its articulation and participants are asked to guess the meaning after each stop. Over the last decades, this experimental methodology has been used to investigate both word recognition (Grosjean, 1980, Frauenfelder & Tyler, 1987, Lindfield, Wingfield & Goodglass, 1999) and sign recognition (Grosjean, 1981, Clark & Grosjean, 1982, and

Emmorey & Corina, 1990). Earlier findings on American Sign Language (ASL) showed that signs are recognized earlier than words. Emmorey & Corina (1990:1241) claim that this is due "to the ASL phonotactics and to the early availability of phonological parameters in the sign signal."

3.1 Methods

3.1.1 Participants

For our gating study, eighteen deaf signers (mean age: 26.4, SD = 4.7; eight women and ten men) were recruited through a counselor in the Turin Institute for the Deaf. Twelve participants were born to deaf parents and have been exposed to LIS since birth (native signers), while six participants (non-native signers) were born to hearing parents and were exposed to LIS later (during high school or college). All signers resided in Turin or in the surrounding areas and were in contact with the local Deaf community. They all had normal or correct to normal vision and none of them had any associated disability or further sensory deficits. All participants signed informed consent forms prior to participating and were remunerated for their participation.

3.1.2 Materials and procedure

The stimuli used during the experiment are 40 LIS signs recorded by a Deaf signer. Following a criterion for material selection adopted by Emmorey & Corina (1990), each sign is a member of a minimal pair (five minimal pairs for each of the four formational parameter, namely handshape, movement, location, and palm orientation). Lexical neighborhood of these signs was not controlled for, since there is no comprehensive dictionary for the variety of LIS used in Turin.

Our linguistic consultant worked in strict collaboration with Deaf signers in Turin to choose LIS signs that were supposedly familiar to the Deaf people living in the city. Each sign has been produced in front of a digital camera in a spontaneous way, at normal speed, and in isolation. Afterwards, the video clips have been segmented into frames (1 frame corresponds to 41.67 ms).

In order to construct the gating experiment, we had to decide where to stop the sign. In previous gating studies (cf. Emmorey & Corina, 1990) a sign was presented frame by frame and the participant was asked to guess the meaning of the sign after each interruption. However this procedure may become tiring for the participant and may affect his/her performance. Therefore we decided to select only three stops for each sign. Ideally, the first stop should coincide with the beginning of the sign, the second stop with the middle of the sign and the third stop with the sign end. However, the issue of deciding when a sign starts is tricky. As extensively discussed by Jantunen (2015), under a phonological perspective (which is reflected in the way in which signs are identified and annotated in dictionaries and corpora), the beginning of the sign is when the place of articulation is reached by the hand(s) *and* the movement of the sign starts (this convention excludes any transitional movement from the preceding to the following sign). However, under a phonetic perspective, the situation is different. It is fairly uncontroversial that the beginning of a word is determined by the first occurrence of any articulatory feature associated with the word. However, as stressed by Jantunen, transposing this perspective to signs has non-trivial consequences, since the phonetic beginning of a sign may end up preceding its phonological beginning by many frames. The reason is that the articulatory features of handshape and orientation are often present before the hand reaches the place of articulation of the sign (under this perspective, a portion of transitional movement can be part of the sign).

Given this complex situation, we decided to adopt two different segmentations. According to the first segmentation (which corresponds to the phonological perspective summarized above), the first stop corresponds to the frame in which the hand(s) realize(s) the target handshape and reach(es) the place of articulation. The third stop coincides with the frame in which the hand(s) drop(s) the target handshape. The exact frames corresponding to the first and third stop have been identified by our consultant. As for the second stop, it has been mathematically determined by calculating the midpoint (i.e. the frame in the middle between first and third stop).

According to the second segmentation (which is closer to the phonetic perspective summarized above), the first stop coincides with the boundary between the end of the transition movement and the beginning of the (movement of the) sign. In some cases, the two types of segmentation (almost) overlap; in other cases the discrepancy is bigger. We decided to proceed as follows: for the experiment construction we considered the first segmentation (first frame with the target handshape in the place of articulation). Thus, the actual videos were interrupted at this frame.

However, for the quantitative analysis we considered only those signs for which there is no big discrepancy between the two possible types of segmentation (i.e. discrepancy is not larger than 4 frames).[1] To illustrate how the two types of segmentation can differ from each other, we briefly discuss a representative case, namely the sign HEART. This sign is realized by moving the open hand with bent middle finger towards the signer's chest. This movement is repeated so that the middle finger touches the chest twice. According to the first segmentation (cf. *Figure 1*), the first stop corresponds to the frame in which the middle finger actually reaches the place of articulation of the sign (i.e. touches the chest for the first time). However, according to the second segmentation (*Figure 2*), the first stop occurs earlier, because it occurs at the frame in which the transition movement ends and the hand starts moving towards the chest. As HEART is a case in which the difference between the two types of segmentation is bigger than 4 frames, it is among the pool of signs that are *not* considered in the analysis.

 

FIGURE 1 – First stop for the sign HEART according to the first segmentation.
FIGURE 2 - First stop for the sign HEART according to the second segmentation.

[1] The list of signs for which there is consensus between the two coders is reported in the appendix (English and Italian glosses).

The experiment was run using E-Prime2 software (Psychology Software Tools, Pittsburgh, PA) on a laptop computer. Participants were tested individually in a bright room at the Deaf Institute of Turin. Before starting the test, each participant watched a video in which instructions on the procedure were provided directly in LIS. The experiment proceeded as follows: participants were shown a sign from the beginning to the first stop and were asked to try to identify the sign accordingly. If their answer was correct, the experiment moved on to the following sign. In case of wrong answer or no answer, participants were shown the non-identified sign from the beginning to the second stop. If the participant failed to identify the sign for the second time, the sign was shown from the beginning to the third and last stop. In our experiments, unlike some previous gating studies, participants were not asked to rate the confidence of their answer.

At the end of the experiment, each participant was asked to give a feedback and whether (s)he was familiar with the signs used in the experiment.

3.2 Results

One sign, GAS, was removed from the analysis because it was not recognized by most of the participants (15/18). Probably this is due to diachronic variation: the Deaf signer that was consulted for stimuli selection was older than the actual participants in the experiment and the lexical entry for the sign GAS used by young Deaf people in Turin is another one.

All analyses were performed using R software (R Development Core Team. 2010). Quantitative analysis was performed by means of regression models. The R package lme4 (Bates & Maechler, 2010) was used for mixed-effects models. In order to evaluate the inclusion of fixed effects in the model we used likelihood ratio tests: we included an effect only if it significantly increased the model goodness of fit (Gelman & Hill, 2006).

All the regression models included a by-subjects and a by-items random intercept to account for participant-specific variability and for item-specific idiosyncrasies. We will report p-values related to the best fitted model. Firstly, we counted for each sign if lexical identification occurred at the first, second, third stop, or none of them.

Table ***1*** represents the percentages of signs lexically identified at the first, second or third stop, or non-identified signs (Stop = 0) for native (N = 13) and non-native (N = 5) signers.

TABLE 1: Percentages (mean and standard deviations) of signs lexically identified at the different stops (0 = not identified).

		Native	Non-native
Stop	1	82 (38)	55 (50)
	2	15 (36)	30 (46)
	3	2 (13)	10 (29)
	0	1 (1)	5 (21)

Most of the signs were identified at the first stop and this is true for both native and non-native signers, although the percentage of signs identified at the first stop is markedly higher in the group of native signers (82% vs. 55%). On the contrary, the percentage of signs identified at the second stop is higher in the non-native group than in the native group (30% vs. 15%). The percentage of signs identified at the third stop in the native group is smaller than in the non-native group (2% and 10%, respectively). The percentage of non-identified signs is small in both groups (1% native, 5% non-native). The descriptive analysis suggests that overall signs are early identified, although early identification is more salient for native than non-native signers.

This was confirmed by regression analysis. Accuracy was our dependent variable, Group (Native vs. Non-native) and Stop (1 vs. 2, 3) the evaluated fixed effects. The best fitting-model was the full model with Stop and Group and interaction among them ($\chi^2(3) = 49.066$, $p < .0001$).

As previously described, our stimuli were elicited in a very naturalistic way, asking a Deaf signer to sign a list of words as spontaneously as possible. When analyzing our data, we noticed that in some clips, but not in others, some mouthing was present at the first stop. We decided therefore to analyze whether the presence of mouthing played a role. Adding the interaction with the factor Mouthing (yes/no) significantly increased the model goodness of fit ($\chi^2(6) = 30.117$, $p < .0001$). The Mouthing effect is clearly observable in *Table **2***, that shows the influence of mouthing on early identification (i.e., identification at the first stop).

TABLE 2: Percentages (mean and standard deviations) of signs lexically identified at the first stop if Mouthing was present (yes) or not (no) before the first stop. Difference between native and non-native signers.

	Native	Non-native
Mouthing: yes	90 (30)	64 (49)
Mouthing: no	76 (43)	47 (50)

Finally, we list all the signs identified at the Stop 2 or at the Stop 3, counting how many participants identified them at those late stops (see *Table **3***). The purpose of this list is to observe which signs were more often late identified, and to propose possible explanations.

TABLE 3: List of the signs identified at the II or III stop and N of participants who identified those signs "late"

Native (N = 13)		Non-native (N = 5)	
Sign	N of participants	Sign	N of participants
GRATIS	13	GRATIS	5
ITALY	6	WATER	4
FOOL	5	POLITE	4
PATATA	4	FIAT	3
POTATO	4	ITALY	3
FIAT	3	POSSIBLE	3
HARD	2	MAIL	3
POLITE	2	UGLY	2
SPEAK	2	FOOL	2
WATER	1	GLASSES	2

KNOW	1	SPEAK	2
GLASSES	1	POTATO	2
MAIL	1	UNCLE	2
IDIOT	1	GOOD	1
		HARD	1
		TRY	1
		IDIOT	1
		SCHOOL	1

The qualitative explanations we propose to account for the problems in identification reported in *Table **3*** take into consideration only the most frequently non-identified signs, since the uncommon errors may well be due to mere distraction. The main factors that we think may be responsible for late sign recognition are:

i. handshape change. Signs involving the change of handshape from one configuration to another, like the item GRATIS in which the fist is followed by the extended forefinger, are harder to be recognized at the first stop because at that point only the first handshape is shown.[2]

ii. manual and non-manual similarities. For example, the item POTATO is very similar to the sign FATHER both in the manual realization and in the mouthing (at the first stop, POTATO (it. PATATA) is realized with 'pa' mouthing, which is fully compatible with FATHER (it. PAPÀ)'s mouthing;

iii. diachronic change. The items ITALY and FIAT are used in the Turin area mostly by middle-aged and old signers and therefore are less accessible to our young participants;

iv. limitations of bidimensional stimuli. In some cases, early sign

[2] GRATIS is very similar to the sign FORGET, except for the second handshape (in FORGET the fist is followed by the open 5 handshape). At Stop 1, all participants responded FORGET. In contrast to Emmorey & Corina's study (1990), in which handshape change did not delay sign recognition, our study shows that handshape change does exert a delayed effect. Probably, incomplete phonetic information led to choices based on lexical frequencies (FORGET is likely to be more frequent than GRATIS).

recognition might be difficult because of the lack of depth cues in video clips. For example, the item FOOL requires extended forefinger and middle finger but on the screen only one extended finger is clearly visible.

Focusing on the non-native signers, we identified a couple of specific motivations that might play a role in this group, namely:

i. lack of access to the full repertoire of variant forms. For example, the sign WATER is usually realized in Turin through two distinct variant forms. The proposed item WATER was not early recognized by non-native learners probably because they were more acquainted with the other variant form;

ii. lack of mouthing. Those signs in which no mouthing can be detected at the first stop, like POLITE, are likely to be harder for non-native signers (see also *Table 2* and relative analysis).

3.3 Discussion of the results of the gating study

Although there are differences in the experimental settings that do not allow a direct comparison between the different studies, our experiment with LIS signs is in line with Emmorey & Corina's (1990) and Grosjean's (1981) main finding, namely sign recognition is very early. Emmorey and Corina found that on average signers were able to identify a monomorphemic sign after seeing 34% of it. In our study, most signs were identified at the first stop and virtually all signs were identified at the second stop. These results suggest a difference between spoken and sign languages, since gating studies indicate a later point of recognition for words in isolation (cf. Grosjean 1981).

That a very small part of a sign may suffice for lexical recognition is confirmed by two other studies, performed by Arendsen, van Doorn & de Ridder (2009) and by Holt *et al*. (2009). Although these were not gating studies, experimental procedures to identify the moment of sign recognition were used. These studies confirm that the meaning of the sign may be recognized by participants very early on, even during the phase when the hands move from rest position to place of articulation, namely before the hands perform the sign *strictu sensu*.

In a sense, the picture emerging from all these experimental works is far from surprising. Sign morphology is simultaneous, with the information about all four parameters being available from the very beginning. Furthermore, the information about some parameter (handshape and palm orientation) may be available even before the hand reaches the place of articulation of the sign, as we have seen with the LIS sign HEART (see section 3.1.2.). On the other hand, word morphology is concatenative, so the morphological structure becomes available step by step (or morpheme by morpheme) during word articulation.

Still, the gating experiment provides some interesting evidence about the debate on the source of the low sign span. First, the result about very early sign recognition is somewhat at odds with Marshall, Mann & Morgan's (2011) explanation for the low sign span in terms of a larger number of combinatorial possibilities for sign sub-units than for word sub-units. At least prima facie, that explanation would not predict earlier sign recognition, since more combinatorial possibilities mean that at any given stage there should be a large number of possible continuations among which the signer has to choose.

Quite to the contrary, however, it seems that in actual processing signers have ways to identify a sign early on, independently from abstract combinatorial metrics.

The alternative explanation in terms of heaviness of the sign seems to be more consistent with the finding emerging from the gating studies. A sign transmits much information in very few milliseconds, as the information concerning the four parameters is presented simultaneously. It is plausible that this density of information makes sign recognition quicker but makes sign decay quicker as well, given the limited capacity of the phonological store. A related factor might be that a sign may access the phonological store even before it has been completely articulated (or even before the hand reaches the articulation point). In combination with the fact that echoic (auditory) memory lasts longer than iconic (visual) memory, this might contribute to explain why sign retention is hard: the sooner an item enters the phonological store, the earlier the process of decay starts. The decaying process is alleviated by articulatory rehearsal, but probably rehearsal cannot compensate the initial disadvantage for signs.

In this section, we have reported and commented on a gating study. We have hypothesized that signs might be harder to retain for the same reasons that makes them quicker to detect.

4. Ways of coping with limited short-term memory

In this section we go back to the question we have already introduced: how can signers process the complex structures of sign languages in presence of a low sign span?[3]

4.1 The basic hypothesis: a link between sign language grammar and low sign span

As mentioned in the introduction, Cecchetto, Geraci & Zucchi (2006) suggested a direct link between the low sign span and certain aspects of sign language grammar. First, sign languages use space to express a series of grammatical information (agreement, tense, aspect, etc.) which many spoken languages express using morphological affixation and/or function words. The use of spatial relations might be a strategy to reduce the number of concatenative morphemes and/or independent signs (word-like elements) in a signed sentence. As the sentence is composed of fewer (and/or shorter) signs, the load on the impoverished short-term memory system is reduced.

Second, Cecchetto, Geraci & Zucchi (2006) showed how the grammatical constructions that require center embedding in English or Italian can be expressed without center embedding in LIS and went so far as to speculate that center embedding might be altogether banned in sign languages.

Before critically re-examining these claims, a distinction should be drawn between two different ways in which processing factors may influence grammar in general. A first possibility is that a given language internalizes processing preferences as specific grammatical rules (cf. Hawkins, 2004 for discussion of this hypothesis). If so, the usual grammatical *vs.* ungrammatical pattern arises, with the result that grammatical constructions that are more costly for parsing become ungrammatical. Adopting this perspective,

[3] David Caplan and collaborators (cf. Caplan & Waters 1999) have proposed over the years that short-term memory as measured by standard tests, such as the word span test, is not involved in language processing, which instead would rely on a separate short-term memory system. For a summary of the arguments against this ultra-modular view see Cecchetto & Papagno (2011).

one might hypothesize that there is a grammatical rule that blocks center embedding altogether in sign languages, since this configuration exceeds their processing resources. For example, an embedded clause does not occupies a center embedded position in any point of the syntactic derivation but is base generated directly in the right or left periphery of the matrix clause and is linked to the matrix verb by some anaphoric link. Under this view, the difference between production and comprehension is not really crucial, because the problematic configuration for comprehension cannot be created to begin with.

However, there is a second way to interpret the presence of processing pressures on grammar, namely one might assume that, whenever a particular configuration arises that is very hard to process, a further operation replaces the problematic configuration with another which is easier to process. Adopting this perspective, center embedding is not banned by a grammatical rule, much like sentence (2) is *not* banned by a grammatical rule. Under this second perspective, sentences involving center embedding are not produced by signers because they cannot be parsed, although in principle they are compatible with the grammatical rules of the language. Let us make a concrete example for sake of explicitness: no grammatical rule would block base generation of finite clauses or relative clauses in a center embedded position. However they cannot stay there, due to a processing overload. Therefore they must be left or right dislocated. In this view, it is comprehension that is ultimately responsible for the fact that certain configurations do not surface in a given language.

It is useful to keep in mind the distinction between these two perspectives while we describe the pattern of center embedding in sign languages.

4.2 When center embedding is not allowed

The first piece of evidence discussed by Cecchetto, Geraci & Zucchi (2006) and showing that center embedding is not allowed in LIS is clausal complementation. LIS has been described as an SOV language, as shown in (5).

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(5) PIERO CONTRACT SIGN DONE[4]
'Piero signed the contract'

However if the complement is a finite clause, the SOV order is sharply ungrammatical:

(6) * GIANNI PIERO CONTRACT SIGN KNOW
Intended meaning "Gianni knows that Piero signed the contract"

Clausal complementation is possible only if the finite clause is either left (7) or right (8) dislocated:

(7) PIERO CONTRACT SIGN GIANNI KNOW
(8) GIANNI KNOW PIERO CONTRACT SIGN
'Gianni knows that Piero signed the contract'

The second piece of evidence is relative clauses. LIS has a productive relativization structure that is exemplified in (9). In (9) the relative BOY CALL PE, which is co-articulated with a specific non-manual-marking (raised eyebrows), precedes the main clause (the matrix subject can be null, as LIS is a pro-drop language). The relative clause contains a manual sign, glossed here as PE, that agrees with the matrix subject, namely they are articulated in the same point of the signing space. Crucially, the PE-clause can never be center embedded (the pointing sign IX, when present, is articulated in the same position where the sign BOY and PE are articulated).[5]

raised eyebrows
(9)BOY$_i$ CALL PE$_i$ (IX$_i$)LEAVE DONE
'The boy who called left'

This was the state of the knowledge in 2006. However later work shows that, although they are rare or require very special conditions, center

[4] DONE is an aspectual auxiliary which occurs in a postverbal position (cf. Zucchi 2009)

[5] Two analyses have been proposed to account for this pattern. Either relative clauses in LIS are similar to correlatives of the Hindi type (Cecchetto, Geraci & Zucchi 2006) or they are internally headed relatives that are base generated in the center embedded position and moved to the left periphery of the main clause (cf. Branchini & Donati 2009).

embedded relatives and center embedded complement clauses can be found. Let us have a look at some relevant constructions.

4.3 When center embedding *is* allowed

Geraci, Cecchetto & Zucchi (2008) have shown that center embedding is possible if the embedded clause is an infinitival clause selected by a control verb. Geraci (2014) shows that the infinitival clause selected by the raising verb SEEM can also be center embedded in LIS. These cases of center embedding, although interesting, are not particularly challenging for the hypothesis that links the absence of center embedding to the reduced sign span. Infinitival clauses are reduced structures, because they do not project the entire functional layer. Therefore, it is not surprising that a reduced structure is allowed in a position where a richer structure (a finite clause) is not.

However, other cases are more challenging because they suggest that even finite clauses can be center embedded. We discuss here two representative cases from the literature (but see Geraci & Aristodemo 2016 for more examples and a more detailed description of the LIS pattern).

Pfau & Steinbach (2005) analyze relativization in DGS, a language which shares with LIS the property of being SOV. An SOV sentence in DGS is shown in (10). A few words on the notational conventions used in (10) are in order. IX_1 is a first person pronoun (a pointing sign towards the signer body). As the sign MAN is articulated on the body in DGS, the pointing sign IX is used to assign to it a locus in the neutral space (the neutral space is the area in front of the signer where non body-anchored signs are articulated). This locus can be used for anaphoric dependencies involving MAN. KNOW in DGS is a plain verb, namely it is lexically specified for a place of articulation on the body. Plain verbs can combine with the agreement marker PAM. In (10) PAM, as indicated by the indexes, is articulated from the position in space associated to the subject (the first person pronoun) to the position in space associated to the direct object (MAN).

(10) IX_1 [MAN IX_3] KNOW $_1PAM_3$
'I know this man'
[DGS, adapted from Pfau & Steinbach 2005: 516]

Like LIS, complement clauses are not allowed in center embedded positions in DGS (cf. the ungrammaticality of 11a). In fact, the sentence becomes grammatical only if the embedded clause is dislocated (cf. 11b). As indicated by the indexes, the verb HELP is an agreement verb in DGS, namely is articulated from the position of the subject to the intended position of the direct object.

(11) a. *IX_3 [IX_2 $_2HELP_3$ MUST] SAY
b. IX_3 SAY [IX_2 $_2HELP_3$ MUST]
'He says that you must help him'
[DGS adapted from Pfau & Steinbach, 2005: 516]

In this respect DGS is similar to LIS. However, Pfau & Steinbach (2005) observe that relative clauses can appear in center embedded position (although this is by no means the favored option). An example of center embedded relative in DGS is in (12).

(12) [$_{DP}$ WOMAN [$_{CP}$RPRO-H_{3a} MAN IX_{3b} $_{3a}HELP_{3b}$]] $KNOW_{3a}PAM_1$
'The woman who is helping the man knows me'
[DGS adapted from Pfau & Steinbach, 2005: 515]

Pfau and Steinbach (2005) explain that the sign WOMAN (which is body anchored) is assigned a locus by means of the sign RPRO-H_{3a}. In their analysis, the sequence bracketed CP in (12) is an externally headed relative adjoined to the external head WOMAN, much like its English (or German) counterpart. (12) is a clear counterexample to the claim that center embedding is never allowed in sign languages. Still, suppose momentarily and for the sake of the argument, that in the general case it is correct to say that center embedding in sign languages is blocked because of the reduced sign span. In the case of (12), this would mean that the phonological trace of the matrix subject WOMAN should have already effaced by the moment it must be related to the main verb. But then, why can a signer parse (12) after all? A possible answer is that the signer is helped by the fact that the locus the sign WOMAN is associated to gets activated three times during sentence articulation and this prevents the information associated to the noun WOMAN from decaying. This locus (indicated by the subscript 3a) is first fixed by the relative pronoun RPRO-H_{3a}, then it is used by the agreement verb HELP and it is finally re-activated by PAM. Informally speaking, if the sentence receiver has any doubt on how to retrieve the matrix subject, PAM does the job for him/her. Notice furthermore, that the internal argument of the matrix verb is first person. Remember from our discussion in section 1 that in spoken language a double level of center embedding becomes more tolerable when one argument is realized by a first or second person indexical pronoun. The combination of these two factors might make (12) easier to process. Of course this makes predictions. For example, center embedding should become harder or impossible if PAM is absent in a sentence like (12). We cannot test this prediction for this paper. A related prediction is that languages lacking the equivalent of PAM should be more in trouble with center embedding than DGS. LIS, which indeed lacks PAM, seems to exemplify this.[6]

Our explanation for why (12) can be processed despite its level of complexity is inspired by Geraci & Aristodemo (2016), who show that center embedding becomes possible even with finite clauses under special circumstances that crucially involve a grammatical use of the neutral space. They analyze a very intriguing pattern that involves role shift. Roughly speaking, role shift is a construction in which the signer reports another person's speech or thought by adopting that person's perspective. Morpho-syntactically, role shift typically involves body shift towards the locus in neutral space associated to the person whose perspective is adopted. This type of role shift may be seen as functionally equivalent to direct speech in spoken languages, although role shift can be used in many more contexts than direct speech is.

Geraci and Aristodemo show that center embedding of a finite complement clause becomes available in LIS if role shift applies (cf. Quer 2012 who, in his description of clausal complementation in LSC, made for the first time the observation that role shift makes center embedding available in contexts in which it would be otherwise not allowed).

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[6] By strictly applying the logic in the text one might expect languages like LIS to allow a center embedded relative when the matrix verb is an agreement verb and its direct object is a first or second person personal pronoun. This does not seem to be the case for LIS, which has only relatives in the left periphery of the main clause but more research is needed.

The effect of role shift on center embedding is illustrated in (13), which has a reading with indexical shifting (13 has also another reading not directly relevant for our discussion). Indexical shifting is a well attested effect of role shift by which a first person pronoun does not refer to the signer but to the person whose perspective is adopted (here the first person pronoun is interpreted as the person who is warning, namely Valentina). The non-manual-marking glossed as "role shift" indicates that the relevant portion of the sentence is articulated while the signer shifts his/her body towards the locus associated to the matrix subject (VALENTINA).

(13) $\overline{\text{VALENTINA IX-3}_{\text{Valentina}}}^{\text{topic}}$ $\overline{\text{[IX-1 ARRIVE LATE]}}^{\text{role shift}}$
WARN
'Valentina warned (everybody) that she$_{\text{Valentina}}$ was late.'
[adapted from Geraci & Aristodemo, 2016:110]

As Geraci & Aristodemo (2016) stress, the role of space is crucial in allowing center embedding. For example, in (13) the main verb WARN is actually articulated while the signer has shifted his/her body in the position in space associated to the matrix subject. This is likely to facilitate the matrix subject retrieval, which is the challenging property of center embedding.

Despite the differences between the two cases, a single hypothesis might explain the patterns in (12) and (13). In both cases, matrix subject retrieval is possible because the subject is anchored to a locus which is continuously referred to during sentence processing, so the information about the matrix subject does not decay.

If this hypothesis is on the right track, this is an indication that the signer might complement the purely phonological memory system (which is the counterpart of phonological short-term memory and has the limitation we described in section 2) with a more spatially based memory code. In doing so, the signer might take advantage of the double nature of sign language, linguistic but also spatially anchored.

After this discussion, we can briefly go back to a point we raised in section 4.1. We observed that there are two ways of conceiving the effect of parsing on grammar. According to a first hypothesis, the effect is more pervasive since grammar is shaped directly by parsing, to the extent that there are grammatical rules that block the creation of hard to process configurations to begin with. According to a second hypothesis, grammar is sensitive to parsing, but only in the sense that it contains operations that systematically replace the hard to process configurations with simpler ones (say by operations like left or right dislocation). We can now conclude that examples like (12) and (13) just discussed speak in favor of the second (weaker) hypothesis.

5. Conclusion

In the first part of this paper, we have reviewed the existing literature on short-term memory for signs and have reported the results of a new gating experiment that suggests that a very high density of information is concentrated in a sign, starting from its very onset. We speculated that while this may favor sign recognition, it may hinder sign retention, thus causing the low sign span.

In the second part of the paper we addressed the question of how complex subordinate structures and long distance dependencies are processed by signers, given short-term memory limitations. We reviewed the hypothesis that the grammar of sign languages is partially shaped by processing constraints. Complex structures do exist, but the most challenging configurations for the parser, notably including center embedding, are usually avoided, unless special strategies based on the use of space are activated.

All in all, although the picture is more complex than it might initially appear, the hypothesis that aspects of the sign language grammar are adaptations to the constraints imposed by the short-term memory lays the foundation for a research program that is still interesting to pursue.

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Appendix 1. List of signs used for the analyses (at most 4 frames difference between the two coders).

English gloss		**Italian gloss**
WATER		*ACQUA*
CAREFUL		*ATTENTO*
UGLY		*BRUTTO*
GOOD		*BUONO*
KNOW		*CONOSCERE*
HARD		*DURO*
POLITE		*EDUCATO*
FOOL		*FESSO*
FIAT		*FIAT*
GRATIS		*GRATIS*
ITALY		*ITALIA*
GLASSES		*OCCHIALI*
SPEAK		*PARLARE*
POTATO		*PATATA*
POSSIBLE		*POSSIBILE*
MAIL		*POSTA*
TRY		*PROVA*

CLEAN		*PULITO*
IDIOT		*SCEMO*
SCHOOL		*SCUOLA*
UNCLE		*ZIO*

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