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CICLO XXVII

DOES SOUND MATTER?

Studies of information encoding in short-term memory of signers and speakers.

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Summary

The short-term memory (STM) span, which corresponds to the longest sequence of items correctly recalled in a specific order, represents a widely used measure of STM capacity. STM span is shorter with signs as compared to speech, a robust finding that has been documented in different languages and populations using a variety of experimental paradigms.

Attempts to characterize the source of modality-specific variations in STM span have been primarily of two types. Some accounts have drawn attention to structural differences between signs and verbal stimuli, supposing that signs are more complex in their internal structure and require more processing load for simultaneous integration of different features (movement, orientation, location, handshape) and longer articulatory duration. While a few results lent support to accounts assuming structural differences, findings showing that shorter STM spans persisted even when signs were carefully matched to verbal stimuli in duration, complexity, similarity etc., weaken accounts that identify structural differences as a primary cause of the disadvantage observed with signs.

A second type of accounts hinges on the hypothesis that the reduced span is an effect of modality, stemming from greater STM capacity for encoding serial information in auditory STM as compared to visuo-spatial STM.

The critical role these accounts assign to the encoding of temporal order information is justified by findings showing that when the task was free recall, without a requirement of a specific order, comparable spans appeared across modalities. The findings from free recall demonstrate comparable encoding of sign and speech, and working memory tests show comparable performance across modalities. Therefore the disadvantages for signs restricted to serial order recall lend support to a hypothesis linking the reduced STM capacity for signs to sequential order information.

The present study aims to contribute to the investigation of the sequential order hypothesis that associates the reduced span of sign to the limitations of visuo-spatial STM processes in encoding temporal sequences. Research has shed light on the representation of serial order used in verbal STM, revealing that positions are encoded with respect to both start and end positions.

The problem addressed in the present study is the source of the span reduction for ordered recall of signs, and a first question that arises is whether the same position scheme for order encoding in STM is used for signs and speech. We can explore this by identifying the scheme used to represent the position of items in a sequence in STM for signs and compare that to previous results from STM for speech. Here, we examined the perseverations that signers of Italian Sign Language produced in an immediate serial recall tasks. Perseverations were analysed to determine whether their occurrences reflected the encoding of serial positions with respect to both edges that characterizes verbal STM.

In the core experiment of the present study we presented sequences of consonants of Italian sign language (LIS) alphabet to a group of 20 deaf students of Magarotto Institute in Padua, a secondary school where the communication among students and teachers is based on LIS. Sign sequences varying in length from 4 to 7 consonants were randomly presented on a computer screen at a rate of 1 second per sign. At the end of each sequence, participants were instructed to recall the letter signs in the same order. The length of the sequences was often purposely overspan to generate errors. We analysed the perseveration error pattern using the same technique as Fischer-Baum (2010).

The results showed that, compared to hearing people, deaf participants demonstrated a reduced span, however, we found evidence for the same both-edges representation of position in STM for signed stimuli, suggesting that the same scheme is used to represent position in this task as is used in the STM for speech stimuli task.

A next step was repeating the same experimental paradigm only using words and not letters as stimuli. Data was collected from 20 participants. However, in that case participants tended to produce responses of the same length, that made impossible to discern between different position encoding schemes. Those data were not enough to draw any definite conclusions from. A drastic extension of the subjects pool could have solved this problem, but at the moment it was not possible.

There was, however, a possible bias: since the signers are literate, can read and write and possess strong skills of lip reading, there was a possibility that some phonological information could be involved in verbal material processing. To control for that, a study has been conducted involving two groups of participants: 20 signers (Magarotto institute students) and 15 speakers (University of Padua students). Two sets of experimental words were selected: similar in sign and similar in sound. Two matching control sets were balanced to experimental sets. The task was recalling sequences of 4 words, the 4 words were selected from one of the 4 sets. The hypothesis was that if the signers use phonological information, then words similar in sound would elicit more interference and would lead to weaker recall than a matching control group. However, the results demonstrate that signers show a strong effect of interference only in case of recall of words similar in sign, and no effect of similar sound, so we can conclude that there's no phonological information involved in signers' processing.

An extended control study was also conducted to explore the contribution of the phonological loop in positional information encoding, since many theoretical explanations of the differences between STM of signers and speakers suggest that it's the core structure for verbal information encoding for speakers. In this study the phonological loop was artificially blocked in speakers by means of adding articulatory suppression to the task of verbal stimuli memorizing and recall. However, the results of that study show that articulatory suppression leads participants to produce a greater rate of errors, but they use the same both-edges position encoding scheme, so we can conclude that the phonological loop doesn't play a crucial role in serial order encoding scheme construction.

We may have to search further for an intermediate problem of binding the elements of the input to serial position slots, that however exist in short term memory for signs as well as for spoken material, as it has been demonstrated by our studies.

Riassunto

Lo span di memoria a breve termine (MBT), che corrisponde alla sequenza più lunga di elementi ricordati correttamente in un ordine specifico, rappresenta una misura della capacità di MBT ampiamente utilizzata. Lo span di MBT è più breve per il materiale in lingua dei segni rispetto al materiale in lingua parlata, è un risultato robusto che è stato confermato in diverse lingue e popolazioni utilizzando una varietà di paradigmi sperimentali.

I tentativi di caratterizzare la fonte di differenze di span di MBT dovuti alla modalità di stimoli sono stati essenzialmente di due tipi. Alcuni hanno focalizzato la loro l'attenzione sulle differenze strutturali tra i segni e gli stimoli verbali, supponendo che i segni sono più complessi nella loro struttura interna e richiedono più carico di elaborazione per l'integrazione simultanea di diverse caratteristiche (movimento, orientamento, posizione, forma della mano) e la durata articolatoria più lunga. Mentre alcuni risultati mostrano evidenze a favore di questo approccio che assume differenze strutturali, ci sono altri risultati che dimostrano l'abbassamento di span di MBT anche quando i segni sono stati accuratamente abbinati e bilanciati rispetto agli stimoli verbali in durata, complessità, somiglianza ecc., e queste evidenze indeboliscono le ipotesi che assumono differenze strutturali come causa principale dello svantaggio osservato nello span per i segni.

Un secondo tipo di approccio teorico si basa sull'ipotesi che lo span ridotto è proprio un effetto della modalità, derivante dalla maggiore capacità di MBT per codificare informazioni nell'ordine seriale nella modalità uditiva rispetto alla modalità visuo-spaziale.

Il ruolo critico che questo secondo tipo di approcci assegnano alla codifica delle informazioni di ordine temporale è giustificato dai risultati che mostrano che quando il compito richiede di ricordare gli stimoli nell'ordine libero (free recall), senza l'obbligo di mantenere l'ordine di presentazione, lo span di MBT è comparabile tra le diverse modalità. I risultati di recall libero dimostrano capacità di codifica comparabili per segni e parlato, e anche i test di memoria di lavoro mostrano prestazioni confrontabili tra le diverse modalità. Quindi gli svantaggi per i segni sono limitati alla capacità di ricordare le sequenze di stimoli nell'ordine seriale, e questo rinforza l' ipotesi che collega la capacità di MBT ridotta per i segni con la capacità di codificare le informazioni dell'ordine sequenziale.

Il presente studio cerca di contribuire all'esplorazione dell'ipotesi dell'ordine sequenziale che associa lo span ridotto per i segni con dei limiti dei processi nella MBT visuospaziale nella codifica

delle sequenze temporali. La ricerca ha messo in luce la questione delle rappresentazioni dell'ordine utilizzati nella MBT verbale, rivelando che in molti casi le posizioni sono codificati rispetto all'inizio e la fine della sequenza.

La questione che ci poniamo nel presente studio è la fonte della riduzione di span per i segni, e, come primo passo, bisognerebbe capire se lo schema di rappresentazione della posizione per la codifica ordine in MBT è lo stesso per i segni e per il parlato. Possiamo esplorarlo identificando lo schema utilizzato per rappresentare la posizione degli elementi in una sequenza nella MBT per i segni e confrontandolo con i risultati precedenti ottenuti con la MBT per il parlato. Abbiamo esaminato gli errori di perseverazione che i parlanti della Lingua Italiana dei Segni producono in un compito di recall seriale ordinato che coinvolge i segni della lettera. Perseverazioni sono stati analizzati per determinare se i loro occorrenze riflettevano la codifica delle posizioni di serie rispetto a entrambi i bordi che caratterizza STM verbale.

Nel principale esperimento del presente studio abbiamo presentato sequenze di consonanti di lingua dei segni italiana (LIS) ad un gruppo di 20 studenti sordi dell'Istituto Magarotto di Padova, una scuola specializzata in cui la comunicazione tra studenti e insegnanti è basata sulla LIS. Sequenze di segni di lunghezza da 4 a 7 consonanti sono stati presentati in ordine random sullo schermo del computer alla velocità di 1 segno per secondo. Alla fine di ogni sequenza, i partecipanti erano chiesti di ripetere i segni nell'ordine di presentazione. La lunghezza delle sequenze era spesso volutamente overspan in modo tale da generare errori. Abbiamo analizzato il pattern di errori di perseverazione con la stessa tecnica che ha usato Fischer-Baum (2010).
I risultati hanno mostrato che, rispetto agli udenti, i partecipanti sordi hanno uno span di MBT ridotto, tuttavia, abbiamo trovato la conferma per la rappresentazione della posizione di un elemento della sequenza ancorata a due estremi della sequenza, suggerendo che lo stesso schema è utilizzato per rappresentare la posizione dei segni che per il materiale parlato.

Un passo successivo era ripetere un esperimento con lo stesso paradigma sperimentale utilizzando parole e non le lettere come stimoli. I dati sono stati raccolti da 20 partecipanti. Tuttavia, in quel caso i partecipanti tendevano a produrre risposte della stessa lunghezza, che hanno reso impossibile distinguere tra diversi schemi di codifica di posizione. I dati ottenuti non sono stati sufficienti a trarre conclusioni definitive. Un aumento significativo della quantità di partecipanti avrebbe potuto risolvere questo problema, ma al momento non è stato possibile.

C'era, però, un possibile bias: visto che i segnanti sordi sono comunque in grado di leggere e scrivere e hanno anche le competenze di lettura labiale, c'era una possibilità che alcune informazioni fonologiche potrebbero essere coinvolte nell'elaborazione del materiale verbale. Per controllare questo, abbiamo condotto uno studio con due gruppi di partecipanti: 20 segnanti (studenti dell'Istituto Magarotto) e 15 parlanti (studenti dell'Università di Padova). Abbiamo selezionato due gruppi di parole come stimoli sperimentali: parole simili in segno e simili il suono. Per il controllo abbiamo aggiunto due gruppi di parole corrispondenti, bilanciate alle parole sperimentali, ma dissimili tra di loro. Il compito era ricordare sequenze di 4 parole, dove la sequenza di 4 parole apparteneva a uno dei gruppi. Ci aspettavamo che se i segnanti usano informazioni fonologiche, allora le parole simili in suono avrebbero suscitato più interferenza portando alla prestazione peggiore che nel gruppo di controllo.

Tuttavia, i risultati dimostrano che i segnanti dimostrano un forte effetto di interferenza solo in caso di parole simili in segno, e le parole simili in suono non elicitano nessun effetto. Allora possiamo concludere le informazioni fonologiche non sono coinvolte nell'elaborazione di stimoli segnati.

Uno studio di controllo esteso è stato condotto per esplorare il contributo del loop fonologico nella codifica dell'informazione posizionale, visto che molte spiegazioni teoriche delle differenze tra MBT di segnanti e parlanti suggeriscono che è la struttura di base per la codifica dell'informazione verbale per i parlanti. In questo studio il loop fonologico dei parlanti è stato bloccato attraverso l'aggiunta di soppressione articolatoria al compito di memorizzazione di stimoli. I risultati dimostrano che la soppressione articolatoria porta i partecipanti a produrre un maggior numero di errori, ma, comunque, usano lo stesso schema di codifica di posizione seriale ancorata a due estremi della sequenza, quindi possiamo concludere che il loop fonologico non ha un ruolo importante nella costruzione dello schema di rappresentazione posizionale.

We may have to search further for an intermediate problem of binding the elements of the input to serial position slots, that however exist in short term memory for signs as well as for spoken material, as it has been demonstrated by our studies.

Quindi dovremmo cercare ulteriormente per un problema intermedio di collegamento di elementi dell'input ordinato alle posizioni rappresentate secondo lo schema ancorato a due estremi, lo schema, che comunque esiste anche nel caso dei segni, come abbiamo dimostrato, però si verifica più problematico il processo di posizionamento di elementi in questo schema.

INDEX

Short-term memory and long-term memory

Short-term memory is a widely used term for the capacity of keeping a small amount of information immediately available for a short time. The time limits for short-term memory (without active rehearsal or other additional activity on the information) have been considered to be small, around 18 seconds for a typical span task. The conventional consideration of the short-term memory capacity is 7 ± 2 elements. Long-term memory, on the contrary, is believed to be able to hold big amounts of information for an indefinitely long time. However, it is very difficult, if not impossible, to demonstrate the exact measure of the duration and capacity of short-term memory because it varies depending on the type of the task, modality of presentation and stimuli to be recalled.

The idea of the two different kinds of memory, short-term and long-term, goes back to the 19th century. William James in 1890 suggested a distinction between primary and secondary memory, where primary was more short-term, and secondary more long-lasting. Hebb (1949) suggested that short-term memory relied upon temporary electrophysiological activity, while long-term memory was connected to more durable neurochemical changes. Atkinson & Shiffrin (1968) developed the classical modal model that supposes that information first passes through a series of sensory stores that are components of perceptual processing, including visual sensory memory (Sperling, 1960), acoustic sensory storage (Crowder & Morton, 1969), otherwise called echoic memory (Neisser, 1967). Then the information gets stored in short-term memory, that stores and controls information for accumulation and retrieval to and from long-term memory. The details of the distinction between the two kinds of memory storage, the information consolidation process and transformation of a memory trace from short-term to long-term memory is until now a subject of continuing research and discussion.

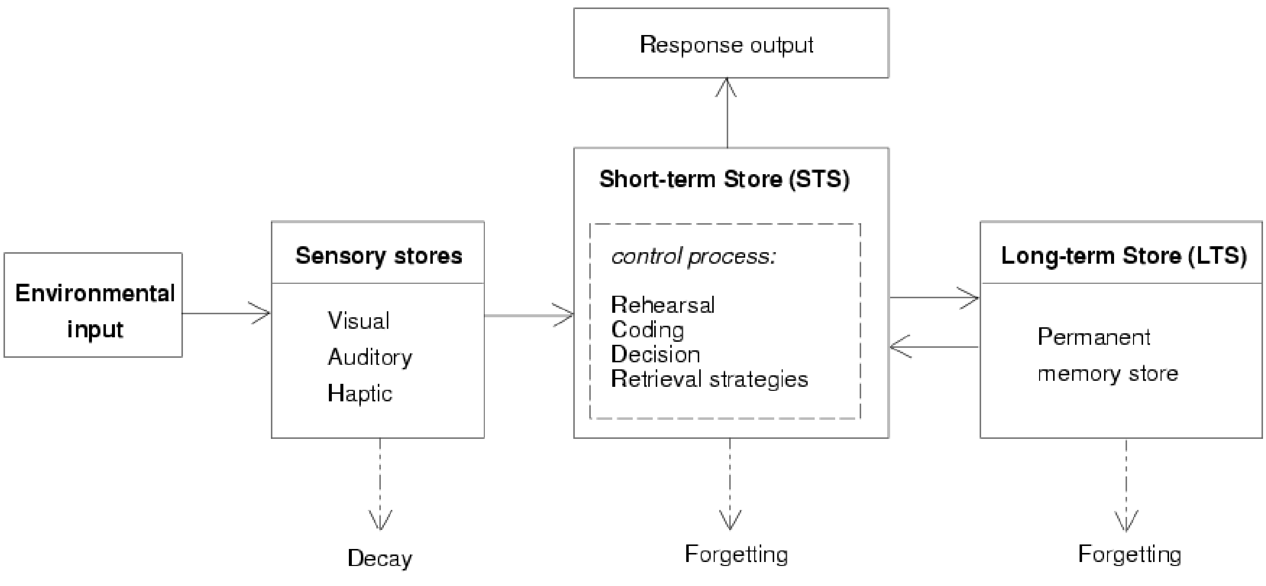


Figure 1. *Atkinson & Shiffrin's information-processing model of memory. Information comes from the environment through sensory registers into a short-term store, which plays a crucial role in managing the information flow in and out of the long-term store.*

Another evidence supporting the idea of a separate short-term memory is the anterograde amnesia, the inability to memorize new facts and episodes, when it comes to long-term storing of the information. However, amnesic patients with bilateral damage to the temporal lobes and hippocampus still maintain a capacity of recalling information presented in a most recent time frame (around 30 seconds), for example, performing well on short-term memory tasks such as digit span, therefore suggesting that they have an intact short-term memory storage while the long-term storage is impaired (Scoville & Milner, 1957, Milner, 1966, Baddeley & Warrington, 1970).

There's also a theoretical approach according to which there are no separate short-term and long-term storages, but a memory is unitary on different time scales (Brown, Neath & Chater, 2007). For this theory, an argument that can be taken into account is the absence of a clear distinctive border between short-term and long-term storage. Some evidence in favour of this approach is provided by Nairne & Dutta (Nairne & Dutta, 1997): they show that the pattern of recall errors is very similar for recall of a list immediately after learning and recall after 24 hours (therefore suggesting the same mechanism for what is supposed to be short-term and long-term storage).

Primacy and recency effects

Primacy effect in short-term memory, when it comes to recall of a list of elements, is a greater probability of the correct recall of the first items of the list. Recency effect is a greater probability of the correct recall of the most recent items. These effects have been demonstrated by Glanzer & Kunitz (1966), summing up a serial position curve with better recall for the first and last items of the sequence, while having a lower recall level for the items in the middle. Important evidence on these effects has been obtained in studies with continual distractor tasks. In the study by R. A. Bjork and W. B. Whitten (1974) word pairs were presented for subjects to memorize, while before and after each word pair, subjects performed a multiplication task for 12 seconds. After the final word-pair, subjects had to do the multiplication task for 20 seconds. As a result, they showed that the recency effect and the primacy effect still remained.

Watkins, Watkins & Crowder (1974) demonstrated that phonological similarity of the items in the stimuli list is beneficial for all items except for the most recent, while in case of serial ordered recall the phonological similarity reduces performance and also acts for lowering or blurring out the recency effect.

However, the recency effect also has been found for free recall: Tzeng (1973) presented 4 blocks of 10 word lists while counting backwards for 20 seconds as a distractor, after the 10 words finished, subjects' task was free recall of the items presented. After the last block, the task was free recall of the words from all four blocks. Both tasks – recall over a 10-word list and recall over the four blocks of 10-word lists – showed recency effect.

A possible explanation of these effects can be adaptation to the distractor task (Koppenaal, & Glanzer, 1990). In their study the long-term recency effect disappeared when the distractor after the last item was different from the distractors that preceded and followed all the other items (e.g., arithmetic distractor task and word reading distractor task).

Neath (1993) suggested an explanation of the existence of the recency effect in a continual distractor condition, and the disappearance of it in an end-only distractor task as the influence of different contextual factors. In his view, the recency effect is a result of the similarity of the processing context of the final items to the processing context of the other items and the distinctive position of the final items versus items in the middle of the list. In the end distractor task, the processing context of the final items is no longer similar to the processing context of the other list items. At the same time, retrieval cues for these items are no longer as effective as without the distractor. Therefore, the recency effect recedes or vanishes. However, when distractor tasks are placed before and after each item, the recency effect returns, because all the list items once again have similar processing context

Short-term memory duration and forgetting

The limited duration of short-term memory suggests that the information stored there spontaneously decays over time. The decay assumption usually comes along with the theory of rapid covert rehearsal: to overcome the time limit of short-term memory and hold information for a longer time, the information must be rehearsed —by articulating it out loud or through a mental articulation rehearsal process, so that the repeated information enters the short-term store again and gets saved for a longer period of time. However, it has been widely discussed, and many researchers disagree with the point of view of the importance of the decay in forgetting (Lewandowsky, Duncan & Brown, 2004; Nairne, 2002; Jonides, Lewis, Nee, Lustig, Berman & Moore, 2008)

One of the famous experimental evidence for the limits of short-term memory storage has been obtained by Brown and Peterson (Brown, 1958: Peterson, L.R. & Peterson, M.J., 1959), in a series of tasks where participants had to memorize a sequence of trigrams while counting backwards by threes between each trigram. Their results show that the was a significantly lower recall of the most recently memorized trigrams, while the items memorized earlier remain intact for recall. A complementary effect, a disruption of early memorized words, while the most recent remain intact, has been obtained in Davelaar et al.'s study (Davelaar, Goshen-Gottstein, Haarmann, Usher, 2005) while manipulating semantic similarity of the words. These results show that short-term recall can be affected by an interfering task preventing rehearsal (counting backwards in threes), while long-term recall suffers an effect of semantic similarity. A general conclusion from these studies can be that short-term memory and long-term memory are subject to different independent changes and factors of influence.

Keppel & Underwood (1962) showed that forgetting in Brown and Peterson's tasks was minimal for the first trial of the experiment, rising quickly with the next trials. They suggest an explanation of proactive interference for forgetting.

An alternative explanation for forgetting in short-term memory can be an interference instead of decay. When several elements (pictures, digits, or words) are held in short-term memory simultaneously, their representations compete with each other for recall, or degrade each other. Therefore, new information gradually pushes out older items, unless the older items is actively protected against interference by rehearsal (Oberauer & Kliegl, 2006)

Short-term memory capacity

Whatever the cause of the time limits and forgetting may be, it puts a limit on the amount of new information that can be recalled over brief periods of time. This limit is referred to as the finite capacity of short-term memory. The capacity of short-term memory is often called memory span, in reference to a common procedure of measuring it. In a memory span test, the experimenter presents lists of items (e.g. digits or words) of increasing length. An individual's span is determined as the longest list length that they can recall correctly in the given order.

George Miller in his famous article “The Magical Number seven, plus or minus two” (1956) suggested that short-term memory is capable to hold approximately seven items plus or minus two, obtaining the results on a population of university students performing a digit recall task. More recent research shows a wide variety of spans in different populations tested with different material, and different characteristics of the stimuli used may produce effects on memory: for example, the well-known effects of

- word length (longer words lead to a smaller span when memorizing them) (Baddeley, Thomson & Buchanan, 1975)
- phonological similarity (words that are similar phonologically interfere with each other and lead to a span reduction also) (Conrad & Hull, 1964)

Also, frequency, familiarity, age of acquisition and other stimuli characteristics have to be taken into consideration when measuring memory span (Poirier & Saint-Aubin, 1996).

Semantic similarity also has its effect on the memory span, making recall better when all the words in a sequence belong to the same semantic category (Poirier & Saint-Aubin, 1995)

The theory of “chunking” in short-term memory suggests that information may get quantified and chunked, and the span depends on the chunking possibility, being around four chunks (Cowan, 2001), which applies to ordered recall, while for free recall no chunking limit is posed, but rather a limit of time before decay of the memory trace (Tarnow, 2010)

However, it is very difficult, if not impossible, to demonstrate the exact capacity of short-term memory because it varies depending on the nature of the material to be recalled.

STM spans vary a lot with phonological complexity and word length, and are different across languages. Native speakers of languages in which digit names are shorter to enunciate, such as Chinese, tend to have longer digit STM spans (Elliott, 1992), whereas speakers of languages with longer digit names, such as Welsh, show shorter STM spans (Ellis & Hennelly, 1980).

Cowan (2001) explored the limits of the visual short term memory capacity in span tasks with non-nameable material and showed it to be most commonly around 4±1 elements at a time, the finding was later confirmed by Vogel & Machizawa (2004) however, accounting for large inter-individual variability determined by neuropsychological predictors (which was revealed in their ERP study of visual memory) as well as other possible factors.

Short-term memory and working memory

How short-term memory is related to working memory is a widely discussed and differently described question, however, the two concepts are not the same, but rather closely connected.

Working memory is related to a theoretical framework of a temporary storage system under attentional control, operating the information in an active and available state, also connected to the cognitive control and executive functions, and referring not only to the structure, but to the processes of perception, attention and manipulation with the information, being an interface between perception and action, between attention and action. The term has been introduced by Miller, Galanter & Pribram (1960), and further developed in research by Atkinson & Shiffrin, Baddeley & Hitch and many other outstanding researchers. Short term memory commonly refers to a on a simple unitary temporary component of working memory system, serving as storage of information, and not performing the organization and manipulation of the information stored there, implying quick encoding and quick recall of the information from this temporary storage.

The term “short-term memory” is used more commonly to describe tasks where immediate serial recall of limited amounts of information is required, while the term “working memory” refers more often to a broader system typically involving attentional control and allowing the manipulation of the information held in short-term storage. However, many studies focused on short-term storage use the term “short-term memory” as referring both to the tasks and to the underlying processes, so that the exact meaning for a certain case can be defined by the context (Gathercole & Baddeley, 1996; Vallar & Papagno, 2002). Thus, while there are short-term memory components to working memory models, the concept of short-term memory storage system is one of the underlying and composing components of a more general and broad concept of working memory.

Kane and colleagues (Kane, Hambrick, Tuholski, Wilhelm, Payne & Engle, 2004) compared the performance of subjects in verbal and visual short-term memory and working memory tasks, showed the domain-specific differences for short-term memory, while more cross-domain correlations for working memory tasks. Short-term memory tasks are simple span tasks, letter, word or digit for verbal STM, arrow span (as in Shah & Miyake, 1996 or Kane et al., 2004), matrix span or ball span for spatial STM.

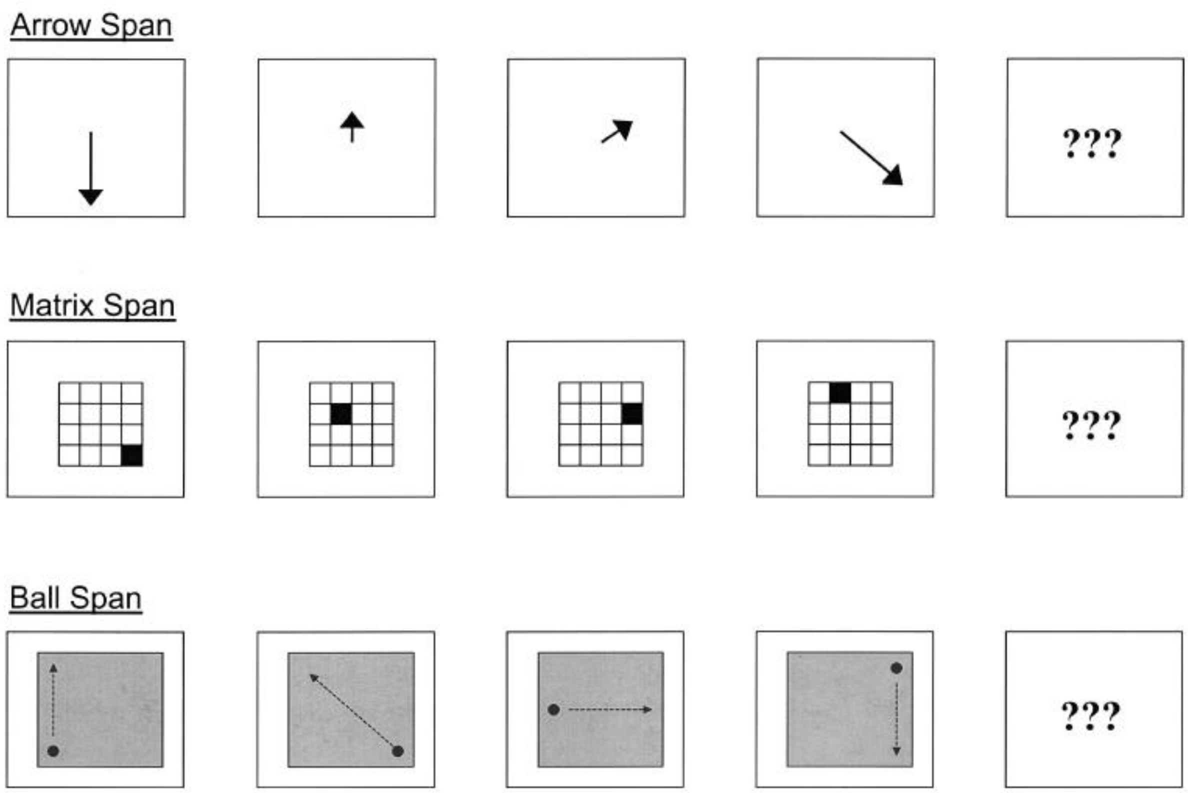


Figure 2. *Visuospatial STM span tasks, from Kane et al., 2004. The broken arrows depicted in the ball span task represent the direction that the circle moved in, over the course of 1 second, as it travelled to the opposite side of the screen. The participants' task was to reproduce each of the sequences in correct order by drawing them.*

Working memory tasks required information manipulation, included, for verbal working memory:

- operation span (words recall with a background arithmetic task – a task that was supposed to interfere to the storage demands of the primary task and thus require control/executive capacity),
- reading span (similar to Engle, Tuholski, Laughlin & Conway, 1999, where a letter recall is required with a background reading task),
- counting span (digits recall with a background counting task).

For visuospatial working memory:

- rotation span (similar to Shah & Miyake, 1996; recall of sequence of arrows with a background letter rotation task),
- symmetry span (recall of locations with a background symmetry-judgement task)
- navigation span (recall of paths of moving balls with a background task of letter navigation).

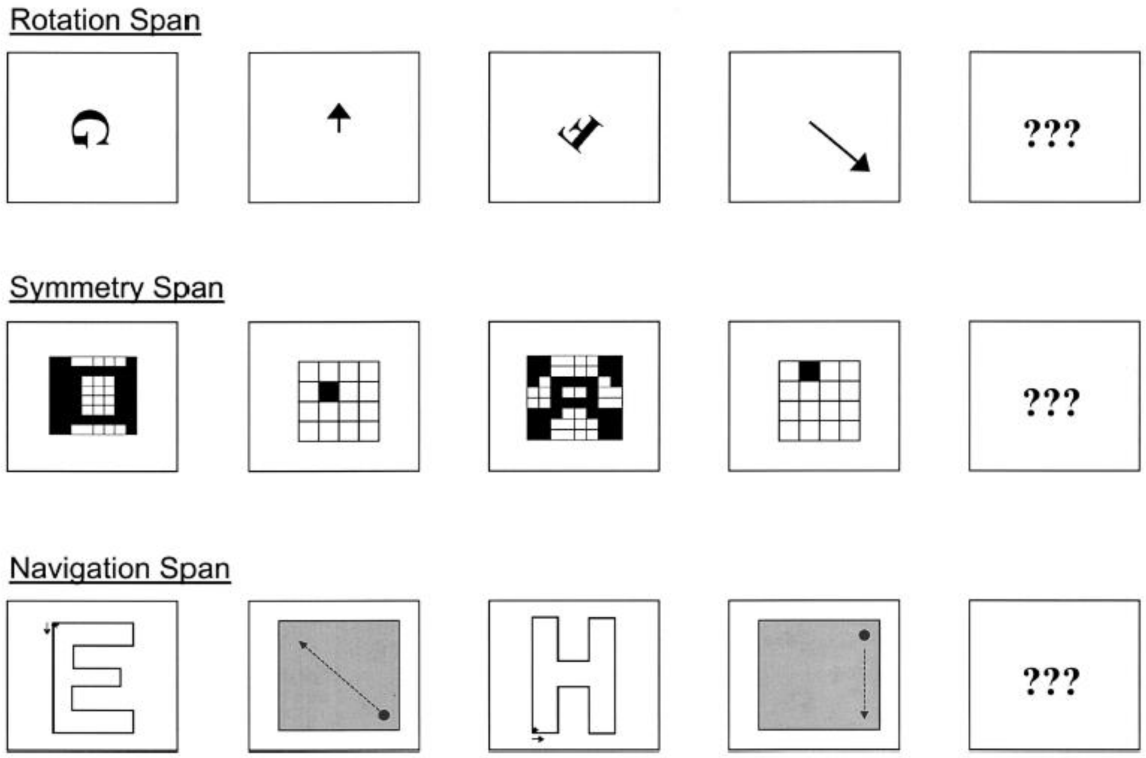


Figure 3. *Visuospatial working memory span tasks, from Kane et al., 2004.*

Rotation span: participants had to recall a sequence of arrows radiating from the centre, while processing a background letter rotation task: after each arrow a rotated letter was presented, and the participants had to indicate whether the letter was mirror-reversed or normal.

Symmetry span: participants had to recall a sequence of red square locations, while performing a background task of symmetry judgement: after each square an image was presented and participants had to indicate whether it was symmetrical.

Navigation span: participants had to recall the paths of moving balls, while performing a background task of mental navigation of an asterisk along a letter, following the directions of an arrow, indicating whether at the end of navigation the asterisk was at the top/bottom edge of the letter or not.

The results show that even though verbal and spatial STM tasks were structurally more similar to one another than were the verbal and spatial working memory tasks, verbal and spatial measures of short-term memory had less shared variance than unique variance (40% shared). This accounts for a suggestion of more modality-specificity for short-term memory storage, as opposed to working memory resources.

Baddeley & Hitch's model

The influential Baddeley & Hitch's model of working memory (e.g. Baddeley, & Hitch, 1974; Baddeley, 1986) suggests a multimodal system underlying the mechanisms of working memory, referring to the functional role of the system, rather than simply a storage capacity. The model includes two distinct parts of the short-term storage: the phonological loop and the visuospatial sketchpad, with a central executive element that performs general processing operations over the stored information, integrates and manipulates information available in the short-term storages along with that retrieved from long-term memory (Burgess & Hitch, 2005; Cowan, 2008). Evidence for the distinction between verbal and visuospatial storage comes from numerous empirical dissociations in dual-task, neuropsychological, and neuroimaging studies (Henson, 2001; Jonides et al., 1996; Logie, 1995, Kane et al., 2004). The phonological loop has probably been the most thoroughly studied component, however, there's also been a rise of the research of the visual (Luck, S. J., & Vogel, E. K., 1997) and spatial (Parmentier, Elford & Mayberry, 2005) short-term memory.

The phonological loop is assumed to be able to hold and rehearse speech-based verbal/acoustic information as a short-term trace, while the visuospatial sketchpad holds visual and spatial information as a short-term trace. Short-term memory research using verbal material usually refers to the phonological loop, as it's a storage that allows for rehearsal and sequential information encoding.

Figure 4. *Baddeley & Hitch's three-component model of working memory*

The phonological loop has a typical span of about 7+−2 verbal/spoken elements, holding auditory and linguistic information. The functioning of the phonological loop has been characterized by a series of well-known effects including phonological similarity, word length, and articulatory suppression effects (Baddeley, 1992; Baddeley, Thomson, & Buchanan, 1975) that have shown how verbal short-term memory span can be lowered when items are phonologically similar, word length is bigger, and when rehearsal in the phonological loop is suppressed by articulating an unrelated sound.

Newer working memory models suggest the existence of an episodic buffer - a new component to be added, above and beyond the visuospatial sketchpad and phonological loop initially included by Baddeley and Hitch. The importance of considering episodic traces in memory was underlined by E. Tulving (1983), based on the observation that in most cognitive tasks, whether sentence processing or scene understanding, the context of occurrence is necessary to uniquely qualify a memory trace (Potter, 1993; Tulving, 2002). One of the core functions of the episodic buffer is integrating information across various encoding dimensions, including phonology, orthography, visual shape or semantics into an all-in-one memory trace (Bavelier, 1999; Kahneman, Treisman & Gibbs, 1992; Pylyshyn, 1989). Thus a specific role of the episodic buffer is to allow for unique representations of the information and events providing a temporal, spatial and semantic context in which the event occurred (Kahneman et al., 1992; Pylyshyn, 1989).

Baddeley himself revised the original model in 2000, including the episodic buffer as a separate component, since his experimental studies demonstrated that some neuropsychological patients can recall a story despite an impaired phonological loop (Baddeley & Wilson, 2002; Baddeley, 2000, 2003, 2012; Repovš & Baddeley, 2006). The episodic buffer in this new model is assumed to be controlled by the central executive, which is capable of retrieving information from the storage, reflecting on that information, manipulating and modifying it.

The buffer’s capacity is set in terms of chunks of information, so its central feature is binding dispersed information into unified chunks. The buffer itself is limited in capacity by the number of chunks it’s able to maintain (Cowan, 2005).

It is assumed to be a temporary storage system capable of combining information from the phonological loop, visuospatial sketchpad, long-term memory and/or sensory input into a coherent episode trace. The buffer provides a link between the central executive component and the long-term memory storage. It may provide a multidimensional coding, thus allowing the information from the phonological loop to be encoded semantically. Rudner & Ronnberg (2008) argue that the episodic buffer helps form unitary multidimensional representations and is involved in language processing.

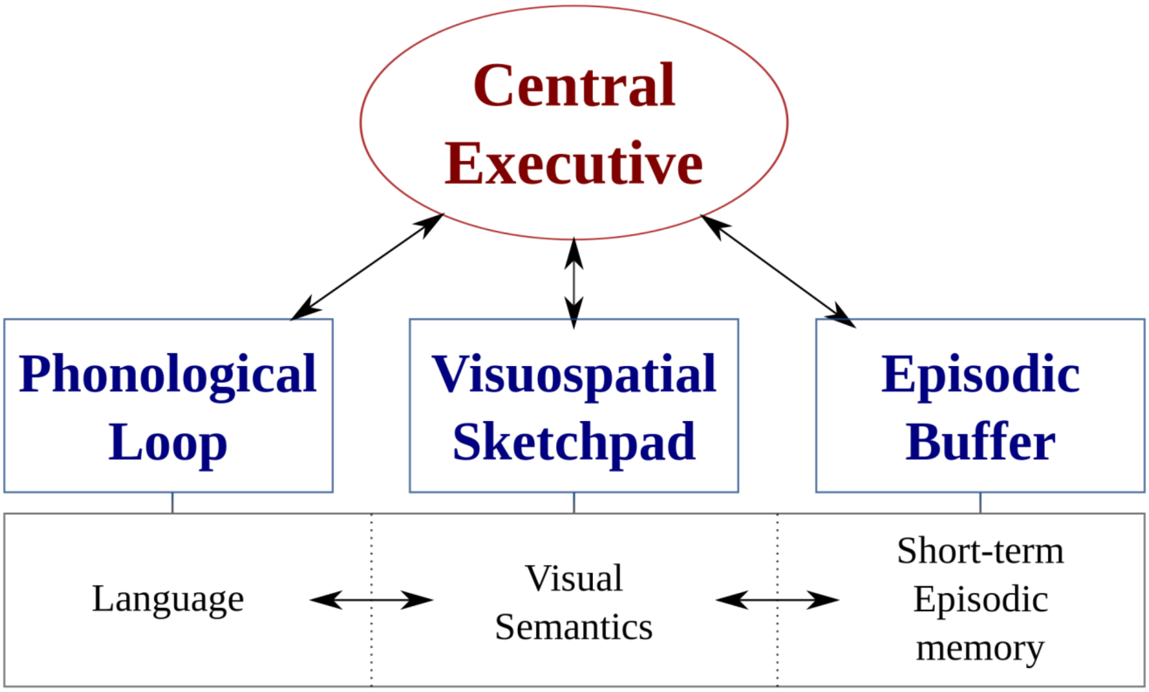


Figure 5. *Revised model of working memory, by Baddeley (2000).*

Overall, neuropsychological data as well as evidence from research on language processing leads to a conclusion that language comprehension requires representations of a higher level than of those stored in the phonological loop. The episodic buffer is a crucial element for binding words to the semantic context and drive sentence comprehension in full (Hirshorn, Fernandez & Bavelier, 2012). To represent such a complex structure it's not enough to store its elements as a sequence and rehearse them as such, as it happens in the phonological loop (Potter, 1983; 1999). Therefore, episodic memory traces necessary for solving local ambiguities or re-evaluation of meaning.

Visuo-spatial short-term memory

Both in the original model (Baddeley & Hitch, 1974) and in subsequent advances (Baddeley, 1986, 1990, Hanley, Young & Pearson, 1991, Logie, , 1989, 1991, Morris, 1987) visuo-spatial component has been thought of as a complementary to the phonological loop.

The visuospatial sketchpad has been demonstrated to have an average capacity of holding a span of 4 visual/spatial elements. The underlying mechanism involved with the sketchpad is assumed to be a mental representation of the identity and the location of an object in memory (Kosslyn, 1981).

As a parallel with phonological similarity effect occurring in the phonological loop, some studies explored visual similarity effects. Hue and Erickson (1988) show visual similarity effect in recall of Chinese characters (unfamiliar to the participants); Wolford & Hollingsworth (1974) report visual confusion errors in recall of verbal stimuli that were presented visually, but very briefly. Logie and colleagues (Logie, Della Sala, Wynn & Baddeley, 2000) report visual similarity effects with words, comparing in visual presentation visually similar words ((e.g. *fly, cry, dry; hew, new, few*) with visually distinct words (e.g. *guy, sigh, lie; who, blue, ewe*), and with letters, comparing letters for which upper- and lower-case versions were visually similar (e.g. *Kk, Cc, Zz, Ww)* or were visually dissimilar (e.g. *Dd, Hh, Rr, Qq).* The task with letters consisted in a presentation of a sequence of letters in different cases, where participants had to recall not only the letters, but also the case of presentation. Letters that were visually similar in upper and lower case elicited more confusion in recalling the case. Their results suggest the presence of a visual code for retention of visually presented verbal sequences in addition to a phonological code, and they are consistent with the use of a visual temporary memory in verbal serial recall tasks. They also report that under articulatory suppression subjects are more likely to rely on visual coding, supporting it with evidence that when subjects performed the recall task under articulatory suppression, they had more difficulty recalling the case of presentation of the letters from the set where upper and lower-case versions were visually similar.

Logie (1995) posed a question whether visuospatial part of the memory could be divided into visual and spatial part. He reports studies with Brooks matrix task (from Brooks, 1967, 1968): subjects are told a set of numbers and their relative spatial locations within a matrix (e.g., “place a 4 in the upper left corner; the place a 3 below this position”). Baddeley and colleagues (Baddeley, Grant, Wight & Thomson, 1975) used the matrix task adding a distractor task, and they found that the spatial matrix task could be disrupted with a secondary task of tracking a moving target, but that the tracking task had no disruptive effect on a task of verbal sequences recall. Also, Baddeley & Lieberman (1980) show that the matrix task is not disrupted by a concurrent purely visual task. These results suggest that there is indeed a dissociation between visual and spatial components of the visuospatial system, that there are independent resources for each of them.

Logie & Marchetti (1991) explored visual and spatial recall capacity separately, by designing the stimuli to be specifically visual or spatial: the visual display was a simultaneous presentation of squares located in different positions, each in different hue of the same colour. The spatial display was a series of squares presented one after another, each in different hue of the same colour. The secondary tasks were a movement task and presentation of irrelevant pictures. The results demonstrate a clear differential disruption, i.e. the movement task disrupted performance on spatial display recall, while irrelevant pictures disrupted visual display recall.

However, it turned out to be difficult to discern between a what is a spatial task and what is a general load of executive functions. Perceptuo-motor performance requires resources overlapping with retention of spatial information (Baddeley & Lieberman, 1980; Johnson, 1982; Smyth, Pearson & Pendleton, 1988). It's worth further questioning, what exactly is meant by the spatial component. The term "spatial" may be understood as a reference to different locations in space, or to a movement in space. The most pragmatic way of interpretation is taking it in a broad sense, assuming a reference to any kind of movement, imagined or physical, but it need not involve any visual input, as the physical locations can be determined by touch or hearing, and many studies demonstrate spatial representations in the blind (Cornoldi, Cortesi & Preti, 1991; Kerr, 1983; Millar, 1990).

Smyth, Pearson and Pendleton (1988) compared spatial and verbal tasks and reported a span for a serial recall of movements to be 4.33, as compared to mean verbal spans of 5.12 in the same subjects. They also introduced secondary tasks, showing that a secondary arm movement task disrupts recall of movement sequence, but not verbal sequence. Articulatory suppression disrupts both. Tapping a square pattern produces no effect in either task. In their subsequent experiments, subjects performed a Corsi block test with a secondary arm movement task, that elicits no disruption of recall, while tapping a square pattern did reduce recall. These results suggest that the spatial/movement component of working memory is linked to the planning and control of movement.

Quinn (1988) conducted a study, combining the Brooks matrix task and verbal recall task with either arm movement, or brightness judgement secondary task. He found that movement task interfered with the matrix task, but so did brightness judgement, even if not so strongly. This is a result contrasting a lack of differential interference shown by Baddeley & Lieberman (1980). Movement and brightness also had small disruptive effects on verbal material recall, but only if secondary task was performed during the encoding of the primary task material.

These results showing effects of disruption in any case, point to a general processing load involved in performing these tasks combined, involving some general processing functions that deal with visuospatial storage only as a part of general cognitive system (Morris, 1987; Quinn, 1988; 1991; Quinn & Ralston, 1986).

SIGN LANGUAGE

Overview

A sign language is a language using primarily manual communication, and also body language and facial expressions to transmit linguistic information, as opposed to acoustically transmitted sound languages. Sign languages may include simultaneous production of hand shapes, different orientations and movements of the hands, arms, sometimes also the body, and facial expressions to express a speaker's thoughts. They share many similarities with spoken languages (expressed mainly through sound), which is why linguists consider both to be natural languages, but there are also some significant differences between signed and spoken languages.

The term “sign language”, as opposed to “gesture communication”, has been chosen to emphasize that it is a language of full value, a system of arbitrary symbols and grammatical rules that change across time that are shared by the members of a community and are used for interaction, communication and expression of ideas, emotions and specific culture. Also, it is to distinguish the signs from the gestures produced by hearing non-signers accompanying their speech, that are not independently encoded symbols, but an auxiliary system to vocal speech.

Wherever communities of deaf people exist, sign languages have been developed. Signing is not only used by the deaf, it is also used by people who can hear, but cannot physically speak. While they use space for grammar in a way that spoken languages do not, sign languages show the same linguistic properties and use the same language faculty as do spoken languages (Stokoe, 1960; Stokoe, Casterline & Croneberg, 1965). Hundreds of sign languages are in use around the world and are at the cores of local deaf cultures. Some sign languages have obtained some form of legal recognition, while others have no status at all.

A common misconception is that all sign languages are the same worldwide or that sign language is international. Aside from the pidgin International Sign, each country generally has its own, native sign language, and some have more than one, though sign languages may share similarities to each other, whether in the same country or another one.

Although sign languages are not representations of either spoken or written language, some sign languages include finger spelling that can represent separate letters, and that is used for proper names production etc. (Brentari, 1998). There are many different finger spelling alphabets (Carmel,

S. J., 1982) that are used to construct a word where a sign for the whole word doesn't exist (Bergman & Wikström, 1981; Sutton-Spence & Woll, 1999)

It is not clear how many sign languages there are. The 2013 edition of Ethnologue lists 137 sign languages (Lewis, Simons & Fennig, 2013)

History

The first systematic description of a sign language used by deaf people comes from Abbé de l'Epée in the mid XVIII century discovered that his deaf students communicated through a "langue des signes naturels", and decided to use this communication form to teach written and spoken language, adding the signs corresponding to French verb tenses, gender forms etc(see Stokoe, 2005 for historical overview).

French illuminist tradition of the end of XVIII century showed a major interest towards this form of communication. Sicard, the head of a school for the deaf in Paris and Abbé de l'Epée's successor was a great researcher of the sign language. French sign language (LSF) was introduced in the USA by Thomas Hopkins Gallaudet, who, having discovered Sicard's work, went to France and studied there for a year, and afterwards returned home in 1816 together with Laurent Clerc, an expert deaf teacher of LSF (Lane, 1984). Thanks to Gallaudet and Clerc, who founded a first school in Hartford, Connecticut, and then other schools as well, the sign language diffused all around the United States, being intermixed with the signs already in use for communication in American deaf communities. This explains the similarities that exist until today between ASL (American Sign Language) and LSF.

A specific sign language was used by the deaf in Italy as well. First mentions of it are seen in writings from early XIX century, where teaching methods based on gestures are described. But after a Congress in Milan on 1880 it was obstructed, because of the claims that the oral method is necessary for proper education (Facchini, 1981; Volterra, Beronesi & Massoni, 1990)

Research

In many countries, the interest for sign languages from the linguistic point of view arose only in the 1960s, thanks to the works by William Stokoe (1960, 2005), who traced in ASL a structure internally similar to those of the vocal languages: like the way in which from a combination of a limited number of sound without a meaning (phonemes) emerges a huge number of entities that bear a meaning (words), the same way a combination of a limited set of minimal units (cheremes) emerges a possibility to produce a huge array of units bearing meanings (signs).

According to his analysis, a sign can be decomposed to the following parameters:

- Location in space, where the hand(s) execute the sign.
- Configuration of the hands while the sign is being executed
- Movement for sign execution.

For ASL, 19 configurations, 12 locations and 24 movements have been identified, and their combinations create all the possible signs of ASL. For example, two different signs may have the same configuration, but an execution in different locations, or vice versa, have the same movement, the same location, but have a different handshape.

Another important parameter identified later after the original analysis performed by Stokoe is the orientation of the palms of the hands. Some signs have the same configuration, the same location and the same movement, but they can be distinguished by the orientation of the palms.

This kind of analysis traces a lexical and sublexical organisation in a sign language that is similar to one of spoken languages. For example, two similar words like “fall” and “ball” have completely different meanings, and they constitute what is called a minimal pair. The existence of a minimal pair of this kind leads to the claim that “f” and “b” are two distinct phonemes. The same way, in a sign language the existence of a minimal pair, i.e. a pair of two signs that are differentiated only by a modification in one of the parameters, can be a criterion to decide that these two parameters can be considered two distinct cheremes of this language.

There has been a misconception that sign language lacks morphology and syntax, since it doesn’t have an inflection system, has almost no use of articles and prepositions, doesn’t seem to make distinctions between verbs and nouns, and in the end has a relatively free order of elements within a sentence. But in fact, careful research on ASL structure demonstrated the existence of various mechanisms that enable the encoding of the information expressed in vocal languages through articles, prepositions, inflection system or words order within a sentence.

These mechanisms are

- a specific use of space

- systematic modification of a movement for sign execution
- non-manual movement production: head, eyes, facial expressions, body orientation and posture.

Not only linguistic analyses, but also psychological research techniques have been applied to the reality of the described parameters. Bellugi, Klima & Siple (1975) demonstrated the relevance of the formational parameters of the sign from the perspective of short term memory. Analysing the errors that occur in sign language production, as well as in vocal languages, it has been found that these errors are often a result of a substitution of one of the parameters and even if the errors are not real ASL signs, they can be predictable according to the hypothesized restrictions (Bellugi & Klima, 1979). And in the end, as well as the vocal languages enrich the vocabulary adopting words of another language or creating compound words, the same thing happens in ASL where the vocabulary expands constantly through the same mechanisms.

It has been established that ASL has a series of exact grammatical rules (Bellugi & Klima, 1979): small variations of sign execution, sometimes invisible for the eyes of those not accustomed to the use of sign language, can bring important changes at morphological an syntactic levels.

Therefore it's been shown that a system exists in ASL with analogous characteristics of a morphologic, phonological and syntactic systems in spoken language, even if a difference persists, given to the modality of expression.

But one of the important differences between signed and spoken languages is that in spoken languages elements that form a word form a linear time-based sequence, while the elements of a sign are presented simultaneously or can be superimposed, and therefore they cannot be analysed as temporal sequences but rather in terms of spatial units and movements that coexist within a temporal unit.

On the traces of research of ASL, in the past years there has been extensive research work on other sign languages as well: Swedish, Norwegian, British, French, Danish, Dutch, Chinese, Japanese etc.

Italian sign language

Italian sign language has recently become a subject of linguistic research (Montanini, Fruggeri, Facchini & Battacchi, 1979; Volterra, 1981; Attili & Ricci Bitti, 1983). Italian sign language has many regional variations according to different deaf communities all over the country, so it's difficult to speak of a presence of a totally uniform symbolic system, but rather an ensemble of communication modes, with general common features and local variations. For a long time sign language has been in an oppressed position due to the dominance of the oralist approach, that dictated teaching spoken and written Italian to the deaf people instead of sign language, claiming that it would facilitate the communication between the deaf and hearing, thus reducing the isolation of the deaf. This led to a development of specific sign language variations in close communities of the deaf all over the country, without a unified education tradition and without an efficient way of communicating in sign language beyond the small community. Even until now sign language is not widely used on a national or international level, but mostly in family or special schools contexts, and that contributes to the difficulty of a definition of one standard and uniform Italian Sign language. That is one of the actual problems for deaf communities in Italy, a necessity of a common communication system, while respecting dialectal features of different regions. Therefore a sign language is also a product of social, political and cultural circumstances, and it undergoes a constant development and modification as these circumstances and actual deaf community needs change.

SHORT-TERM MEMORY FOR SIGNS

Overview

A large number of studies has been dedicated to the exploration of working memory, and in particular, its information storage defined as short-term memory. Many evidence shows there is a significant relationship between the short-term memory capacity for linguistic material and language abilities (e.g. Martin & Freedman, 2001; Baddeley, 2003), many studies have been dedicated to the exploration of the short-term memory mechanisms and the limits of its capacity. A common measure of STM capacity is the digit span task (Wechsler, 1955), where subjects must repeat lists of digits in the same order as they are presented (i.e., forward serial recall). The number of digits to be recalled is progressively increased, and the STM span is defined as the longest sequence reported correctly. As noted in a seminal study in 1956 by G. Miller, our ability to process information in such short-term memory tasks has a capacity limit defined by the ‘magical number’ of 7 ± 2, and this finding has been widely confirmed multiple times in later studies. However, we cannot affirm that it’s a general standard for STM capacity. When non-nameable stimuli are presented for recall, the span can be reduced to 4±1 elements (Cowan, 2001). One of the explanations of the relatively high span of 7 ± 2 is specific to verbal/linguistic nature of the stimuli, another possibility, however, is that it may be the effect of modality, auditory/verbal STM being more adapt for serial order information processing, than the visual STM.

An important insight for a better understanding the mechanisms underlying STM functioning in general and distinguishing between these possibilities can come from sign language research. There is an extensive body of research on how short term memory works with different kinds of stimuli presented in different modalities, and sign language memory research holds a special place, because it regards not only a particular modality of presentation, but also a possibly different way of perception. Sign languages are a primary and in some cases the only way of communication for many people, and they are equal to spoken languages in terms of having rich internal structure, complex syntax, morphology and grammar (Klima & Bellugi, 1979; Emmorey & Lane, 2000). Signed material is equal to spoken in terms of being verbal/linguistic, having all the natural language properties. However there are also differences between spoken and signed linguistic material, due to the intrinsically different means and modes of production and perception, and that may be an important factor for STM functioning with these different kinds of material (Klima and Bellugi, 1979; Emmorey, 2002; Sandler & Lillo-Martin, 2006; Andin, Rönnberg & Rudner, 2010).

For spoken language, phonology is represented by the combination of sounds, while for sign language phonology refers to how sublexical components of signs are put together with respect to handshape, location, orientation, and movement (Sandler and Lillo-Martin, 2006). Signs that share one or more realizations of these features are considered to be phonologically similar (Klima and Bellugi, 1979; Sandler and Lillo-Martin, 2006).

Importantly, the perception and encoding of signs in STM rely on these phonological features, as is the case for spoken words (Boutla, Supalla, Newport & Bavelier, 2004). In the case of speech, STM mechanisms have been best described by the phonological loop model of Baddeley (1986, 2000, 2003). In this model, spoken items are encoded in STM based on their phonological properties (*i.e.*, as they sound).).

There are several distinct effects in STM, first described by Baddeley within the framework of the three-component working memory model, observed in immediate serial recall of verbal material supposedly encoded through the phonological loop (Baddeley, 1986, 1990, 2003; Gupta & MacWhinney, 1995; Neath, Surprenant & LeCompte, 1998; Wilson & Emmorey, 1997)

These effects are

- phonological similarity effect (worse recall of similar-sounding items);
- word length effect (worse recall of longer items);
- articulatory suppression effect (worse recall while articulating irrelevant sounds);
- irrelevant speech effect (worse recall while listening to irrelevant sounds)

Exactly the same effects have been observed in STM for signs (see Wilson, 2001 for review), which can lead to an assumption of basically similar mechanisms of serial information encoding, and of an existence of a mechanism analogous to the phonological loop that allows for information processing in the same way, even in absence of acoustic information, but still basing on the signed phonology of the language.

Span differences

However, when it comes to measuring short term memory span, it’s been confirmed in many different studies involving different sign languages that the span is shorter with signs as compared to speech (Bellugi, Klima, & Siple, 1975; Boutla et al., 2004; Conrad, 1970, 1972; Hall & Bavelier, 2011; Pintner & Patterson, 1917).

Reduced STM capacity has in fact been reported in American Sign Language (e.g., Bellugi, Klima, & Siple, 1975), Auslan (Logan, Mayberry, & Fletcher, 1996), British Sign Language (Conrad, 1970; MacSweeney, Campbell, & Donlan, 1996), Italian Sign Language (Geraci, Gozzi, Papagno, & Cecchetto, 2008), Israeli Sign Language (Miller, 2007), and Swedish Sign Language (Rönnberg, Rudner, & Ingvar, 2004).

Differences in STM capacities were demonstrated with stimuli as diverse as printed digits, letters and words (e.g., Belmont, Karchmer, & Pilkonis, 1976; Pitner & Paterson, 1917; Wallace & Corballis, 1973), as well as their corresponding signs (e.g., Bonvillain, Rea, Orlansky, & Slade, 1987; Krakow & Hanson, 1985; Liben & Drury, 1977). Furthermore, span differences persisted despite variations in the responses (written vs. signed; e.g., Hamilton & Holzman, 1989; Lichtenstein, 1998; Shand, 1982) or order of recall (forward vs. backward; Bavelier, Newport, Hall, Supalla, & Boutla, 2008).

As highlighted by several researchers, these differences in STM span are especially puzzling in light of other findings revealing striking similarities in the processes supporting immediate recall of sign vs. speech (Wilson, 2001). For example, span reduces as duration of stimuli increases both with signs (Wilson & Emmorey, 1998) and spoken words (Baddeley, Thomson, & Buchanan, 1975), possibly reflecting the limited capacity of STM buffer or the functioning of rehearsal mechanisms (Baddeley, 1986). Researchers have long recognized that understanding what causes such discrepancies in STM span is of potential relevance for defining STM mechanisms and how language and specific language modalities affect STM processing.

A first explanation of the phenomenon could have been the assumption that serial order processing, that is required for short term memory span task, is facilitated by the exposure to the auditory stimuli in the course of cognitive development, due to continuous stimulation and training of the sequential stimuli processing, and that is the 'Auditory Scaffolding Hypothesis' that proposes that experience with sound provides the proper foundation for the development of more general cognitive abilities related to representing temporal patterns (Conway, Pisoni &Kronenberger, 2009).

However, shorter STM spans were observed with signs produced both by deaf signers and bimodal bilinguals, i.e. hearing individuals proficient in sign language, who show a normal span when tested in their spoken language, but a reduced span when tested in sign language (Boutla, Supalla, Newport, & Bavelier, 2004; Hall & Bavelier, 2011), therefore performance in short-term memory tasks cannot be easily attributed to cognitive skills difference due to the deafness itself (Boutla et al., 2004; Hall & Bavelier, 2011).

Further attempts to characterize the source of these variations in STM span have been primarily of two types.

“Universal capacity” explanations

Some accounts have drawn attention to structural differences between signs and verbal stimuli, and assume a fundamental difference between spoken and signed language (Bellugi & Fischer, 1972), supposing that the general short term memory capacity tends to be universal and modality-independent, and searching for the answer in the stimuli characteristics.

The encoding mechanism for signs is supposed to be the same as for speech, and the signs are assumed to be elaborated through a speech-based code, with a rehearsal in short-term memory that is in many ways analogous to the phonological loop for spoken speech (Wilson, Bettger, Niculae, & Klima, 1997; Wilson & Emmorey, 1997, 1998).

Thus, the signs may be considered “heavier” in terms of processing load, since they require simultaneous integration of multiple features, such as handshape, location, movement, orientation (Marschark & Meyer, 1998; Wilson, 2001; Wilson & Emmorey, 1997; 2006; Wilson, M., Bettger, J. G., Niculae, I., & Klima, E. S. 1997;). Mann et al. (2010) show that a heavier short term memory load due to sugn language could be connected with a higher number of formational parameters as well as from lesser constraints on the possible ways these can be combined (Mann, Marshall, Mason, & Morgan, 2010).

Wilson and Emmorey in 2006 reported a study where they used letters for both groups of participants, matching for stimuli duration and phonological similarity. They controlled the spans for letters and digits with hearing participants and found that digits yield a better performance in STM. When they compared performance on letter span between signers and speakers, they found no significant differences between the groups. Their conclusion was that there’s no difference in underlying STM capacity between signs and speech, while other factors, like articulatory duration, may affect the STM span, and it’s in most cases longer for sign language than for spoken. Therefore they suggest a universal STM constraint regardless of modality

However, more recent findings show that shorter STM spans persisted even when signs were carefully matched to verbal stimuli in duration and other possible varied characteristics such as complexity and phonological similarity (Bavelier, Newport, Hall, Supalla, & Boutla, 2006; Bavelier et al., 2008; Boutla et al., 2004; Geraci et al., 2008, Gozzi, Geraci, Cecchetto, Perugini, & Papagno, 2011, Andin et al., 2013), therefore a “universal” explanation of short term memory span reduction, that supposes the only differences to be in the characteristics of the stimuli, cannot fully explain the phenomenon.

Debating with the results obtained by Wilson & Emmorey, Bavelier et al. (2006) used letter spans for both groups of signers and speakers and controlled their stimuli for articulatory duration and phonological similarity. Their results demonstrated a lower span for signers.

The studies of serial order recall in sign language have been using different stimuli and controlled for different variables. When the task in question was digit span, signers' performance was poorer than the speakers' (Koo et al., 2008; Andin et al., 2011).

However in some studies the comparison was drawn between the letter span for deaf signers and digit span for hearing speakers (Boutla et al., 2004), since they tried to select the stimuli to be as simple and phonologically dissimilar as possible. For speakers, the digits have a low phonological complexity, are dissimilar and are a subset of a limited pool of elements. To match these properties, for the signed test finger-spelled letters were selected, since they are also phonologically simple and highly familiar to signers, and a subset of highly dissimilar letters can easily be selected, which isn't for signed digits. The articulatory duration and dissimilarity was matched, but the nature of the stimuli in this experiment was different, therefore performance obtained with digits cannot be compared directly with letters.

Another counterargument to this point of view is the body of findings regarding the deaf signers' capacity of free recall: as first shown by Hanson (1982), in comparison with hearing subjects, deaf signers recall significantly fewer items when ordered recall is required, but not when free recall is required. In her experiments, she compared groups of signers and speakers in ordered recall and free recall tasks, using English words as stimuli, and found that signers showed, again, a lower recall performance in ordered recall tasks, but did not differ significantly from the hearing participants in free recall.

Therefore an important factor for span dimension is the temporal order information: as long as serial recall is not required, and items could be recalled in any order, comparable spans appeared across modalities (Bavelier et al., 2008; Hanson, 1982; Krakow & Hanson, 1985; Rudner & Rönnberg, 2008; Rudner et al., 2010). While findings from free recall demonstrate comparable encoding capacity for signs and speech, disadvantages for signs restricted to serial order recall make the hypothesis of an involvement of temporal order information highly plausible. Further converging evidence was obtained by Bavelier et al. (2008). Even when instructions allow free order recall, relative order of presentation is often preserved between some of the recalled item, as for C and D in the following example: ABCDE → ECDBA. Bavelier et al. (2008) found that relative order was more likely to be preserved in speech than sign, a result confirming difficulties in encoding serial order with visually presented signs as compared to auditorily presented speech stimuli.

Yet another evidence questioning the consideration of higher general processing load of signs is the body of findings regarding the comparisons of performance of signers and speakers in working memory tasks. Working memory refers to the capacity-limited ability to maintain and manipulate information relevant to an ongoing task, and short-term memory is the part of working memory that refers to maintenance of information for a short period of time. Individual differences in WM have also proven quite critical to account for inter-individual variability in a wide range of cognitive tasks, as well as fundamental group differences (Daneman & Carpenter, 1980; Engle, Kane, & Tuholski, 1999; Just & Carpenter, 1992).

The crucial finding in the working memory research that regards deaf signers is that their working memory capacity in a task with linguistic material has been reported to be equal to those of the speakers (Boutla et al., 2004, Andin et al., 2013). Boutla et al. (2004) used the following test for working memory: participants were presented with sequences of nouns (signed, through a video recording) and the task was to recall each noun in a separate self-generated sentence.

Andin et al. (2013) used the dual-task operation span test based on Turner and Engle (1989). Participants were presented with simple mathematical operations, where they had to judge if the displayed result was correct or not. After a sequence of 2-5 mathematical operations, the participants had to recall each displayed result in order of presentation. No language modality differences were found in this task either.

Therefore the account for a universal memory capacity impaired by the nature of signed material doesn't seem to hold, since in other tasks involving the same signed stimuli but not requiring ordered recall (free recall tasks, working memory tasks), the signers' capacity showed no difference from the speakers' one.

Modality-specific explanations

Another group of theoretical accounts for the problem of the reduced short term memory span for ordered recall of signed material hinges on the hypothesis that the reduced span is an effect of modality, stemming from greater STM capacity for encoding serial information in auditory STM as compared to visual STM (Boutla et al., 2004; Conrad, 1970; Hamilton & Holzman, 1989; Hanson, 1982; Koo, Crain, LaSasso, & Eden 2008; Lichtenstein, 1988; Miller, 2007).

In studies exploring the differences between auditory and visual modalities, it's often shown that the performance in the auditory modality is better when it comes to temporal order processing, whereas the visual modality is more adapted to process spatial information (Penney, 1989).

Reviewing the previous sign language research, Wilson (2001) comes to a conclusion that speech-based memory encodes serial order in terms of time, whereas sign-based memory may be able to encode serial order in terms of space. Evidence in favour of this hypothesis comes from different studies (Mayberry&Eichen, 1991;Wilson, Bettger, Niculae, & Klima, 1997) demonstrating that deaf participants show equally good performance in backward and forward recall tasks, while for hearing individuals backward recall task is consistently more difficult. In the experiment by Wilson et al. (1997) deaf and hearing participants were presented with digit sequences from the WAIS-R (Wechsler, 1981), using different sets of sequences for the forward (repeating the sequence in order of presentation) and backward (repeating the sequence in reverse order) recall tasks. Figure 6 shows the results of this experiment for three groups of participants: hearing speakers, native deaf signers, non-native deaf signers. The hearing and non-native groups show lower recall on backward task than in forward one. The deaf native group shows no difference. The deaf native group scored lower than the hearing group in forward recall task, but higher than the hearing group in backward recall.

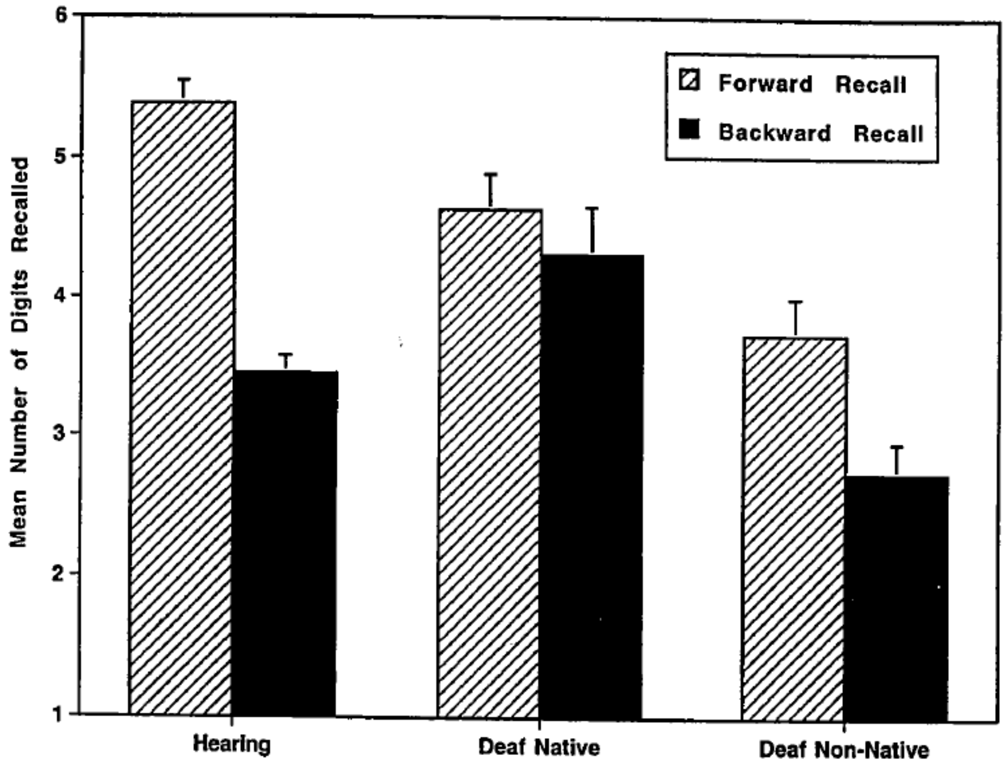


Figure 6. *Forward and backward recall in different groups (deaf native signers, deaf non-native signers, hearing). From Wilson et al., 1997.*

This leads to suggesting that it's not a reduced span per se, but a different way of encoding the order. Sign language structure favours ordering in base of space as opposed to speech which is more adapt to ordering in base of time sequence. There is evidence from sign language for a reduced memory span for "fixed location" signs (anchored to a particular part of the body and therefore impossible for a spatial rehearsal – a rehearsal in a neutral space), as compared to span for "neutral location" signs, which are formed in front of the torso without any specific collocation with a body part, and thus allow spatial rehearsal (Wilson & Emmorey, 1998). Hearing participants, however, do not benefit from associating words with specific locations in serial recall, and this may even create interference (Li&Lewandowski, 1993, 1995; Serra & Jonas, 1996).

The advantage of the auditory modality in short-term memory tasks is often explained by longer decay of auditorily as compared to visually presented stimuli, and to the automaticity of processing in the phonological loop (Baddeley, Lewis, & Vallar, 1984). Research of short term memory of deaf signers brings further evidence in support of this account, demonstrating a disadvantage for serial order verbal recall but a better performance in visuospatial stimuli recall (Emmorey, Kosslyn & Bellugi, 1993). For the visuospatial memory, deaf signers perform significantly better in tests of mental rotation (Emmorey & McCullough, 1998; McKee, 1988), memory for number in spatial arrays (Zarfaty, Nunes, & Bryant, 2004) and face recognition

(Bellugi & Hickok, 1993). Another evidence for a prevalence of a spatial coding comes from a study on deaf and hearing children: in a task where the two groups have to choose the “middle” digit from a group of three sequentially presented digits, but with a temporal order incongruent with the left-to-right spatial arrangement, deaf participants tended to choose the digit that was in the middle according to the spatial arrangement, while hearing participants tended to choose the one that was presented in the middle in terms of time-based sequence (Hermelin & O’Connor, 1975; O’Connor & Hermelin, 1973).

It’s important to note that the visuospatial advantage may be due to the exposure to sign language experience and not deafness, per se. For example, the Corsi Block task reveals higher spatial span in deaf than hearing (Wilson et al., 1997), but only in children that have had experience with sign language. Deaf children with no knowledge of sign language show the results on the Corsi Blocks Task on the same level as hearing children Parasnis, Samar, Bettger, & Sathe, 1996). Sign language experience also can enhance performance of hearing participants: hearing adults or children familiar with sign languages demonstrate increased span on the Corsi Blocks Task (Capirci, Cattani, Rossini, & Volterra, 1998; Keehner & Gathercole, 2007)

One of the important theoretical bases for explaining the verbal span reduction in sign language, speaking in the theoretical framework of the “modality-specific” approach, are the different components of the working memory model by Baddeley & Hitch (Baddeley & Hitch 1974; Baddeley 1986, 2000, 2003), and here the main assumption refers to the distinct parts of the model responsible for elaboration of stimuli: according to the different type of material presented in memory tasks, different memory components come in action and act differently, one being more suitable to the task than the other. Namely, spoken linguistic material is elaborated through a phonological loop (Baddeley, 1990; Gupta & MacWhinney, 1995; Neath, Surprenant, & LeCompte, 1998;Wilson& Emmorey, 1997), while signed information, being substantially visual in its nature, gets processed through a visuospatial sketchpad, that is less capable of encoding serial order information, since visual information does not necessarily require the appearance of elements in a specific time-based sequence, as it is inevitable in case of auditory modality, but rather allows a simultaneous space-based encoding. The mechanism underlying the visual-spatial sketchpad is possibly a storage for a mental imagery representation of the identity and the location of an object in memory (Kosslyn, 1981). In the further discussion of this model a consideration emerged that serial ordering processes in language production are maintained in verbal short term memory with a greater contribution of the process of phonological encoding (Acheson & MacDonald, 2009).

Visuospatial and verbal contributions to signers and speakers' STM

To explore the contribution of the visuospatial sketchpad (that is supposed to encode the visual-spatial information) and the phonological loop (that is supposed to elaborate verbal linguistic information) Hirshorn et al (2012) conducted an experimental study where different encoding modalities (visuospatial and phonological-verbal) were presented to deaf and hearing participants, splitting the contribution of each modality separately:

In their experiment A only the visuospatial mode of encoding was available (the stimuli were squares in different spatial locations with no letters on them), and under this conditions the signers showed a significant advantage:

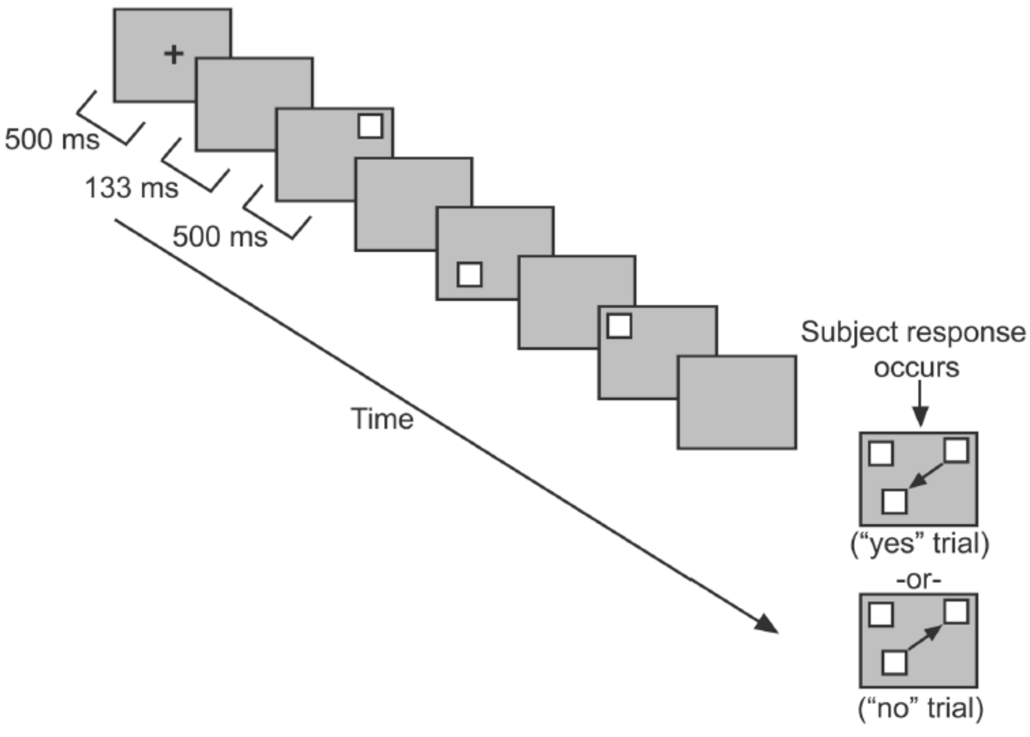


Figure 7. *Experiment A from Hirshorn et al.(2012. Participants were presented with a spatial STM task, where they had to decide whether the two squares shown on the response screen were presented in the same locations in the stimuli sequence ("yes" trial) or one of them was in a different location ("no" trial).*

However, in the experiment B, when the presented material allowed both visuospatial and verbal encoding (the stimuli were squares with letters written on them, appearing in spatial different locations), signers and speakers performed equally.

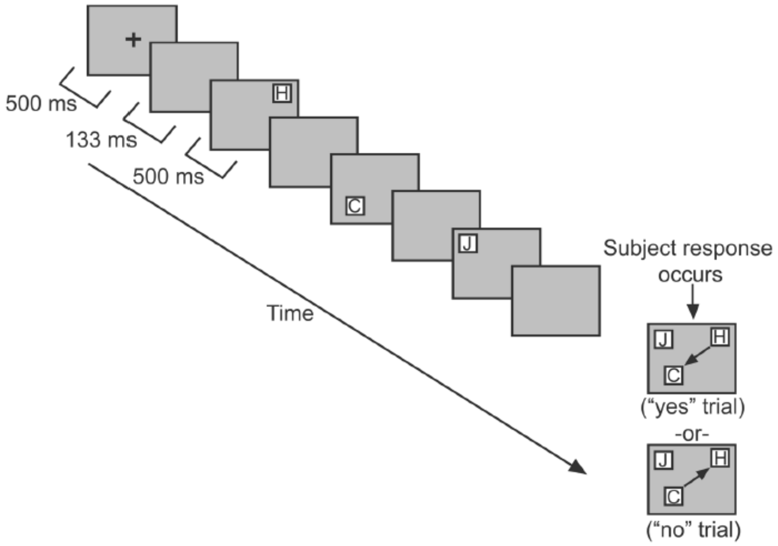


Figure 8. *Experiment B from Hirshorn et al.(2012). The sequence of stimuli was similar to those of Experiment A, but each square in this experiment had a letter on it. As a result, both phonological and spatial encoding could be used.*

In experiment C only the verbal encoding was allowed, without the spatial component (the stimuli were letters, but the response trial had no spatial collocation), the speakers showed a significant advantage:

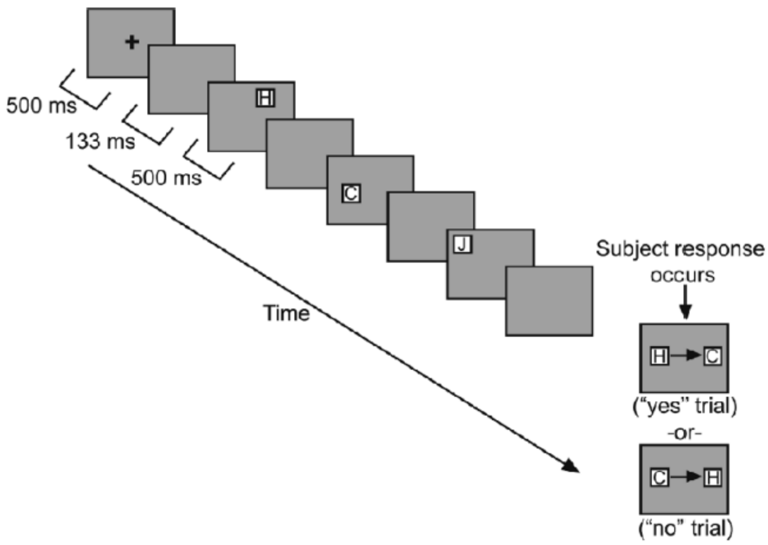


Figure 9. *Experiment C from Hirshorn et al. (2012). The sequences of stimuli were identical to those of Experiment B, but the response screen showed the stimuli centrally and not in their previous locations, ruling out the spatial encoding.*

See in figure 10:

Experiment A was designed to require precise tagging of when/where and favoured deaf signers.

Experiment B allowed both when/where tagging and phonological codes. Such dual coding raised overall performance and led to equal performance across groups.

Experiment C disabled when/where tagging and favoured hearing speakers.

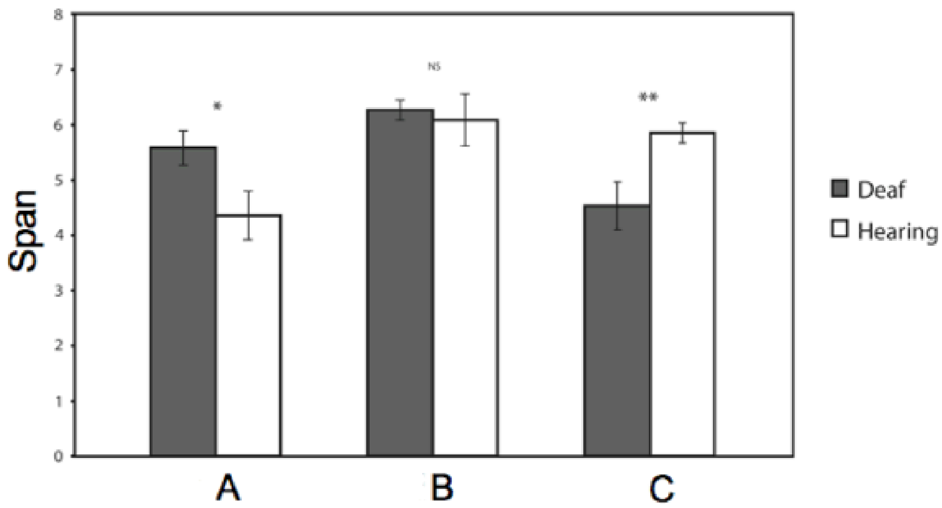


Figure 10*, from Hirshorn et al. (2012): group differences in each experiment. Deaf signers have an advantage in Experiment A, when only spatial coding was used; when both spatial and phonological coding were used, deaf and hearing spans did not differ; in experiment C, without a possibility for spatial coding, the hearing had an advantage.*

Exploring the phases of information encoding

To explore and distinguish the different stages of linguistic information elaboration, Hall & Bavelier (2011) conducted a study where they manipulated the language of the stimulation for every stage: encoding, rehearsal and recall.

The study has been conducted with ASL/English bilinguals.

- For the experimental manipulation of encoding, the stimuli were presented either in ASL or in English.
- For the rehearsal, participants were instructed to make the shadowing of the stimuli either in ASL or in English.
- For the recall, it has been asked to provide the response in ASL or in English.

Their results show a significant disadvantage of sign language in the encoding phase, but no difference for the rehearsal and even a slight advantage for the recall.

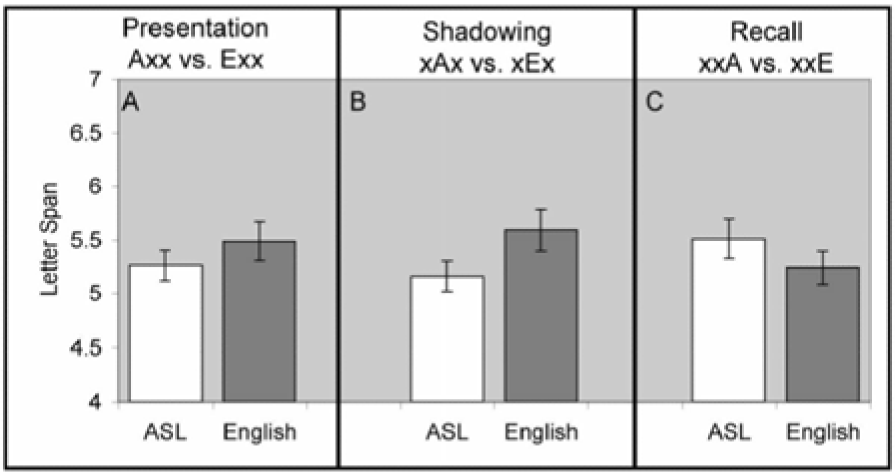


Figure 11*, from Hall & Bavelier (2011). The results of the experiment show that using speech for presentation and shadowing works for a higher span, but recall favours sign. Error bars represent SEM.*

Results described above seem to converge to a suggestion that shorter memory span for signed material can be demonstrated on certain kinds of stimuli, but the source and mechanisms of such a difference still remains unclear and not fully explored.

Our experimental work aims to contribute to the investigation of the association between the reduced span for signed material and the limitations of short-term memory processes of encoding temporally ordered linguistic information in absence of acoustic spoken input, basing only on signed information.

SERIAL ORDER ENCODING

In the studies of short term memory, findings from free recall demonstrate comparable encoding capacity for signs and speech, so the disadvantages for signs are restricted to serial order recall. Here arises the hypothesis that temporal order information is involved in these encoding processes and is one of the key elements of the difference between encoding of signs and speech.

Even when instructions allow free order recall, relative order of presentation is often preserved between some of the recalled items, as for C and D in the following example: ABCDE → ECDBA. Bavelier et al. (2008) found that relative order was more likely to be preserved in speech than in signs, a result confirming difficulties in encoding serial order with visually presented signs as compared to speech stimuli presented in auditory modality.

It seems necessary to investigate deeper the properties of the order encoding that lead to the reduced span for signs, to find an explanation of the limitations of visual STM processes in encoding temporal sequences. It is therefore important to understand how serial order positions are encoded in short-term memory and whether there are differences in order encoding mechanisms between signs and speech representations.

Sequence representations contain information both about the identity of the items, as well as their positions. The position of an item in a sequence could be defined using a variety of p*osition representation schemes* (Fischer-Baum, McCloskey & Rapp, 2010).

Schema of order, that is a set of representations and processes that determine the sequence of specific items independently from the content of what is being ordered, is a concept first described by Lashley (1951). He suggested that different types of cognitive processes involving serial order elaboration use the same schema of order. "Analysis of the nervous mechanism underlying order in the more primitive acts," he writes, "may contribute ultimately to the solution even of the physiology of logic". From this point of view, the schema of order is a general principle which determines how the position of an item in a sequence is represented, independently of the item's specific features. Grossberg (1978, 1986) pointed out the limited neuronal capacity for computational operations, which, according to his view, leads to "saving" by means of using the same representational scheme for different domains. Wickelgren (1969) suggested that position of an item in a sequence is represented as context-sensitive associations between items. Many authors come to a suggestion propose a specific representational scheme, where the beginning and end of a sequence are the anchoring points for position representation scheme (Mozer, 1987, 1989; Jacobs, Rey, Ziegler, & Grainger, 1998; Endress et al., 2009). Peressotti & Grainger (1999) propose a scheme of encoding according to three anchor points: the beginning, the end and the middle of the sequence (the eye fixation position). The middle anchor point serves to assign a minimal amount of relative-position information to the surrounding elements of the sequence.

In various cognitive tasks where order representation is required, similar patterns have been observed, which counts as evidence supporting the hypothesis of existence of a general position representation scheme (e.g., Acheson & MacDonald, 2009; Glasspool, 1998; Houghton & Hartley, 1995). The persisting tendencies across these tasks are:

- Beginning and end specificity: elements closer to the beginnings and ends of sequences are more likely to be recalled accurately.
- Length effect: the recall accuracy decreases with longer sequences.
- Similarity effect: if the elements of a sequence are similar, the recall accuracy decreases (including incorrect order in recall and transpositions of elements)
- Recency intrusion effect: elements from recent responses are more likely to be erroneously recalled within the current sequence.

These similarities suggest that the mechanisms and/or representations used to produce items in the correct order are not unique to a specific sequence type.

There's an extensive body of research regarding the theoretical and experimental approaches to serial position representation in immediate serial recall (Botvinick & Plaut, 2006; Brown, Preece & Hulme, 2000; Brown, Neath & Chater, 2007; Burgess & Hitch, 1992, 1999, 2006; Farrell & Lewandowsky, 2002; Henson, 1998; Lewandowsky & Farrell, 2008; Lewandowsky & Murdock, 1989; Page & Norris, 1998; Wickelgren, 1965) The central questions regard the specific way of encoding a position of an item in a sequence, for example, if the stimulus presented is ABCDEF, how would an individual represent the position of the C?

Some theories of immediate serial recall (e.g., Brown, Preece, and Hulme, 2000; Burgess & Hitch, 1992; Lewandowsky & Farrell, 2008) assume beginning-based position representations, where an item in a sequence is encoded with respect to the distance from the beginning of the sequence. According to a beginning-based scheme, the C in ABCDEF is in the third-from-the-start position (S+3).

Other theories suggest the end-based scheme where an item is encoded basing on the distance from the end of the sequence (e.g., Neath & Crowder, 1990). According to the end-based scheme, the C in ABCDEF is in the fourth-from-the-end position (position E-4).

Yet another theories stand for both-edges representations (e.g., Henson, 1998; Farrell & Lelièvre, 2009), where the positions are represented with respect to both beginning and end points of the sequence (i.e., in ABCDEF the C would hold the position S+3 and E-4). Different theories that posit the both-edges representation scheme have different views on whether all list items (Henson, 1998), or only the last (Farrell & Lelièvre, 2009), are coded in relation to the end of the list.

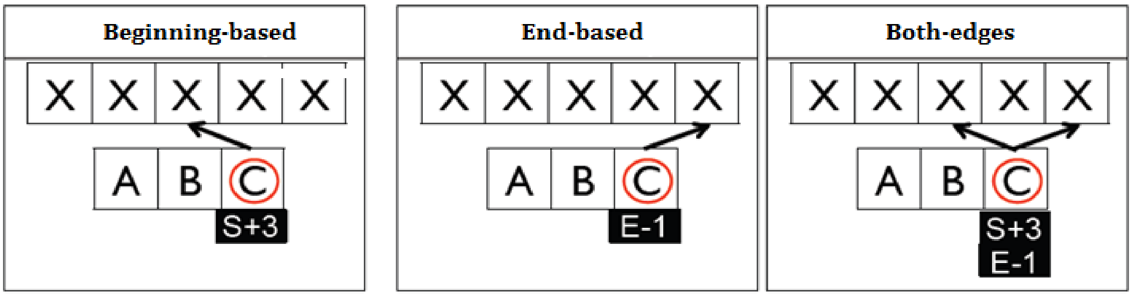


Figure 12. *Position representation schemes: beginning-based, end-based and both-edges.*

Another way of approaching the question tends to explain position representation in terms of chaining or item-to-item association, where the position is dependent on the surrounding elements of a given item. (e.g., Lewandowsky & Murdock, 1989; Wickelgren, 1965).

Context-dependent schemes, in which an item's position is represented with respect to other items in the list, garner some support from results demonstrating that associations between items within a list influence serial recall performance (e.g., Baddeley, Conrad & Hull, 1965; Botvinick & Bylsma, 2005; Wickelgren, 1966; Lewandowsky & Murdock, 1989). In a context-dependent scheme the C in ABCDEF might be represented as the letter following B and preceding D.

There are also hybrid theories of immediate serial recall, that integrate some features of context-dependent schemes, combining them with and non-contextual position schemes (e.g. Botvinick & Plaut, 2006; Dennis, 2009; Solway, Murdock & Kahana, 2012).

Extensive research of position encoding has been conducted with hearing participants on different kinds of material organized in sequences (sequences of letters in spelling, sequences of sounds in spoken production etc.).

Many researchers suggest an existence of common processing mechanisms for encoding of different types of material (e.g. words versus locations, Depoorter and Vandierendonck, 2009; lexical versus sublexical units, Martin and Gupta, 2004). If the mechanism is indeed common for various types of stimuli, then the encoding should be supposed to use the same representational scheme.

Several lines of evidence show that for many types of stimuli the positions are represented with respect to both beginning and end positions (Farrell & Leliévre, 2009; Henson, 1998). That is, the position of D in the sequence ABCDE is represented by specifying its distance from the beginning of the list (fourth-from-the-start position; S+4) as well as from the end of the list (second-from-the-end position; E-2).

This both-edges scheme – where the position is anchored relative to both the beginning and end of the sequence – underlies position representation for nearly all of the sequence types tested – letters in reading and spelling, phonemes in spoken production, words in verbal working memory, object orientations in spatial working memory. This both-edges position representation scheme, therefore, appears to be a general principle of position representation used by a number of different cognitive systems (Fischer-Baum & McCloskey, 2014).

However, this positional encoding scheme does not apply to all types of material. For non-verbal material – a sequence of visually presented locations on a grid, a beginning-based representation scheme is used. i.e. an element is anchored only basing on its distance from the beginning of the sequence (Fischer-Baum, 2010)

A subsequent distinction has been cleared between discrete and graded schemes (Glasspool, 1998; Glasspool & Houghton, 2005; Houghton, Glasspool & Shallice, 1994, Henson, 1998).

A graded scheme suggests that there is a similarity structure among the symbolic representations of position such that symbols that represent nearby positions are more similar than symbols that represent far away positions (Fischer-Baum, 2010). Graded schemes weigh the relative strength of the position based on how far an item is from the reference point. According to this approach, the farther an item is from a reference point, more weakly it is encoded in a position defined relative to that reference point. Graded position representations have been used in a number of position representation schemes (e.g., Burgess & Hitch, 1999; Davis & Bowers, 2004, 2006; Gomez et al., 2008; Houghton, Glasspool & Shallice, 1994).

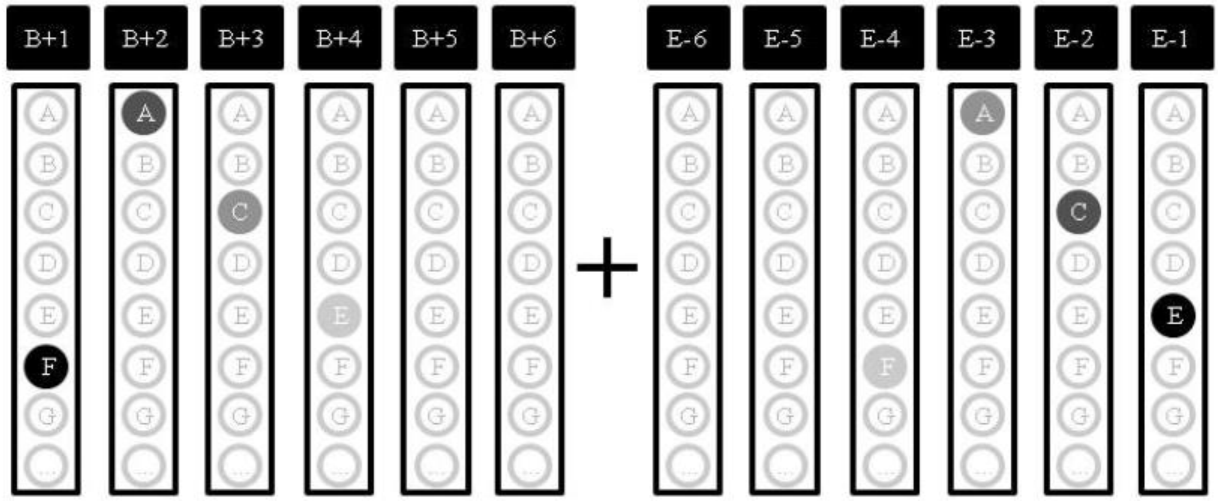


Figure 13. *The representation of the word "face" according to a both-edges scheme where the weight of a position representation decreases with distance from referent edge. (from Fischer-Baum, 2010)*

The present research has been focused to explore the positional encoding scheme used by signers. We investigated whether evidence of both-edges positional scheme can be found when signs are the stimuli for immediate ordered recall. Evidence of a both-edges positional encoding in ordered recall of signs would provide evidence supporting the hypothesis that discrepancies in STM capacity between sign and speech do not reflect differences in the representation of item position within a sequence, and the underlying positional encoding mechanism could be supposed to be substantially the same. If, however, evidence of a different positional representation scheme would have been found, this would reveal that STM representations of signs lack an important component for position coding that allows for a more efficient immediate recall with speech. As an alternative hypothesis a beginning-based scheme may be expected for signs serial recall, as it has been found in tasks requiring encoding of visuospatial material (sequences of spatial locations).

Critical evidence on the encoding schemes of sequences of items in verbal STM was gained from intrusion errors. Intrusion errors arise when an item not included in the original sequence appears in the recalled list. An example is F in the list ABCDFE produced in recall instead of the expected sequence ABCDE which was the stimulus. Intruded items are often items that appeared in one of the immediately preceding responses that are produced in serial recall tasks (Conrad, 1960; Estes, 1991; Osth & Dennis, 2013; Werner, 1947). That is, some of the intrusion errors are likely to be so-called *perseverations* from prior responses. This would be case if the intruded letter F in the previous example ABCDFE appeared in the immediately preceding response MXBFT. The sequence from which the perseveration originates can be called the *source* of the perseveration.

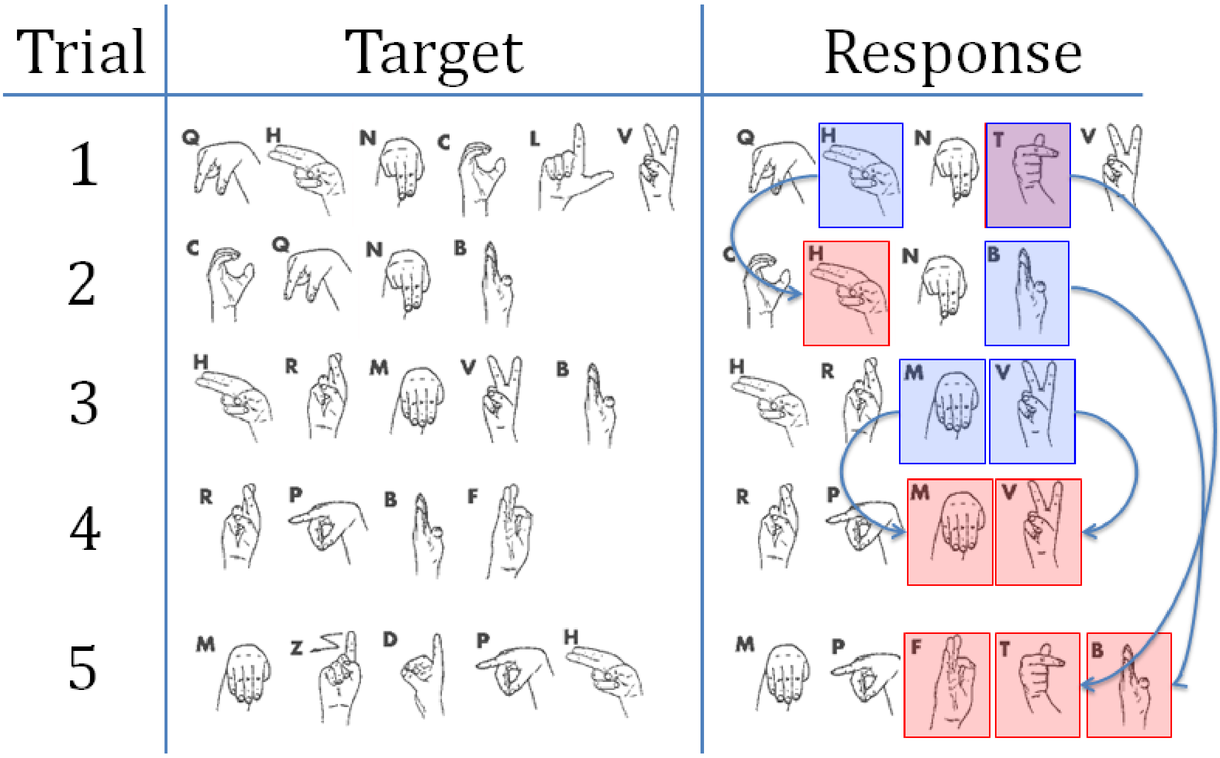


Figure 14. *Intrusion errors are marked in red. Intrusions that are perseverations are connected by arrows with their sources. Sources are marked in blue.*

Perseverations are potentially informative for accounts on serial position encoding if perseverated items occur at positions not determined by chance but rather depending on the positions of the perseverated items in prior responses. The position of the intruded item often tends to match the source position (Conrad, 1960; Estes, 1991). If we look at two first trials in the figure 14, we can see that the intruded H in the second response maintains source position according to beginning-based scheme (position S+2, i.e. second from the beginning).
However, it's not the same position according to an end-based scheme: from its point of view the intruded and source items are in different positions (E-4 and E-3, respectively). More generally, in cases when the source and the response containing the intrusion are not of the same length, beginning-based and end-based schemes are different in terms of what counts as the same position, and therefore may be different with respect to whether the intrusion position counts as matching the source position.

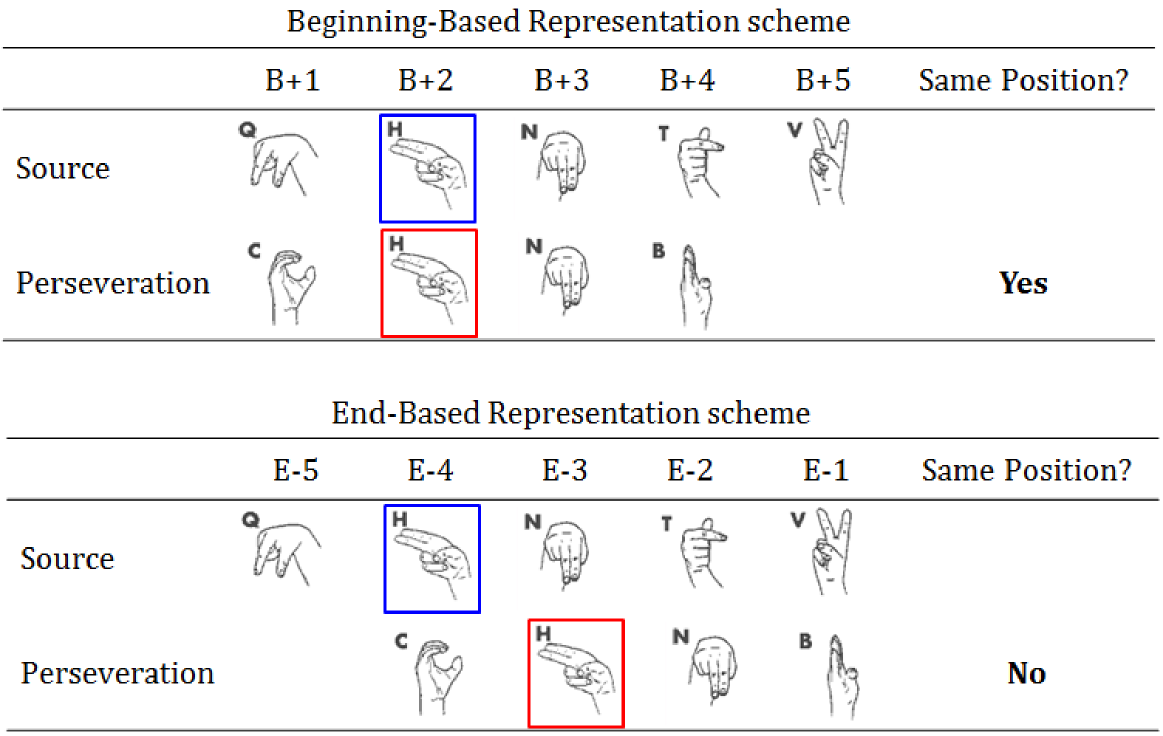


Figure 15. *Intrusion that maintains position according to a beginning-based representation scheme.*

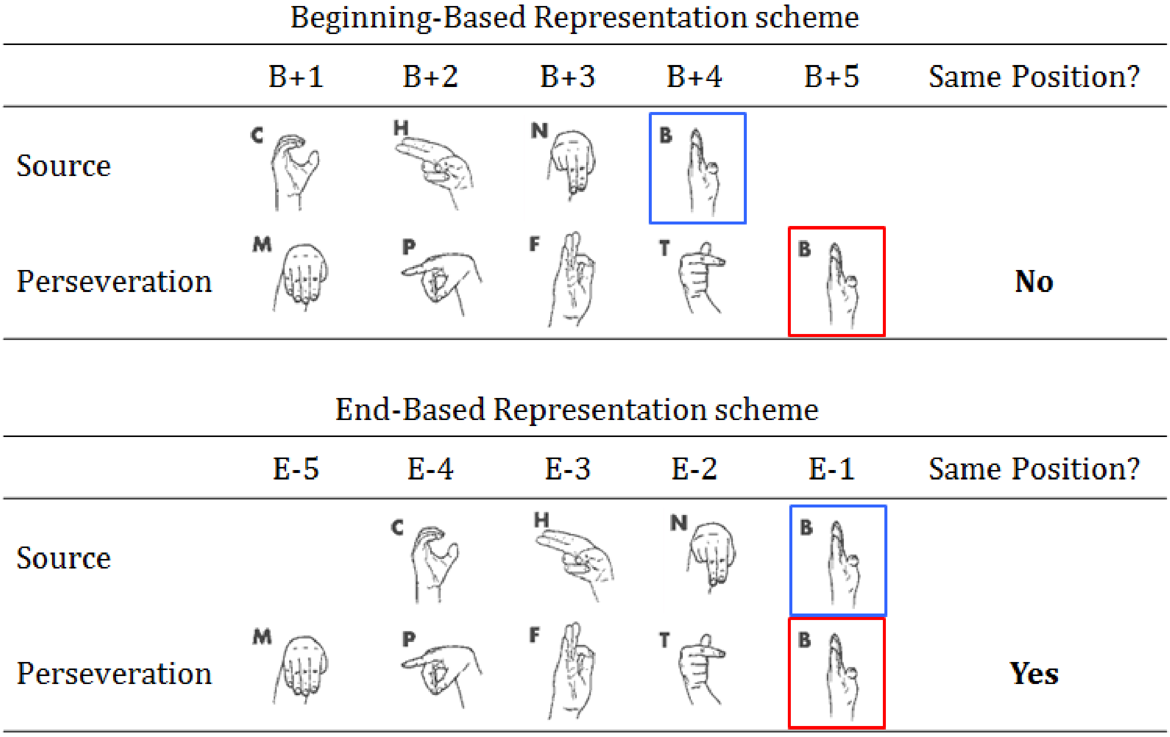


Figure 16. *Intrusion that maintains position according to an end-based representation scheme*

According to Henson (1999), perseverations produced in verbal serial recall tasks not only differed from distributions expected by chance, but they also conformed to predictions of accounts positing beginning- and end-based positional encoding.

What is important here is to find the way to establish whether those errors maintaining position are just a product of random chance or they are anchored to certain positions. To test for the casual probability of this pattern of errors, a Monte Carlo analysis is used, generating control response pools to estimate the proportion of intrusion errors at a given position expected by chance, and the simulated pool of errors is subsequently compared with the data obtained in the experiments. For every intrusion error produced in the experimental data set, the program randomly samples a response from the control pool, and specifies whether that response included the intruded letter. The program then computes the proportion of sampled control responses that contain the intruded letter. This random sampling of a control response for each letter intrusion, and the computation of the proportion of responses that contained the intruded letter is carried out 10,000 times for the complete set of letter intrusions for each participant, thus producing 10000 simulated samples of possible responses, each of them containing a certain number of intrusion errors that could be produced purely by random chance.

STUDIES OF SERIAL ORDER ENCODING IN SIGNERS

Experiment 1

In the previous chapters we revised the research done so far in the field of short-term memory in general and short-term memory for signs in particular. The data obtained by the moment gives a strong evidence support to the fact that the short-term memory span for signs is significantly lower, than for spoken verbal material. However, the reduction of memory capacity for signs regards only the case of immediate serial recall: in free recall tasks and working memory tasks there are no differences between signers and speakers. Therefore we may suggest that the problem lies in the domain of serial order encoding.

Mechanisms of serial order encoding have been studied profoundly with different kinds of material in hearing participants, but there's been much less research on that with signs. Many researchers, exploring the way in which hearing speakers encode verbal material, come to a conclusion that they use a both-edges scheme, i.e. one where a position of an element in a sequence is encoded with respect to the beginning and the end of the sequence. While this is true for verbal material, another kind of result emerges when the stimuli are of a visuo-spatial nature, without a verbal component to them (e.g. a sequence of locations of squares): in this case, hearing speakers make use of a beginning-based scheme, anchoring the position of an element in the sequence only to the beginning point.

The signs are with no doubt verbal material, but they are also presented in a different modality from spoken language, and that brings them close to the visuospatial domain. Many theoretical explanations of span reduction for signs regard the modality specificity of serial order encoding capacities, stating that the auditory modality is best suited for it.

One of the possibilities to make these questions clearer is investigate the way in which serial positions are represented in case of signs. We may apply the methods of position representation studies, used with hearing speakers, to an experiment with signers. Then we may compare the results with those obtained with a population of speakers, and investigate the similarities and/or differences of the serial encoding schemes. We may expect to obtain a beginning-based encoding scheme, if the signs in an immediate serial recall task are inherently visuospatial, and the differences are due to modality specificity; or otherwise, we may expect a both-edges encoding scheme, if the signs are treated in the same way as spoken verbal material

Exploring the encoding scheme for signs is important to for a better understanding of the nature of the short-term memory mechanisms underlying the serial order position elaboration, and providing additional evidence for the existing theoretical debate of the nature of the phenomenon of sign span reduction.

In the present experiment we explore the mechanisms underlying serial order encoding for sign language, using signs as stimuli. We analyse the errors that participants make in immediate serial recall of sequences of signs, to explore the scheme of position representation.

Participants

Twenty deaf signers took part in the experiment (8 female; mean age = 17.5, SD = 2.8, range = 14-25). They were deaf from birth or became deaf before age 2. They were students of Magarotto institute in Padua, a specialized institution, where Italian Sign Language is a principal means of communication and teaching. A short questionnaire was given to the participants before the start of the experiment, which was subsequently stored being associated only with the subject number and not participant's name. The questionnaire is reported in Appendix 1.

All participants were informed about the nature and aims of the experiment, they participated on a voluntary basis and had a possibility to terminate the participation at any moment. All the explanations have been translated in sign language and given to the participants by one of the Magarotto institute teachers.

The participants who were over 18 years old signed the informed consent, reported in appendix 2.

For those who were under 18, the parents were informed about the nature and aims of the experiment, and signed the informed consent transmitted to them by Magarotto institute teachers. The parents' informed consent is reported in Appendix 3.

The participants were proficient in Italian Sign Language (self-report and teachers' assessment), had little ability and knowledge of spoken language, but were relatively good in lip reading and possessed knowledge of written Italian (reading and writing abilities). All participants were deaf from birth or became deaf before the age of 2. Two of the participants had hearing aid devices, installed at age 12 and 15. 13 of the participants were born to deaf parents. 7 of the participants had deaf siblings. 6 other participants had hearing siblings. 14 of the participants learned Italian sign language before 3 years of age, 6 others – before 7 years of age (self-report data).

Method

Materials. Letters from the Italian Sign Language were presented as stimuli in the STM task. To avoid sequences corresponding to Italian words or syllables, we only showed the 16 consonants used in this language (B, C, D, F, G, H, L, M, N, P, Q, R, S, T, V, Z). Sequences varying in length from 4 to 7 items were created by randomly selecting these signs with the constraint that a letter was not repeated within a sequence. Sequences exceeded the span of deaf populations (~4; Bavelier et al., 2006; Boutla et al., 2004; Marschark & Mayer, 1998) to elicit the perseveration errors on which the present investigation focused. A total of 120 letter sequences were created for each participant. Sequences of various lengths were equally represented (N=30) and individual letters appeared between 40 and 45 times within the list presented to each participant. Consonants require one-hand signs in Italian Sign Language, and while the signs of the consonants G, H, P, Q, R, S, and Z involve movements, those of the other consonants are still. Signs were videotaped by a native Italian Sign Language speaker. Each sign was filmed starting from a neutral position (hands put still in the lower end of the screen frame), had all the sign execution movement, and a return into neutral position. A video for each sign was 1 second long. Within each sequence, signs appeared at 1 s intervals, the presentation rate used in several prior studies on the STM of signs (e.g., Conrad 1970, 1972; Emmorey, 2003; Hanson 1982; Wilson & Emmorey, 1997). Following Henson (1999), sequences were presented in a pseudo-randomized order so that immediately adjacent lists were never of the same length. This procedure facilitates the testing of alternative accounts of position encoding, since in case of same-length responses it's impossible to discern between beginning-based and end-based position representation schemes: an intrusion in a given position accounts for both (for example, if the source and the persevered response have the same length, like CHNB-QHRT, then the intruded letter (H) preserves the source position according to both schemes.). Like in Fischer-Baum and McCloskey (2014, in press), identical letters were allowed to appear in consecutive sequences.

Procedure. Participants started each memory trial by pressing the space bar of the keyboard, which triggered the presentation of a sign sequence on the computer monitor. Immediately after the presentation of the last sign in the sequence, the response screen appeared with a written instruction indicating participants to repeat, by signing, the sequence they just saw. Few of the previous studies on STM and deafness (e.g., Hamilton & Holzman, 1989; Krakow & Hanson, 1985; Lichtenstein, 1998) showed written stimuli or required written responses, a procedure demanding a print-to-sign translation that would further reduce the STM span recorded from deaf participants. To avoid such a translation and investigate STM processing more directly, both stimuli and responses involved signs in our studies. Instructions, presented in Italian Sign Language, explicitly required producing the signs in the order in which they were presented. A short practice session of 12 trials preceded the experimental task. Signed responses were videotaped for scoring purposes, the videos were then encoded anonymously (not preserving the link between the participant's identity and the scored responses, leaving only participant's numbers as identifiers), providing lists of letters.

Results

Deaf participants recalled the entire sequences 13% of the times, with accuracy steadily declining as sequence length increased (4-letters = 47%; 5-letters = 22%; 6-letters = 6%; 7-letters= 2%; F (3,57) = 53.3, $p < .0001$, all pair-wise comparisons were significant at $p < .01$ by Tukey HSD test except the difference between 6- and 7-letter sequences). Responses exhibited primacy effects, as shown in Figure 17, and recency effects were observed for the shorter lists (4- and 5-letters) but not for the longer lists (6- and 7-letters). Errors included omissions (FLTRS → FLTR), movements (FLTRS → FLRTS), and intrusions. The latter were defined as errors in which letters not present in the stimulus sequence appeared in the response as additions (FLTRS → FLTRPS) or substitutions (FLTRS → FLTGS). Incorrect responses could also include multiple errors, as in FLTRS → FTLC where L and T exchange their positions, R and S are deleted, and C is intruded. Some of the consonant names sound similar in Italian, for example B (/bI/) and C (/tʃI/) that share their vowel.

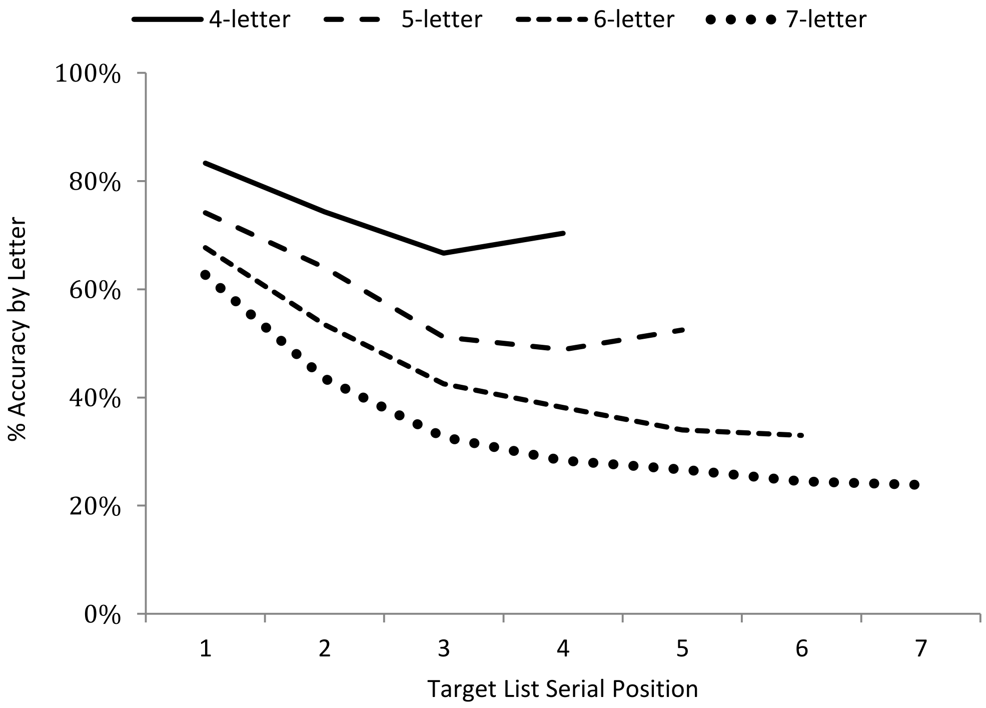


***Figure 17**. Serial position effects for lists of signed letters of different lengths. While primacy effects appeared with all lists, recency effects appeared only with short lists (4- and 5-letters).*

Intrusion Error Analyses

Many of the errors produced in our STM task were intrusions, with approximately half of the erroneous responses including at least one intruded sign. Intruded signs often occurred in one or more of the several immediately preceding responses, raising the possibility that some of the intrusions were perseverations from prior responses. An example is illustrated in Table 1. The response on trial T contains the intruded sign H that also appears in the response QHNTV produced on trial T-1, immediately prior to the response intrusion. Conceivably, then, the sign H was a perseveration from the T-1 response. However, an intruded item could have occurred in a prior response simply by chance (Page & Norris, 1998). To demonstrate that the intrusions observed in our STM task represented true perseverations from prior responses, we must show that the intruded signs appeared in the prior responses more often than expected by chance. After we identify the perseverations, and if we find that they happen to occur more frequently than expected by chance, we may move on to the position representation scheme analysis.

Perseveration Analysis

We analysed the sign intrusions pooled across all 20 participants. A computer program first tabulated whether an intruded sign was produced in the response on trial T-1. Based on these tabulations, the program calculated the percentage of intruded signs produced in the corresponding T-1 responses. Next, the program computed the percentage of intruded signs that did not appear in T-1 responses but did appear in T-2 responses. The program then computed the percentage of intruded letters that did not appear in T-1 or T-2 responses, but were part of T-3 responses; and so forth through trial T-5. The percentages of intruded letters repeated in trials 1-5 are shown in Figure 17 (solid line). These results reveal that, for example, 56% of the sign intrusions (985/1746) were previously produced on trial T-1.

The computer program also estimated the likelihood of an intruded sign occurring by chance in trials T-1 through T-5. It was reasoned that if an intrusion was unrelated to the intruded item appearing in the immediately preceding responses, then the intruded item should be just as likely to occur on trials distant from the intrusion trial. Chance estimates were computed using the Monte Carlo analysis described in Fischer-Baum et al. (2010) and McCloskey et al. (2006). The analyses were carried out for trials T-1 through T-5 and chance estimations were calculated for each trial. We illustrate the procedure with reference to T-1 trial.

For each of the intruded signs—whether or not the actual T-1 response contained the intruded sign — a *control response* was selected at random (by the program) from among the responses that (a) had the same length as the actual T-1 response, (b) were made by the same participant, and (c) came from a trial outside the vicinity of the intrusion trial (i.e., beyond five trials preceding/following the intrusion trial). For example, in the case of the intrusion error CQNB → CHNB illustrated in Table 1, 39 control responses were identified (e.g., PNGTV, BQMDV, VPNHD) that matched the T-1 response QHNTV for length and and that were outside the vicinity of the intrusion error. By chance, the intruded sign could be included in the control response, an event that in our example could have happened in the response VPNHD.

Table 1*. Error CQNB → CHNB and the five immediately preceding responses*

Trial	Stimulus List	Response
T-5	PQNTL	PNL

T-4	TDGRF	TMRFG
T-3	STFWM	STFWM
T-2	PLMR	PLG
T-1	QHNTV	QHNTV
T	CQNB	C<u>H</u>NB

On each run of the Monte Carlo analysis, a control response was randomly selected for each of the 1746 observed intrusions, and it was then tabulated whether the signs forming the control responses matched the intruded signs. The result of each run of the Monte Carlo analysis is a single estimate of the % of perseverated signs for which a match between perseveration and source is expected by chance. The entire process was carried out 10,000 times, yielding a distribution of chance percentages for T-1 responses. The same procedure was independently applied to the other prior responses (T-2 to T-5). The analysis technique and computer program used were based on Fischer-Baum, McCloskey & Rapp, 2010. Results of the chance analysis are presented in the dotted line on Figure 17. Averaging across the 10,000 runs of the chance analysis program for the T-1 response, 35% of the intruded signs matched a sign in the control responses. In none of the 10,00 runs was a value as high as or higher than the observed value for T-1 responses (56%) found, indicating a p-value of less than 1/10,000 ($p < .0001$). Reliable differences from chance also appeared in trials T-2 ($p < .05$), but not in trials T-3 through T-5 (*p*s > .5). In short, there appears to be genuine perseverations of signs from T-1 and T-2 responses. These results also provide an empirical basis for defining the *window of perseveration* — the range of preceding trials from which items may perseverate into the current response — that, for letters, appears to span two trials.

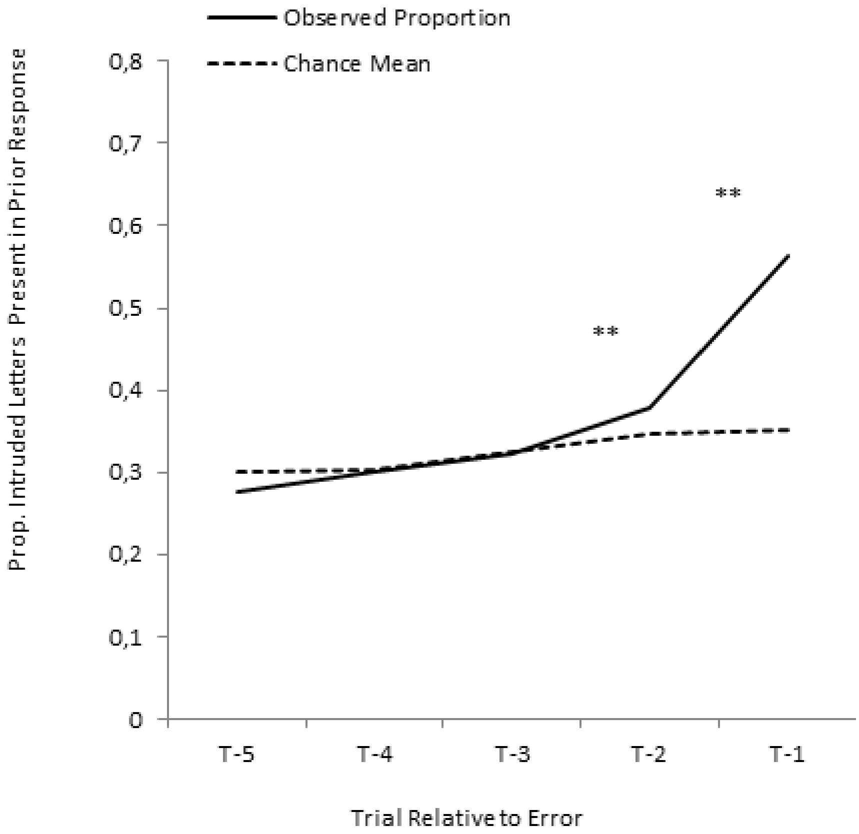


***Figure 17**. Distribution of perseverated signs on the five immediately preceding trials: observed responses (solid line), mean proportion expected by chance based on Monte Carlo chance analysis (dashed line). Reliable differences from chance appeared on T-1 and T-2 (** indicate p < .0001).*

Position Analyses

The following analyses are aimed to shed light on how positions are encoded in representations held during the immediate recall of signs. They were conducted on potential perseveration-source pairs in which the intruded sign appeared in one or more of the responses within the perseveration window that, as revealed by the analyses above, includes up to 2 trials prior to the error. A total of 1742 such pairs were identified across participants. The whole sample comprises a mix of “true” pairs and “pseudo” pairs that correspond to responses in which the intrusion is either not a perseveration from a prior response or is not paired with its true source. We had no way of discriminating between true and pseudo pairs. Fortunately, even when using the whole sample, it is possible to determine if *true* perseverations maintain the position of the persevered letter in the *true* source more often than expected by chance. Because, by definition, the intrusions in pseudo pairs are unrelated to the sources, they should appear in source positions no more often than expected by chance. Rates of matching positions exceeding chance level would then constitute evidence that *true* perseverations maintain *true* source positions, even if obtained from the whole sample. The following analyses were conducted on the whole sample.

Analysis 1: Observed vs. chance position matches. This analysis represents a first attempt to establish whether sign positions are specified with respect to both edges (beginning and end), the form of encoding that previous research has demonstrated to be at play in verbal STM (Henson, 1999). Specifically, it was examined whether the matched positions expected by beginning- or end-based schemes exceeded those expected by chance within the whole sample of potential perseveration-source pairs.

A computer program (developed by Michael McCloskey and Simon Fischer-Baum, see Fischer-Baum, McCloskey & Rapp, 2010) assigned positions according to each scheme, and computed whether or not positions were maintained between perseverations and sources. We illustrate this point returning to the example in Table 1 of the sign H appearing in the perseveration response C<u>H</u>NB as well as in the T-1 response Q<u>H</u>NTV. The positions in which H appear in the two responses are identical when defined from the start edge (S+2), different when defined from the end edge (E-3 and E-4). Hence, the program tallied a position match only for the beginning-based scheme.

The program also estimated the proportion of position matches expected by chance under each positional scheme. Chance was estimated on the basis of source control responses, defined as responses that (a) contained the intruded letter , (b) had the same number of letters as the source responses, (c) were produced by the same participant, and (d) did not occur in close proximity to the perseveration responses. To be consistent with the previous analyses, control responses were outside the range from five trials preceding through five trials following the intrusion trials. The procedure of the Monte Carlo analysis used for random sampling and position matching was similar to the one described above for the perseveration analyses; in each run of the chance analysis program, the actual source response was replaced with a randomly selected source control response, and the proportion of these perseveration-source control pairs that matched position by each position representation scheme was tabulated (as in Fischer-Baum, McCloskey & Rapp, 2010 and McCloskey, Fischer-Baum & Schubert, 2013). The chance analysis program was run 10,000 times.

Intruded letters appeared in the same beginning-based position in 24% of the perseveration-source pairs (421/1742), a higher rate than the chance baseline (19%; $p < .0001$). In fact, a rate as high as or higher than 24% was not found in any of the 10,000 runs of the chance analysis program.

For the end-based scheme, the observed rate was 23%, while the chance rate was 20%, and in none of the 10,000 runs ($p < .0001$) was a rate as high or higher than the observed one.

While the latter results suggest that both schemes contribute to the representation of sign positions, the fact that both schemes can equally account for some of the results introduces a potential confounding, which in turn complicates the result interpretation. The confounding occurs when perseverations and sources have the same length (e.g., CHNB-QHRT) because the intruded sign (H) preserves the source position under both schemes. Such a confounding makes it difficult to accurately determine the independent contribution of each scheme. This problem was addressed in Analysis 2.

Analysis 2: Comparing beginning- vs. end-based scheme. Using a *residual* analysis it can be determined whether those pairs that do not match position by one scheme, are more likely to match position by the other scheme, a procedures that permits an accurate characterization of the independent contribution of each scheme. Analyses examined both schemes and are illustrated here with respect to the beginning-based scheme. To assess whether the beginning-based scheme makes systematic contribution above and beyond the end-based scheme, we analysed *residual pairs*, which are potential perseveration-source pairs for which the end-based scheme failed to predict the source position of the intruded letter. The pair CHNB-QHNTV represents an example, since the intruded letter H occurs at position E-3 and E-4, respectively. It was then determined whether the beginning-based scheme was more successful than the end-anchor scheme in predicting the source position of the intruded letters with residual pairs.

The end-based scheme correctly predicted the source position of the intruded letters for 400/1742 pairs. The residuals analysis was therefore carried out over the remaining 1342 pairs for which the end-based scheme failed to predict the source position. The beginning-based scheme correctly predicted the source position for 273 of the residual pairs (20%). Chance was evaluated in the exact same manner in the residual analysis as it was in Analysis 1, with only the residual perseveration-source pairs entered into the analysis. The observed proportion of residual pairs that matched beginning-based position was significantly greater than the proportion expected by chance (16%; $p < .0001$). Complementary residuals analyses revealed that the end-based scheme also performed above chance ($p < .0001$; see data in Table 2). In sum, residuals analyses provide strong evidence that both beginning- and end-based coding contribute independently to the representation of the position of letters in STM.

Analysis 3: Discrete vs. graded both-edges schemes. The both-edges schemes we have considered above are discrete, in the sense that they do not incorporate a similarity structure. Under these schemes, S+2 is a position that is no more similar to S+3 than S+7, nor position E-1 to E-2 than E-6. Most theories of position representation in immediate serial recall (e.g., Botvinick & Plaut, 2006; Burgess & Hitch, 1999; Henson, 1998) assume a graded representation, proposing instead that position representations vary systematically in similarity, such that representations would be more similar between nearby positions (E-2 and E-3) than distant ones (E-2 and E-7). Various lines of evidence indicate that graded representations underlie position encoding in verbal STM (Fischer-Baum & McCloskey, under revision; Henson et al., 1996). To the extent that the present investigation aims to establish whether serial positions are similarly encoded in sign and verbal STM, it is relevant to determine if similarities further extend to graded representations.

Table 2. *Residuals analyses evaluating contributions of beginning- and end-based components to success of the both-edges scheme*

Position Scheme	*Residual PS Pairs*	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
Beginning-based	1342	273 *(20%)*	209 (*16%)*	<*.0001*
End-based	1321	252 *(19%)*	213 *(16%)*	<*.0001*

However small may the difference between 16% and 19% seem for a pure number evaluation, the significance may be illustrated by a graph comparing the distribution of 10000 Monte Carlo simulation runs with the observed value, which, as can be seen in Figure 18, stands remarkably far away even from the last tail values of the chance distribution:

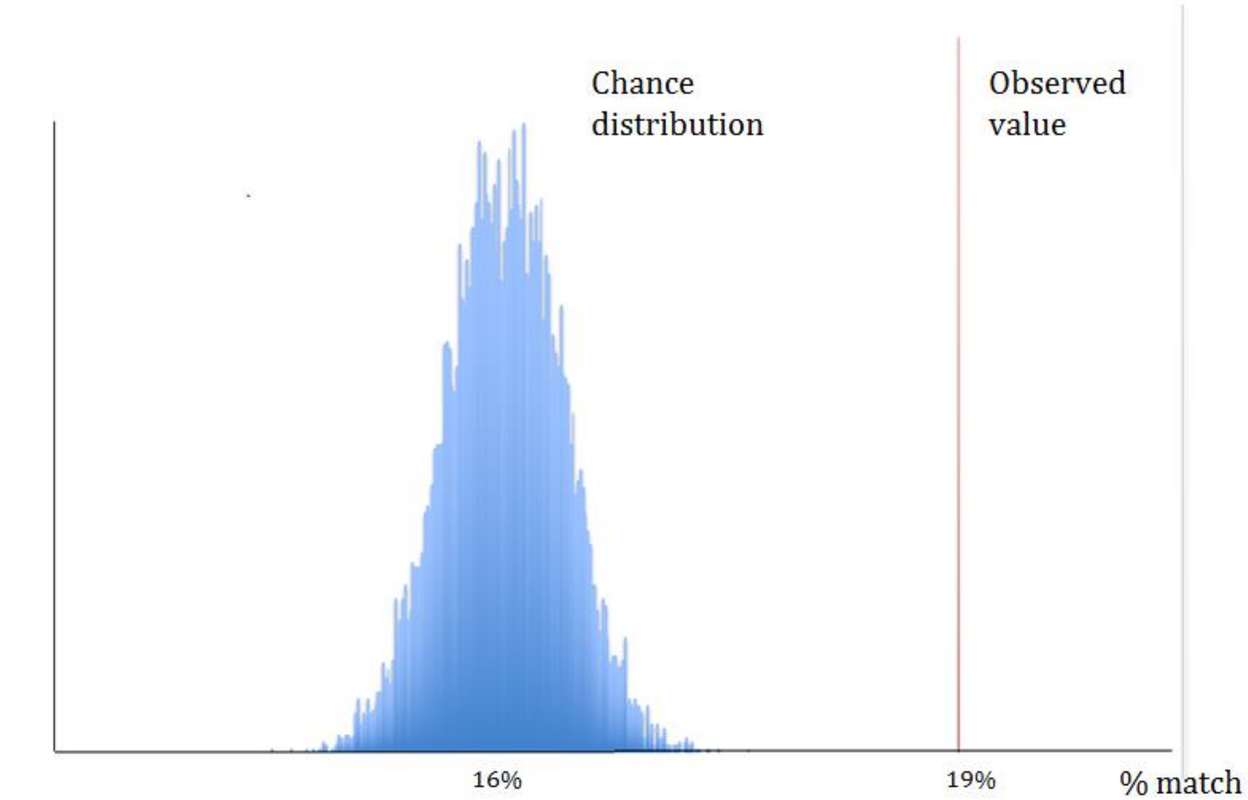


Figure 18. *Chance distribution as compared to observed value*

The analyses described above only count a perseveration as a position match if it appears in the *exact* same position in the perseveration and source response. However, if position representations are graded, we might expect to find a systematic pattern of perseverations matching on *approximate* position, in addition to the *exact* position matching pairs. For example, given a perseveration at position E-3, the most likely source would be at position E-3; however, the adjacent positions E-4 and E-2 might also be plausible sources, as those positions are represented similarly to position E-3. This critical feature of graded representations leads to predictions specific to this scheme that were tested examining adjacent positions defined with respect to both beginning and end positions. To illustrate these predictions, let us consider the error LBPZS → LBGZS that resulted from the perseveration of the letter G and was preceded by the response QGNZF. The perseveration occurred in position S+3 (coded from start) and E-3 (coded from end). The graded both-edges scheme extends the predicted positions to include the source positions adjacent to S+3 (S+2 and S+4), and the source positions adjacent to E-3 (E-4 and E-2). Accordingly, the graded both-edges scheme correctly predicted that the perseverated letter G has its source at position S+2/E-4 in the prior response QGNZF. Within the entire corpus of potential perseveration-source pairs, 1280 out of 1742 (73%) matched position by this graded both-edges scheme compared to 65% expected by chance ($p < .0001$).

In contrast to graded representations, exact position matches are predicted under discrete representations, such that a perseveration at position E-3 should only be associated with a source at position E-3 and not at either E-2 and E-4. In contrast, the adjacent both-edges scheme allows to account for a systematic pattern of perseverations matching on *approximate* position, in addition to the *exact* position matching pairs. It was thus tested if, in line with graded representations, adjacent both-edges scheme contributes above and beyond the discrete both-edges scheme. Residuals analyses were carried out over those potential perseveration-source pairs in which the discrete both-edges scheme failed to predict the source position. The adjacent both-edges scheme performed significantly better than chance at predicting source position, predicting 57% of residual perseveration-source pairs position match, versus 49% expected by chance ($p < .0001$). These findings, reported in detail in Table X, support graded rather than discrete position representations.

Analysis 4: Comparing graded both-edges schemes. Because Analysis 3 indicates a graded both-edges representation of segment position, we must return to the question of whether both the beginning- and end-based component of this graded both-edges scheme contribute to position encoding. Residuals analyses were again carried out to determine whether the graded beginning-based component of the graded both-edges scheme contributes above and beyond the graded end-based component, and vice-versa. The results of the residuals analyses are reported in Table 3 and show that positions are predicted above chance both by the beginning-based scheme (over a pool of pairs that are not predicted by the end-based scheme: 37% vs. 31%, $p < .0001$) and the end-based scheme (over a pool of pairs that are not predicted by the beginning-based scheme: 34% vs. 29%, $p < .0001$). These results indicate that both components contribute significantly and independently to the graded both-edges position encoding.

Table 3*. Residuals analyses evaluating contributions of different components of the graded both-edges scheme.*

Position Scheme/ Complementary Scheme	*Residuals PS Pairs*	*Observed Position Matches*	*Matches Expected by Chance*	*p*-value
Adjacent Both Edges/ Discrete Both-Edges	1069	607 *(57%)*	528 *(49%)*	<*.0001*
Graded Beginning-based/ Graded End-based	732	270 *(37%)*	226 *(31%)*	<*.0001*
Graded End-based/ Graded Beginning-based	704	242 *(34%)*	207 *(29%)*	<*.0001*

Taken together, the results of the position analyses described above provide strong support for the graded both-edges representation of position in immediate serial recall for deaf signers, with contributions of both beginning- and end-based position representations. These results converge with those from verbal STM that have revealed analogous graded both-edges representations of serial positions (e.g., Henson, 1998). They contrast with previous work in visuo-spatial STM, where non-verbal stimuli (sequences of squares) were used, that has revealed beginning-based position representations, with no contribution from an end-based scheme (Fischer-Baum, 2011).

Confusion matrices analyses

Substitutions involving sound similar consonants (B → C) should be relatively frequent if letters were encoded according to speech phonology. Otherwise, if only sign characteristics were involved, similarity in sign execution could lead to a major number of substitution between similar signs. To explore this possible confounding of a greater similarity between some letters we constructed confusion matrices, grouping letters according to the sound similarity (based on spoken language production) and formational parameters (based on sign language execution) and comparing the quantity of confusion errors within the similar group with the quantity of errors outside the group (calculating the proportion respect to the overall quantity of letters vs the quantities inside and outside the group)

This was controlled by analysing the substitutions recorded for the 14 consonants with similar sounding names in Italian. For each of these consonants we calculated the total number of substitutions resulting in sound similar consonants (e.g., B → C, D, G, P, T, V), dividing it by the number of sound similar consonants associated with that consonant (e.g., B = 6). The procedure was repeated with pairs formed by consonants with different sounding names.

First, we identified two groups of letters among the stimuli we used that were more similar in sound production, than the rest of the stimuli, and calculated the error proportions:

BCDGPTV	
within group errors	52.71
outside group errors	48.55

FLMNSR	
within group errors	40.83
outside group errors	46.9

Then we identified a series of letter groups that are more similar in their sign execution than the others, basing on the formational parameters that are an established practice of sign analysis, a sign language native speaker controlled and confirmed this letter clustering.

Letter group	*Parameters of similarity*
BDF	orientation
within group errors	17
outside group errors	17.23

Letter group	*Parameters of similarity*
GH	orientation, movement
within group errors	16
outside group errors	16.07

Letter group	*Parameters of similarity*
MN	orientation, movement
within group errors	9.5
outside group errors	15.93

Letter group	*Parameters of similarity*
PQ	orientation, movement
within group errors	13
outside group errors	12.57

Letter group	*Parameters of similarity*
LP	handshape
within group errors	8.5
outside group errors	14.64

Letter group	*Parameters of similarity*
LRSV	orientation
within group errors	32
outside group errors	33.67

Substitutions occurred with comparable frequencies between consonant pairs with similar vs. different sounding names (mean errors: 7.2 vs. 7.7; $t(13) = 1.12$, n.s.).

This result makes it unlikely that phonological encoding occurred: we don't see any case where the proportion of errors within similarly sounding group would have been significantly greater than the outside of the group, so we may as well rule out the similarity hypothesis when it comes to error patterns analysis, i.e., speech phonology does not in any significant way influence sign encoding.

The analyses conducted 15 consonants with similar signs described above (signs sharing one parameter, e.g., orientation, like B-F, or two parameters, e.g., orientation and movement, like G-H) demonstrated that substitutions occurred more frequently between sign-similar pairs (mean errors: 7.8 vs. 6.4; $t(14) = 2.75$, $p = .01$), a result further confirming a sensitivity to visual/spatial features of signs reflecting visual/spatial encoding.

Summary

In the present experiment we explored serial order encoding schemes in short term memory for signs, using sign language letters as stimuli. We presented sequences of consonants of Italian sign language (LIS) alphabet to a group of 20 deaf signers. At the end of each sequence, participants were instructed to recall the signs in the same order. The length of the sequences was often purposely overspan to generate errors. We analysed the perseveration error pattern using the same technique as Fischer-Baum (2010).

The results showed that, compared to hearing people, deaf participants demonstrated a reduced short-term memory span, however, there is a strong evidence for the same graded both-edges representation of position in STM for signed stimuli, as used by speakers for spoken verbal stimuli, suggesting that the graded both-edges position encoding scheme is shared for spoken and signed verbal stimuli.

Experiment 2

This experiment is a continuation of Experiment 1 in terms of general purposes and paradigm. We continue to search for a position representation scheme used for signed material, to compare it with data obtained with hearing participants on spoken verbal material and on non-verbal visuospatial material. In this experiment we further explore the mechanisms of serial order encoding for signs, this time using word signs as stimuli. The concern is the possible specific status of letters for sign language users, given that the letters are mostly used for fingerspelling, and are a limited set of separately standing signs, that are used mostly to refer to the words of the spoken language; and while spoken words consist of spoken language letters, this is not true for signs: a sign for a word is an independent entity, and not a sequence of finger spelled letters.

Furthermore, a comparison with the data from hearing subjects can be fuller if we use word signs as well, since in experiments with hearing participants words have often been used as stimuli, thus bringing us to the necessity to find out the analogies in signs.

We conducted an experiment with the same paradigm as Experiment 1, changing the stimuli set from letters to words. The information about positional encoding scheme used for word signs could provide additional evidence to combine with the results already obtained and draw more solid conclusions about the short-term memory mechanisms of elaboration of serial order in sign language and compare those to the results found with hearing speakers.

Participants

Twenty deaf signers took part in the experiment (8 female; mean age = 17.5, SD = 2.8, range = 14-25). They were deaf from birth or became deaf before age 2. They were students of Magarotto institute in Padua. The participants were the same students that participated in Experiment 1.

Method

Materials. Sixteen word signs from the Italian Sign Language were presented as stimuli. Disyllabic words were selected among the materials used by Geraci et al (2008; Appendix 4), balanced for length in written form, articulatory duration in signs (as measured by Geraci et al.), frequency, and phonological similarity in sign and in speech. No frequency values are available for LIS signs; however, it is likely that they match the frequency of the Italian words they translate

(Geraci et al., 2008). Since the sign language words are mostly defined by four basic features – handshape, location, movement, orientation – we assured to control for dissimilarity in handshape and movement, as the most determining characteristics of a sign (Emmorey, 2001), i.e. we selected the signs that did not share any formational parameters and were as dissimilar as possible. Words were selected with the help of a native Italian sign language speaker, who also ensured the controls for dissimilarity and equality in duration as well as the correctness of execution, and videotaped each sign in a 1 second video. The stimuli list with English translation is listed in Appendix 4.

Sequences varying in length from 4 to 7 words were created by randomly selecting these signs with the constraint that a word was not repeated within a sequence. Sequences exceeded the span of deaf populations to elicit the perseveration errors. A total of 120 word sequences were created for each participant. Sequences of various lengths were equally represented (N=30) and individual words appeared between 40 and 45 times within the list presented to each participant. Within each sequence, signs appeared at 1 s intervals, the presentation rate used in Experiment 1. As in Experiment 1, sequences were presented in a pseudo-randomized order so that immediately adjacent lists were never of the same length. Identical words were allowed to appear in consecutive sequences.

Procedure. Stimulus presentation procedure was the same as in Experiment 1. Participants were required to repeat, by signing, the sequence they just saw. Apart from the stimuli, that were changed from letters to words, for all other details the procedure was the same as in Experiment 1

Results

Participants recalled sequences of words with many errors that included omissions, movements, and intrusions (i.e. addition or substitutions).

Many of the errors produced in our STM task were intrusions, with approximately half of the erroneous responses including at least one intruded word sign. Intruded word signs often occurred in one or more of the several immediately preceding responses, raising the possibility that some of the intrusions were perseverations from prior responses. In order to verify whether these errors were true perseverations and not chance errors we performed the same analyses as in Experiment 1, showing that the intruded word signs appeared in the prior responses more often than expected by chance.

Intrusion error analysis

We analysed the word-sign intrusions pooled across all 20 participants. Among the intrusion errors, the computer program tabulated the ones that appeared in previous responses until 5 responses back. The program also estimated the likelihood of an intruded word sign occurring by chance in trials T-1 through T-5. Chance estimates were computed using the Monte Carlo analysis described in Fischer-Baum et al. (2010) and McCloskey et al. (2006). Intrusions matching source position appeared to be significantly more frequent than expected by chance, with a significant difference for as far as 3 trials back, as shown in table 4.

Table 4*. Intrusions matching positions in the observed data vs expected by chance, Experiment 2*

Distance between source and intrusion	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
E-1	.612	.350	*<.0001*
E-2	.438	.335	*<.0001*
E-3	.369	.312	*.0186*
E-4	.315	.307	*.4305*
E-5	.274	.315	*.8785*

Reliable differences from chance appear in trials T-1, T-2 and T-3, but not in trials T-4 and T-5. Therefore, there appears to be genuine perseverations from T-1, T-2 and T-3 responses. These results provide an empirical basis for defining the *window of perseveration* — the range of preceding trials from which items may perseverate into the current response — that, for word signs, appears to span for three trials.

Using a window of perseveration of 3 prior responses, we identified 3192 intrusion-prior pairs, of which 1536 were perseveration-source pairs (.481) compared with .349 expected by chance.

Position Analyses

These analyses are conducted on potential perseveration-source pairs in which the intruded word sign appeared in one or more of the responses within the perseveration window that, as revealed by the analyses above, includes up to 3 trials prior to the error. A total of 1536 such pairs were identified across participants.

Analysis 1: Observed vs. chance position matches. This analysis represents a first step in establishing whether sign positions are specified with respect to both edges (beginning and end). Specifically, it was examined whether the matched positions expected by beginning- or end-based schemes exceeded those expected by chance within the whole sample of potential perseveration-source pairs.

A computer program assigned positions according to each scheme, and computed whether or not positions were maintained between perseverations and sources.

The program also estimated the proportion of position matches expected by chance under each positional scheme. The procedure of the Monte Carlo analysis used for random sampling and position matching was similar to the one described above for the perseveration analyses; in each run of the chance analysis program, the actual source response was replaced with a randomly selected source control response, and the proportion of these perseveration-source control pairs that matched position by each position representation scheme was tabulated (see Fischer-Baum, McCloskey & Rapp, 2010 and McCloskey, Fischer-Baum & Schubert, 2013 for a detailed description of the methods). The chance analysis program was run 10,000 times.

Intruded word signs appeared in the same beginning-based position in 22.4% of the perseveration-source pairs, a higher rate than the chance baseline (20.8%).
For the end-based scheme, the observed rate was 21.7%, while the chance rate was 20.5%.

Table 5. *Analyses evaluating contributions of beginning- and end-based schemes independently*

Position Scheme	*PS Pairs*	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
Beginning-based	1536	344 *(22.4%)*	320 (*20.8%)*	.0487
End-based	1536	334 *(21.7%)*	314 *(20.5%)*	*.0990*

Analysis 2: Comparing beginning- vs. end-based scheme.

Using a *residual* analysis it can be determined whether those pairs that do not match position by one scheme, are more likely to match position by the other scheme. Analyses examined both schemes and are illustrated here with respect to the beginning-based scheme. To assess whether the beginning-based scheme makes systematic contribution above and beyond the end-based scheme, we analysed *residual pairs*, which are potential perseveration-source pairs for which the end-based scheme failed to predict the source position of the intruded word. It was then determined whether the beginning-based scheme was more successful than the end-based scheme in predicting the source position of the intruded word signs with residual pairs.

The residuals analysis was carried out over 1202 pairs for which the end-based scheme failed to predict the source position. The beginning-based scheme correctly predicted the source position for 223 of the residual pairs (18.6%). Chance was evaluated in the exact same manner in the residual analysis as it was in Analysis 1, with only the residual perseveration-source pairs entered into the analysis. The proportion expected by chance was 215 (17.9%).

Complementary residuals analyses on the 1192 pairs for which the beginning-based scheme failed to predict the source position revealed that the end-based scheme correctly predicted source position for 213 pairs (17.9%), with respect to 209 (17.5%) expected by chance ($p = .3690$; see data in Table 6).

***Table 6**. Residual analyses evaluating contributions of beginning- and end-based schemes.*

Position Scheme	*Residual PS Pairs*	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
Beginning-not-end-based	1202	223 *(18.6%)*	215 (*17.9%)*	.2538
End-not-beginning-based	1192	213 *(17.9%)*	209 *(17.5%)*	*.3690*

The problem with these results that did not seem to demonstrate a significant difference is that participants tended to provide multiple responses of the same length, therefore introducing a potential confounding, which in turn complicates the result interpretation. The confounding occurs when perseverations and sources have the same length because the intruded sign preserves the source position under both schemes. Such a confounding makes it difficult to accurately determine the independent contribution of each scheme.

The results of this experiment are not able to reveal any significant pattern, but the first problem with evaluation of these results is of the low quantity of perseveration-source pairs where the length differs between source and response: the data obtained from the 20 participants in this experiment seems incomplete and insufficient to draw any conclusions to distinguish between positional encoding schemes because of the main problem encountered in the analysis: participants tended to produce long lists of same-length responses (e.g. if response n was 4 signs long, so will be responses n+1 and n+2) thus making impossible to discern, for any single intrusion error, whether it was due to the beginning-based anchoring or to the end-based one

Experiment 3

Even if the analyses performed with the confusion matrix seemed to be inconsistent with the hypothesis that deaf participants in Experiment 1 used sound-phonology to code for letter sequences, we decide to run a further control experiment investigating the role of similarity in sound and signs in STM for our deaf population.

As a matter of fact, the Italian sign language speakers that took part the previous experiments were literate, knew Italian for reading/writing purposes, and were also good at lip-reading. The concern that they might use also phonological information to code for letter sequences is therefore quite well motivated. If this is the case, it could be the key to the explanation of analogous encoding schemes for speakers and signers, and would lead to the conclusion that both signers and speakers used a both edges coding schema since both groups used a sound-based phonological code, which is better developed in speakers than in signers. In this case our data would not be helpful to understand the nature and the functioning of STM for signs, nor would speak about processing differences between visual and verbal material. It was therefore very important to directly test for this hypothesis.

To this end we compared the effect of the similarity at the level of sound and at the level of signs in groups of signers and speakers. We selected a set of similarly sounding words, and matched them with a control set of dissimilarly sounding ones (balanced by length, frequency, orthographic and phonological neighborhood). We also selected a set of words that were similar in sign language and a matched set of dissimilarly signed words for control.

As already anticipated in the Introduction, the sound-based phonological similarity effect has been demonstrated in many studies (e.g., Baddeley, 1990; 2007; Gupta & MacWhinney, 1995; Neath, Surprenant, & LeCompte, 1998;Wilson & Emmorey, 1997, Schweickert, Guentert, & Hersberger, 1990): phonologically similar items in a short-term memory task lead to reduced memory span as compared to phonologically dissimilar items. Also the sign-based phonological similarity effect has been demonstrated signers (Hanson, 1982; Poizner, Bellugi, & Tweney, 1981; Shand, 1982; Wilson & Emmorey, 1998), Wilson, 2001), so that similar signs elicit more difficulty for subsequent recall and reduce overall accuracy. Here we try to verify to what extent the signers that took part to the previous experiments were sensitive to such effects. Our hypothesis was that if the speech information doesn't play a role in sign recall, then for signers the similarly sounding words would produce no effect, while similarly signed words would lead to lower recall accuracy; whereas for speakers similarly sounding words would elicit the phonological similarity effect, reducing the recall, while similarly signed words would produce no effect.

Participants

Eighteen deaf signers (8 female; mean age = 17.5, SD = 2.8, range = 14-25) and fifteen hearing speakers (10 female; mean age=22.2, SD=1.64) took part in the experiment. The signers were deaf from birth or became deaf before age 2, they were students of Magarotto institute in Padua. They were the same participants as the participants from Experiments 1-2. The hearing participants were university students who reported to be native Italian speakers and have no hearing deficits and no knowledge of a sign language.

Method

Materials.

Sound list.

To test for the effect of sound similarity, we selected 9 sound related words differing one to the other by only a single phoneme (e.g., *forza-forma*, strength-shape; see Appendix 5) and 9 sound-unrelated words (e.g., *forma* was replaced by *libro*, book). Related and unrelated words were matched for length (phoneme number; $t < 1$), in addition to frequency and to phonological and orthographic neighborhood density (ts < 1; norms from Colfis Corpus (Laudanna, Thornton, Brown, Burani, & Marconi, 1995), and Phonitalia Corpus (Goslin, Galluzzi, & Romani, 2014). We also controlled for the hand shape, movement and location of the signs corresponding to the words in the sound list, in order that all signs were dissimilar in handshape and at least one other parameter (for linguistic parameters of signs, see Battiston, 1978; Stokoe, Casterline, & Croneberg, 1965)

Sign list.

To test for the effects of sign similarity we selected 9 word signs sharing 2 parameters (hand-shape and either orientation or movement). The signs in unrelated lists did not share parameters. Related and unrelated lists included signs that corresponded to Italian words matched for length, frequency, and neighborhood density (ts < 1) and were not sound related one to the other.

The words of the sound list and the words corresponding to the signs of the sign list (for a total of 36 words) were recorded by a native Italian speaker. The recording for each word lasted 1 s.

The signs corresponding to the words of the sound list and the signs of the sign list (for a total of 36 signs)were videotaped by a native Italian sign language speaker. The video for each word lasted 1 s.

Procedure.

Each participant was presented with 60 sequences of four words. Each sequence consisted of words belonging to one of the 4 sets (similar in sound, control dissimilar in sound, similar in sign. control dissimilar in sign). The sequences were presented randomly.

Deaf participants were presented with the sequences of signs only. They started each trial by pressing the space bar of the keyboard, which triggered the presentation of a sign sequence on the computer monitor. Immediately after the presentation of the last sign in the sequence, a response screen appeared indicating participants to repeat, by signing, the sequence they just saw. The participants were instructed to reproduce the signs in the exact order in which they had appeared. A practice session of 4 trials preceded the experimental task. Signed responses were videotaped for scoring purposes, the videos were then encoded anonymously, providing lists of signs.

Hearing participants were presented with sequences of spoken words only. The procedure for presentation was otherwise the same as for the deaf participants, except for the fact that the stimuli were presented in auditory modality through the computer speakers..... Participants were required to repeat, by saying aloud, every sequence. Spoken responses were recorded for scoring purposes, the recordings were then encoded anonymously, providing lists of words.

Results

A three-way ANOVA with Group (deaf vs. hearing) as between-participants factor and List (sign vs. sound) and Sequences (similar vs. dissimilar) as within-participants factors was conducted. The main effect of Group was significant ($F(1, 31) = 14.03$, $p = .001$, $\eta^2 = .31$; Consistent with STM for signs being reduced with respect to STM for words,, deaf participants recalled fewer sequences than hearing participants (53% vs. 78%). Each two-way interaction was significant (List x Group, $F(1, 31) = 26.14$, $p < .001$, $\eta^2 = .48$; Sequences x Group, $F(1, 31) = 54.26$, $p < .001$, $\eta^2 = .63$, List x Sequences, $F(1, 31) = 50.01$, $p < .001$, $\eta^2 = .62$). These effects were further specified by the three-way interaction ($F(1, 31) = 10.84$, $p = .002$, $\eta^2 = .26$; see Fig. 19).

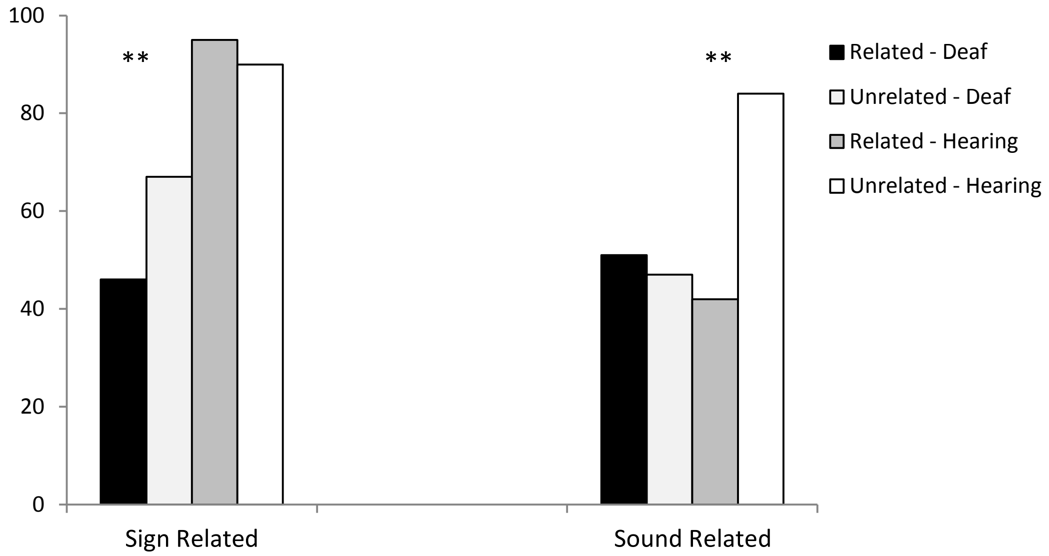


Figure 19*. Percentage of sequences correctly recalled by deaf and hearing participants. Sign similarity affected recall of deaf participants, sound similarity of hearing participants. Asterisks (**) indicate significant differences (p < .0001) between related and unrelated sequences.*

Deaf participants showed reduced span with sign similar list but no effects of sound similarity. By contrast, the recall of hearing participants was affected by sound similarity but not by sign similarity. In short, the strong effects of sound similarity demonstrated by hearing participants were not observed with deaf participants, a pattern of results that makes it unlikely that signs were subjected to speech based phonological encoding in our group of deaf participants. The strong effects of sign similarity found within this group suggest instead that signs were encoded according to a visually based code, as a function of the phonological parameters characterizing signs.

Therefore we may conclude that the deaf participants of our experiments do not use sound-based phonology in encoding the signed material, but instead base on the visuospatial features of the signs, as demonstrated first by Confusion analysis in Experiment 1, and further controlled and confirmed by the present Experiment 3.

Experiment 4

It’s been shown by many studies that a close relationship exists between speech coding and short-term memory. Conrad (1964) showed that the intrusion errors in recall of letter sequences were phonologically similar to the correct item, even though the stimuli were presented visually. Conrad and Hull (1964) showed that short-term memory span for letters is reduced when the stimuli in the task are phonologically similar, while Baddeley (1966) showed a similar effect for words: short-term memory span for similar words was lowered.

These results were initially taken to imply that short-term memory relies on an acoustic store, with visually presented items being translated into an acoustic (phonetic) code. The results were, however, equally interpretable in terms of an articulatory code (based on sensory-motor trace of the production of a given item). There is evidence that short-term memory relies on subvocal rehearsal (Sperling, 1967; Waugh and Norman, 1965; Atkinson and Shiffrin, 1968), and it is equally possible to argue that the code is articulatory rather than acoustic. More support of this theoretical view was brought by the evidence found by Conrad (1970) in studies of short term memory in deaf children. Some of these children showed evidence of phonologically based errors, and these were the children that were judged as better speakers by their teachers. Since they had no ability to hear, it brought to a conclusion that the errors were articulatory in origin.

Baddeley and Hitch (1974) suggested a multi-component model of working memory. They proposed a system with a controlling central executive at the core, that was connected to two other systems: the visuospatial sketchpad and the articulatory loop. The latter was postulated to account for the role of speech coding in short-term memory. In its initial formulation, the articulatory loop was assumed to function like a tape loop of limited duration. The loop was assumed to hold about 1.5 sec of speech-based material in temporary storage and to be capable of maintaining this by means of articulatory rehearsal. Although a very simple concept, the loop was able to account for a wide range of results. These included:

- Phonological similarity effect. Poor immediate memory for phonologically similar items (Conrad and Hull, 1964; Baddeley, 1966) was assumed to result from confusion among items that had similar articulatory codes.
- Word length effect. Memory span for short words is greater than for long (Baddeley, Thomson and Buchanan, 1975), a phenomenon that can readily be explained by assuming that short words are better remembered simply because they can be spoken more rapidly; 1.5 sec of short words will comprise more items than 1.5 sec of long words.

- Articulatory suppression effect. If the subject has to pronounce something irrelevant while performing the memory task, the performance gets significantly impaired (Murray, 1968). Such an impairment would be expected, since suppressing articulation in this way prevents the use of the articulatory loop for maintaining and rehearsing the presented stimuli for further recall.

Since both the similarity and word length effects were assumed to depend on the articulatory system, blocking it with a suppression task could lead to attenuation of both of the effects, and indeed it has been demonstrated with visual stimuli presentation (Murray, 1968; Baddeley et al., 1975). This may imply that the phonological loop may suffer from the articulatory suppression. Therefore if we assume that the phonological loop plays an important role in position representation in immediate serial recall, then the position encoding scheme should also be disrupted by the articulatory suppression.

The concept of the articulatory loop was applied to a range of a phenomena, from the role of phonological coding in learning to read (Baddeley, 1979) to cultural differences in memory span and arithmetic performance (Ellis and Hennelly, 1980) and the development of digit span in children (Nicholson, 1981).

In the present experiment, we explore the role of the phonological loop in the positional information encoding. We previously showed that:

- Deaf signers use the same positional information encoding scheme as speakers, namely, the both-edges scheme, anchoring the element's position on a sequence to both the start and the end of the sequence
- Deaf signers don't use any phonological information while encoding signed verbal material, relying only on word sign properties, and not on the possible auditory rendition of the word.

Still the question of the source of the reduced span for signs stays open. To further explore the mechanisms of different modality information encoding, we get back to Baddeley & Hitch's model (Baddeley & Hitch 1974; Baddeley, 1986; 2000), where the two different short-term memory components are the visuospatial sketchpad and the phonological loop. The spoken verbal information is supposed to be encoded through the phonological loop according to a both-edge schema for position information, as shown by Fischer-Baum's studies with verbal material, whereas the visuospatial information should go through the visuospatial sketchpad, and order position be coded according to a beginning-based scheme. Since the deaf signers don't use any phonological information, we can't assume they encode the information through the phonological loop. Yet, they demonstrate the same both-edges positional information encoding scheme as the hearing speakers. This brings us to the question of the role of the phonological loop in the whole process of sequential information encoding in short term memory.

In this experiment we explore the contribution of the phonological loop in sequential information encoding for hearing speakers. The common and well-known method to isolate the phonological loop is introducing the articulatory suppression that has been shown to interfere with short-term memory rehearsal and impair memory performance (e.g. Murray, 1968; Baddeley et al., 1975, Baddeley, Lewis & Vallar, 1984). We therefore run an experiment in which participants were asked to report word sequences while continuously articulating the same syllable. An expectation could be that if the phonological loop plays a critical role in position representation, then the positional encoding scheme under articulatory suppression should be different from the one observed without suppression.

Participants

Fourty hearing speakers (26 female; mean age = 17.7, SD = 1.1, range = 18-23) took part in the experiment. This experiment was conducted at Rice University, Houston (Texas, USA), and the participants were native speakers of English language. They were Rice University students at the department of Psychology and received course credit for participation.

Method

Materials.

We used a set of stimuli word previously used in analogous position information encoding studies with hearing speakers, in the studies of McCloskey&Fischer-Baum (in press).

Stimuli were word sequences created from a set of 25 five-letter words, each of which had a frequency of less than ten per million (Francis & Kucera, 1982). Each word began with a different letter as well as a different phoneme, and none of the words rhymed. The stimuli are reported in the Appendix 6. Sequences consisted of four, five, six, or seven randomly-ordered (and randomly selected from the pool of 25) words. Following Henson (1999), the ordering of sequences within blocks was pseudo-randomized so that immediately adjacent sequences were never of the same length. A word never occurred more than once in a sequence, but in contrast to the Henson (1999) experiment, words were allowed to appear in consecutive lists.

A total of 135 sequences were created for each participant. Sequences of various lengths were equally represented and individual words appeared approximately the same quantity of times within the list presented to each participant.

Procedure.

The participants started each trial by pressing the space bar of the keyboard, which triggered the visual presentation of a sequence of words one at a time in lower case at the centre of the monitor Each word was shown for 600 ms, with a 250-ms blank period between words. Participants were instructed to read each word silently. Recall was initiated by a response box appearing after the last word in a sequence, indicating the participants to type in the first letter of each word. Participants were instructed to report the words in order of presentation by typing the first letter of each word. No information about the length of the stimulus list was provided at recall, and no constraints were imposed on the length of the participant's response. As the participant typed, the letters were displayed from left to right on the monitor. Pressing the Backspace key erased the most recently typed letter, allowing corrections to be made. Pressing the Enter key terminated the response. Participants were instructed to type a hyphen when they knew that a word had appeared in a specific list position but could not remember the identity of the word.
Six practice trials preceded three experimental blocks of 45 trials each.

Results

Participants recalled sequences of words with many errors that included omissions, movements, and intrusions. The latter were defined as errors in which signs not present in the stimulus sequence appeared in the response as additions or substitutions. Many of the errors were intrusions, with approximately half of the erroneous responses including at least one intrusion. Intrusions often occurred in one or more of the several immediately preceding responses, raising the possibility that some of the intrusions were perseverations from prior responses. To demonstrate that the intrusions observed in our STM task represented true perseverations from prior responses, we must show that the intrusions appeared in the prior responses more often than expected by chance.

The articulatory suppression led to a significant reduction in recall accuracy, in line with the previous results from the literature. In the Fischer-Baum & McCloskey's experiment (in press) where hearing participants were to recall sequences of the same words in the same procedure without articulatory suppression the mean accuracy was 57% of correctly recalled sequences, while in our experiment where suppression was added, the mean recall accuracy was 18%.

Perseveration Analysis

We analysed the word intrusions, 3190 in total, pooled across all 40 participants.

We defined the window of perseveration by comparing the percentage of intrusions with the likelihood of an intruded word occurring by chance in trials T-1 through T-5. Chance estimates were computed using the Monte Carlo analysis, run 10000 times, following the same procedure as in the previous experiments. Intrusions matching source position appeared to be significantly more frequent than expected by chance, with a significant difference for as far as 3 trials back, as shown in table 7.

Table 7. *Intrusions matching positions in the observed data vs expected by chance in experiment 4*

Distance between source and intrusion	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
T-1	.639	.272	<*.0001*
T-2	.408	.276	<*.0001*
T-3	.341	.269	<*.0001*

Using a window of perseveration of 3 prior responses, we identified 3190 intrusion-prior pairs, of which 2260 were perseveration-source pairs (.463) compared with .272 expected by chance.

Position Analyses

The following analyses are aimed to shed light on how positions are encoded in representations held during the immediate recall of signs. They were conducted on potential perseveration-source pairs in which the intruded item appeared in one or more of the responses within the perseveration window that, as revealed by the analyses above, includes up to 3 trials prior to the error. A total of 2260 such pairs were identified across participants.

Analysis 1: Observed vs. chance position matches.

This analysis represents a first attempt to establish whether positions are specified with respect to both edges (beginning and end). Specifically, it was examined whether the matched positions expected by beginning- or end-based schemes exceeded those expected by chance within the whole sample of potential perseveration-source pairs.

A computer program assigned positions according to each scheme, and computed whether or not positions were maintained between perseverations and sources. The procedure of the analysis was analogous to the previous experiments. The chance analysis program was run 10,000 times.

Intruded words appeared in the same beginning-based position in 59.4% of the perseveration-source pairs (1336/2260), a higher rate than the chance baseline (1135, 50.2%; $p<.0001$).
For the end-based scheme, the observed rate was 1288 (57%, while the chance rate was 1117 (49.4%, $p<.0001$).

While the latter results suggest that both schemes contribute to the representation of words positions, but there are cases when both schemes can equally account for the results, namely, when the source and perseveration match in length. To address this question and discern between the contribution of each of the schemes, we ran the residual analysis.

Table 8. *Analyses evaluating contributions of beginning- and end-based schemes independently*

Position Scheme	*PS Pairs*	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
Beginning-based	2260	1336 *(59.4%)*	1135 (*50.2%)*	*<.0001*
End-based	2260	1288 *(57%)*	1117 *(49.4%)*	*<.0001*

Analysis 2: Comparing start- vs. end-anchored scheme.

Using a *residual* analysis it can be determined whether those pairs that do not match position by one scheme, are more likely to match position by the other scheme, a procedures that permits an accurate characterization of the independent contribution of each scheme.

The residuals analysis was carried out over the 972 pairs for which the end-based scheme failed to predict the source position. The beginning-based scheme correctly predicted the source position for 387 of the residual pairs (20%). Chance was evaluated in the exact same manner in the residual analysis as it was in Analysis 1, with only the residual perseveration-source pairs entered into the analysis. The observed proportion of residual pairs that matched beginning-based position was significantly greater than the proportion expected by chance: 304 (16%; $p < .0001$). Complementary residuals analyses revealed that the end-based scheme also performed above chance ($p < .0001$; see data in Table 3). In sum, residuals analyses provide strong evidence that both beginning- and end-based coding contribute independently to the representation of the position of words in immediate serial recall under articulatory suppression.

Table 9*. Residual analyses evaluating contributions of beginning- and end-based schemes*.

Position Scheme	*Residual Pairs*	*PS*	*Observed Position Matches*	*Matches Expected by Chance*	*p-value*
Beginning-not-end-based	972		387 *(39.8%)*	304 (*31.2%)*	< .0001
End-not-beginning-based	924		339 *(36.7%)*	274 *(29.6%)*	< .0001

To summarise, these analyses provide strong evidence that both beginning- and end-based representation schemes contribute independently to the representation of the position of words in immediate serial recall under articulatory suppression. Therefore, articulatory suppression may disrupt STM capacity (demonstrating a mean recall accuracy of 18% versus 57% in an experiment with the same procedure and stimuli but without articulatory suppression) in general and drop the accuracy of recall, but it doesn’t influence the overall position encoding pattern that persists in this condition just as firmly as in control condition without any suppression. Hence, we may conclude that the position representation pattern we find here is analogous to those obtained in studies with hearing subjects encoding verbal material without articulatory suppression, and also with deaf signers encoding signs corresponding to letters, as revealed in Experiment 1 with letter stimuli. Thus, the both-edges position representation scheme may be generalised even further, converging the evidence from exactly the same encoding scheme in case of verbal material (words) use with hearing participants under articulatory suppression.

Summary

We wanted to investigate the contribution of the phonological loop in position representation for hearing speakers. To test for this, we introduced the articulatory suppression in an immediate serial recall task. Articulatory suppression is well known to disrupt the functioning of the phonological loop, therefore, we expected that if the phonological loop played an important role in position representation, then we could obtain a different scheme of encoding under articulatory suppression. However, the results show that although articulatory suppression significantly reduces recall accuracy, the position representation scheme remains the same, and it’s the both-edges scheme.

We might suppose that deaf signers’ encoding mechanisms work like those of the hearing participants when they suppress the use of the phonological loop. The scheme of order encoding may not be strictly related to the use of phonological loop, it’s just the use of the loop that makes the recall more effective and accurate, but doesn’t influence the position representation. Then we must investigate how position is encoded independently of the short-term memory mechanism responsible for its encoding (the phonological loop or the visuospatial sketchpad), and the modality for encoding (visual or auditory). It might be that sign language is encoded like verbal information, even if it presented visually, i.e. all languages are processed through a given architecture independently of whether they are signed, spoken, or written; so that there is a unique way of encoding the order of linguistic elements, which is independent of the nature or the features of those elements.

Transposition analyses

Since the results from the series of experiments on immediate serial recall in deaf and hearing participants revealed the same both-edges positional representation scheme which is used independently of whether the stimuli material is spoken or signed, we still have no solid explanation for the lower short-term memory span for signed material. We need therefore to explore how we can explain the differences in short-term memory span between signs and speech.

If it's been confirmed that the positional representation scheme is in any way the both-edges scheme, but the span is still lower, we must look somewhere in the middle between the input elements and the scheme according to which they are supposed to be encoded in memory.

Another hypothesis that emerged from the different methods of analysis of positional encoding and errors in serial recall was to explore and compare the strength of binding of each particular item to its position, independently of the general position representation scheme. If we assume that for signed material this binding is weaker, we may expect more errors in serial recall due to this weakness, while maintaining the overall position representation scheme.

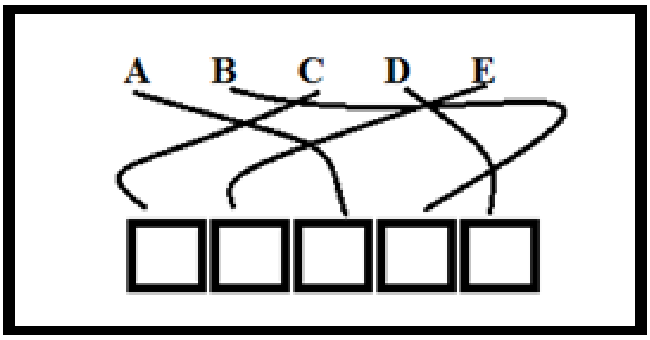


Figure 20. *Hypothetical assumption of a weaker binding of the elements of a sequence to their positions, while the positional slots are intact (as confirmed by the previous findings).*

In the previous analyses we took into consideration the evidence from positional errors, i.e. intrusions of an item from one sequence into another, while maintaining the position of the item between one sequence and another. Here we consider the transposition errors, i.e. changing an item's position within a sequence between the stimulus and response. A distinctive feature of these errors is their distribution: erroneous items are clustered around their correct position, rather than being randomly distributed (Estes, 1972; Henson, 1998). This phenomenon can be seen clearly by means of constructing transposition gradients, which show, for each position in participants' reports, the proportion of items from each position in the corresponding stimuli sequences. These proportions peak when the input and output position match (i.e., for correct responses) and decrease as the difference between the input and output position increases (Henson, 1998). Transposition gradients suggest that items are coded for their position in a sequence, but that there is some similarity between these codes that occasionally causes errors. Errors in relative order of nearby items also produce peaked transposition gradients (Henson, 1996). The interest in this type of errors is due to the fact that they might help to investigate to what extent the lower performance observed with signs might be due to a worse binding of each particular sign to its position. Indeed, if we assume a weaker position binding for signed with respect to spoken material, we should expect wider transposition gradients, i.e. more items recalled in incorrect position within a sequence, with less evident peaks of correct positions.

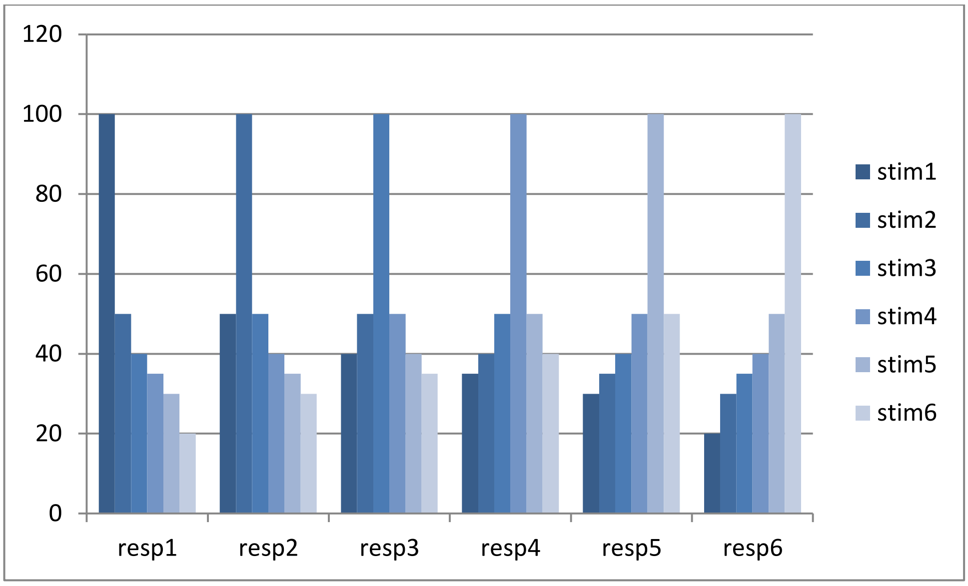
We performed analyses of transpositions between stimulus and response on the two data sets obtained from deaf signers – the one with the letters as stimuli and the one with the words as stimuli, and also on two data sets obtained with speakers: the one with articulatory suppression and also on the data set with speakers without any articulatory suppression (data from Fischer-Baum, 2010), which can be used as a control baseline. A problem we had to solve in running this analyses was how to calculate positions: for example, if a stimulus was ABCDEF, and the response ABCEF, should we consider E and F as a transposition from the 5^{th} and 6^{th} positions, respectively, to the 4^{th} and 5^{th}? Or if we consider it a plain omission of D, how do we calculate the remaining positions? We solved this problem by performing two separate calculations on each dataset: one was calculating positions forward, i.e. starting from the beginning of the sequence, and the other one was calculating backward, i.e. starting from the end.

The following plots report transposition gradients: for each item in a stimuli sequence (stimulus 1, stimulus 2 etc.) a distribution of responses is plotted. Response 1 stands for “reported in first position”, response 3 for “reported in third position” etc. The peaks are always at the point of correct response, i.e. for Stimulus 1 the peak is response 1: the stimulus presented in first position is reported in first position.

If we adopt the hypothesis of a weaker binding for signed material, we should expect wider transposition gradients for signers, i.e. more gradual descent from the peak and higher proportions of distant position transpositions, than for the spoken material.

A hypothetical comparison between transposition gradient width in signs and speech could look like that

Signs:



Speech:

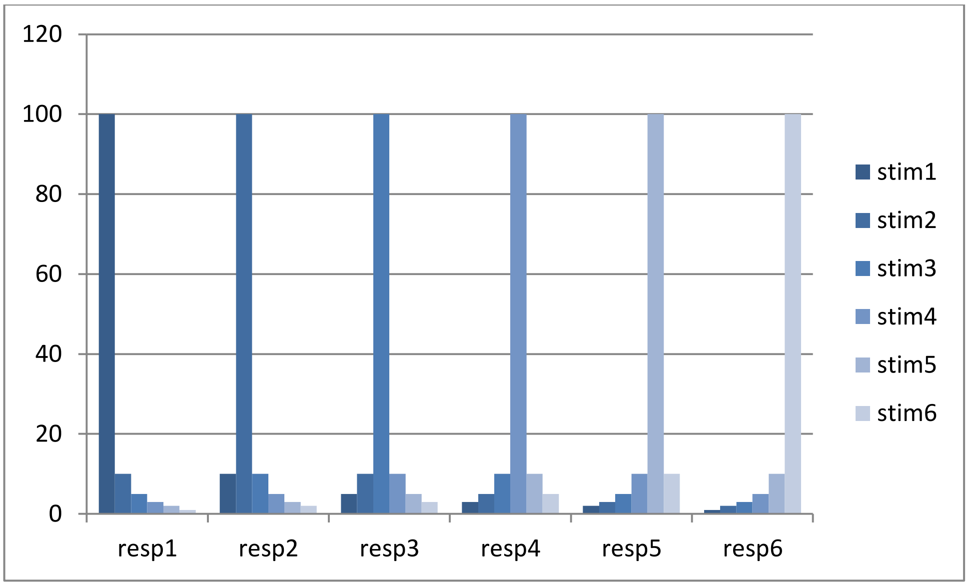


Figure 21. *Hypothetical wider transposition gradients for signs than for speech.*

I.e. the gradients for signs are wider due to weaker position binding.

Results of the transposition analysis:

for hearing participants in baseline control condition:

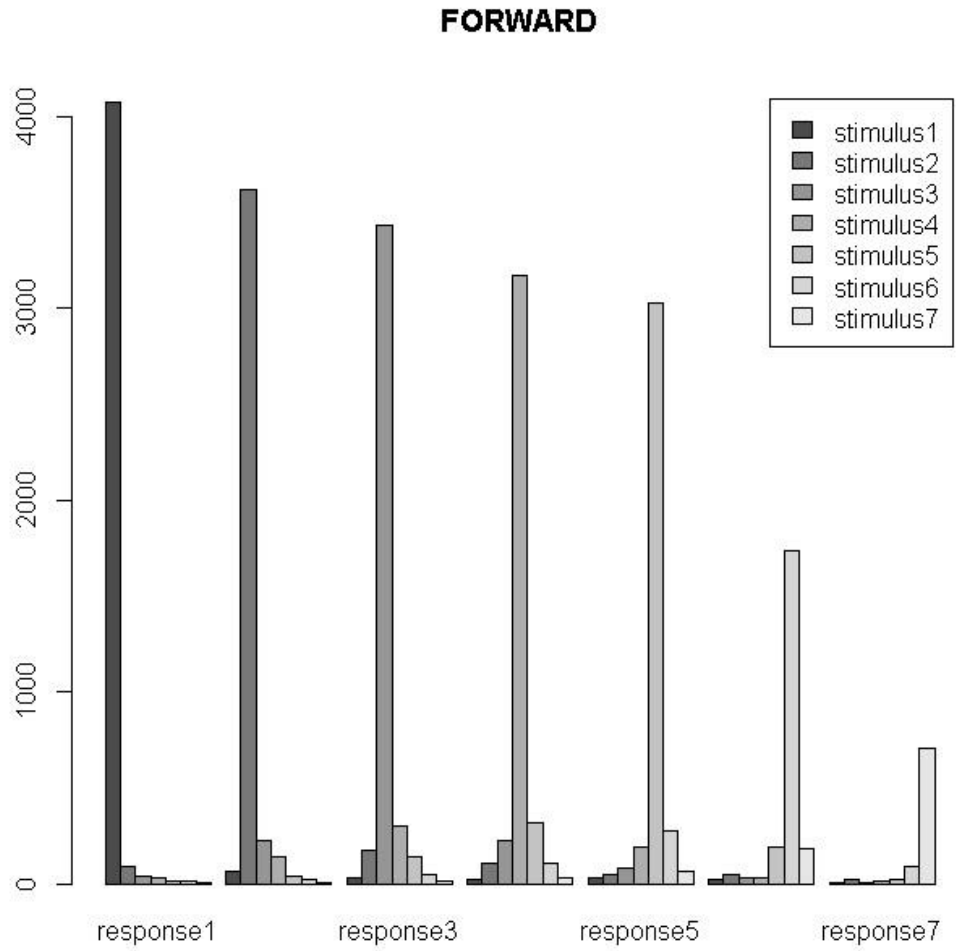


Figure 22. *Forward transposition gradients for hearing/baseline condition*

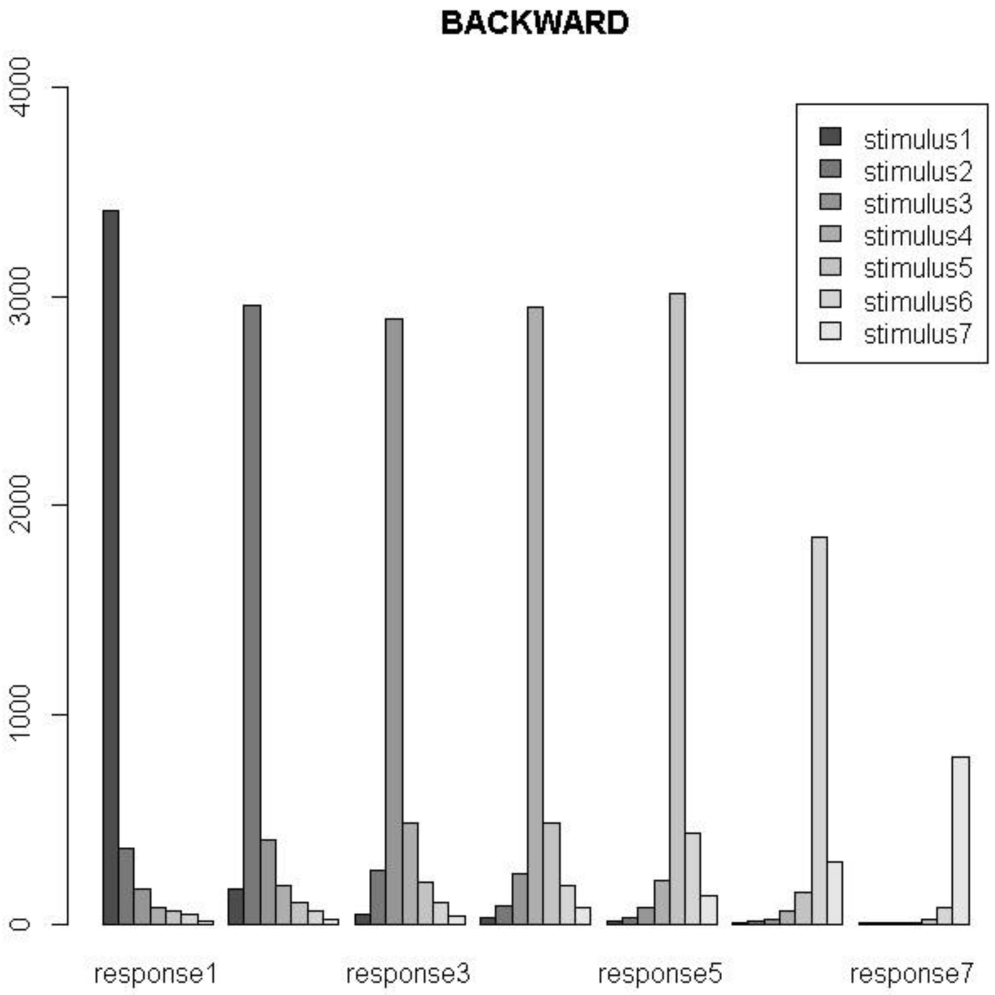


Figure 23. *Backward transposition gradients for hearing/baseline condition*

- for hearing participants in articulatory suppression condition:

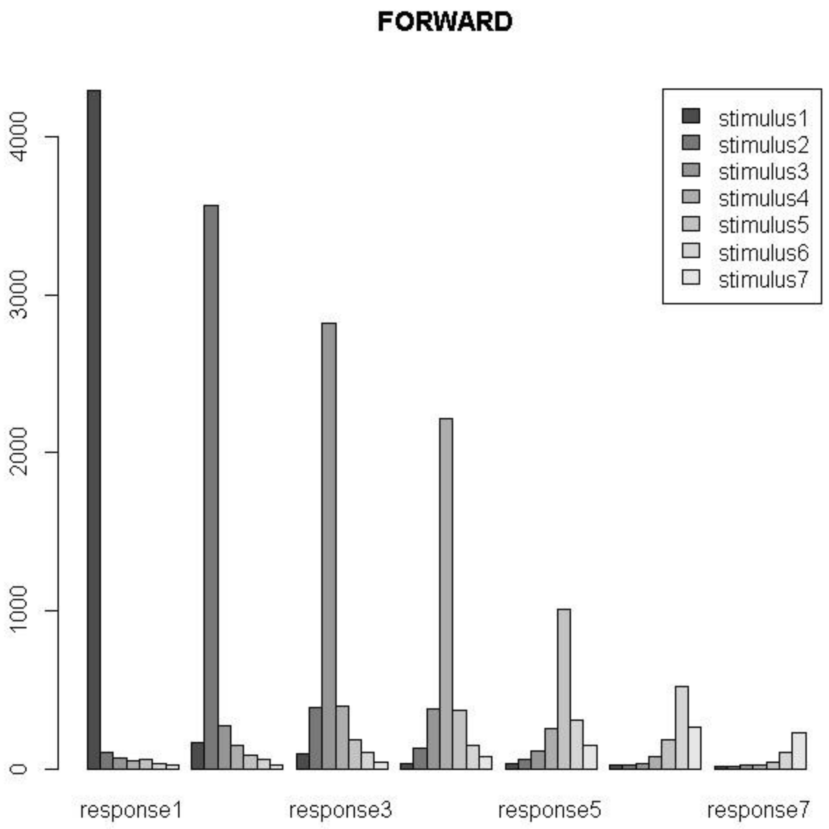


Figure 24. *Forward transposition gradients for hearing/articulatory suppression condition*

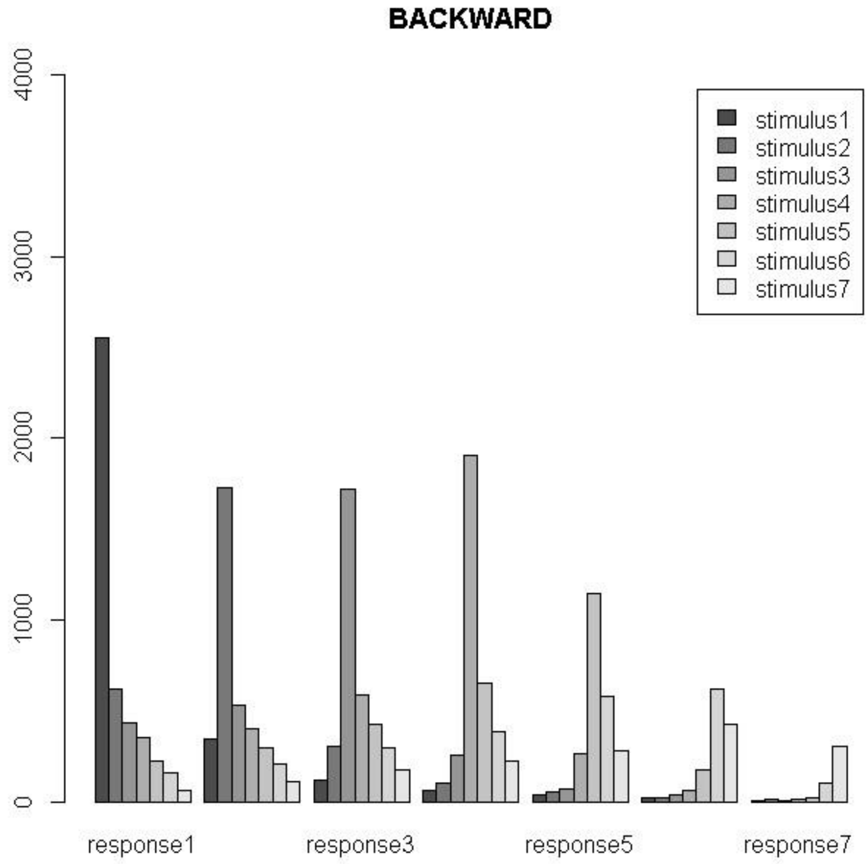


Figure 25. *Backward transposition gradients for hearing/articulatory suppression condition*

- for deaf participants in letter stimuli condition:

Since there's less participants and less data in the experiments with deaf signers, the transpositions are not quite visible when we plot the gradients on the same scale as we plotted the data of hearing participants, for deaf signers we created "zoomed" plots on a smaller scale, to make the transposition dynamics clearer:

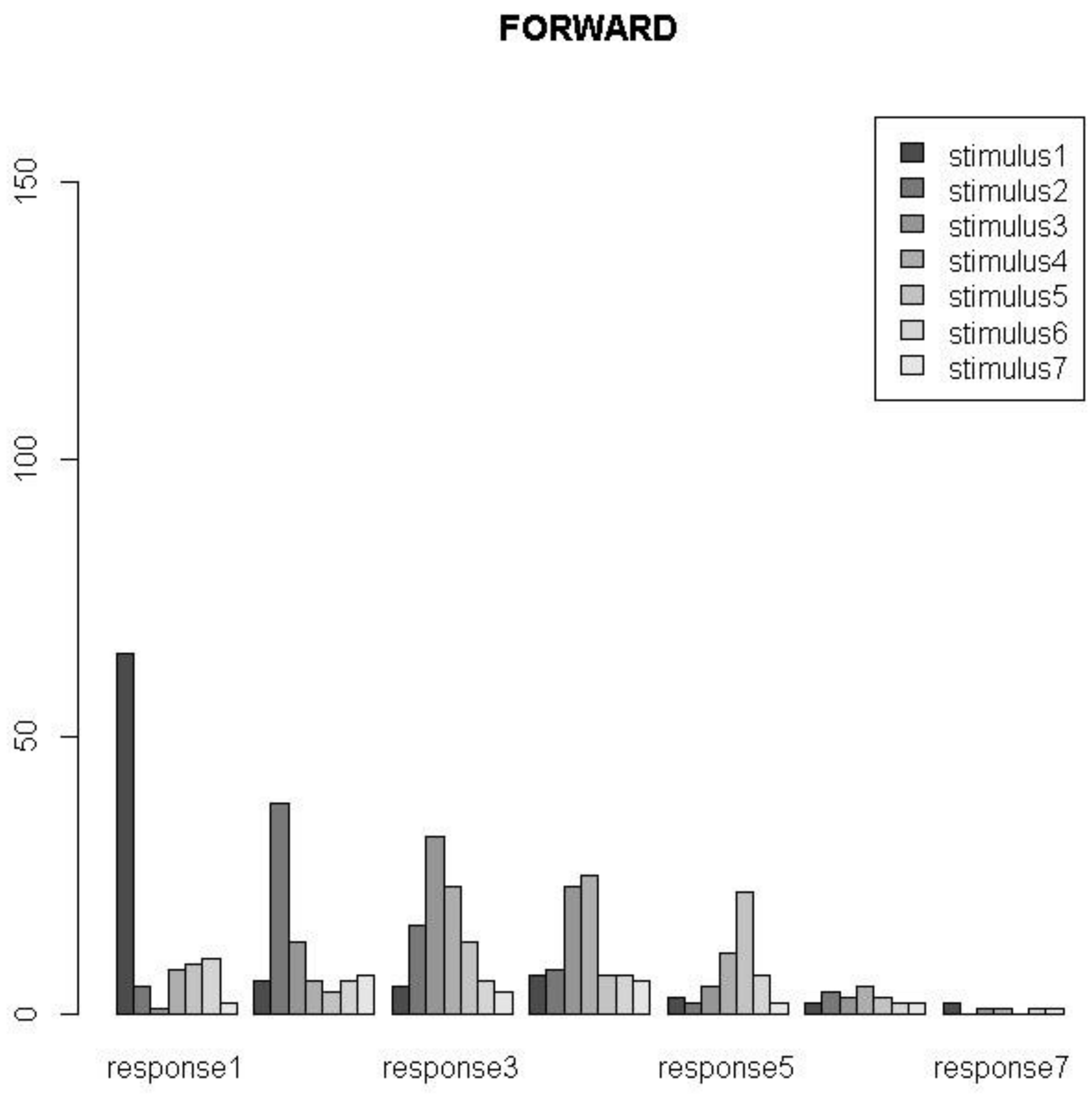


Figure 26. *Forward transposition gradients for deaf in letter stimuli condition*

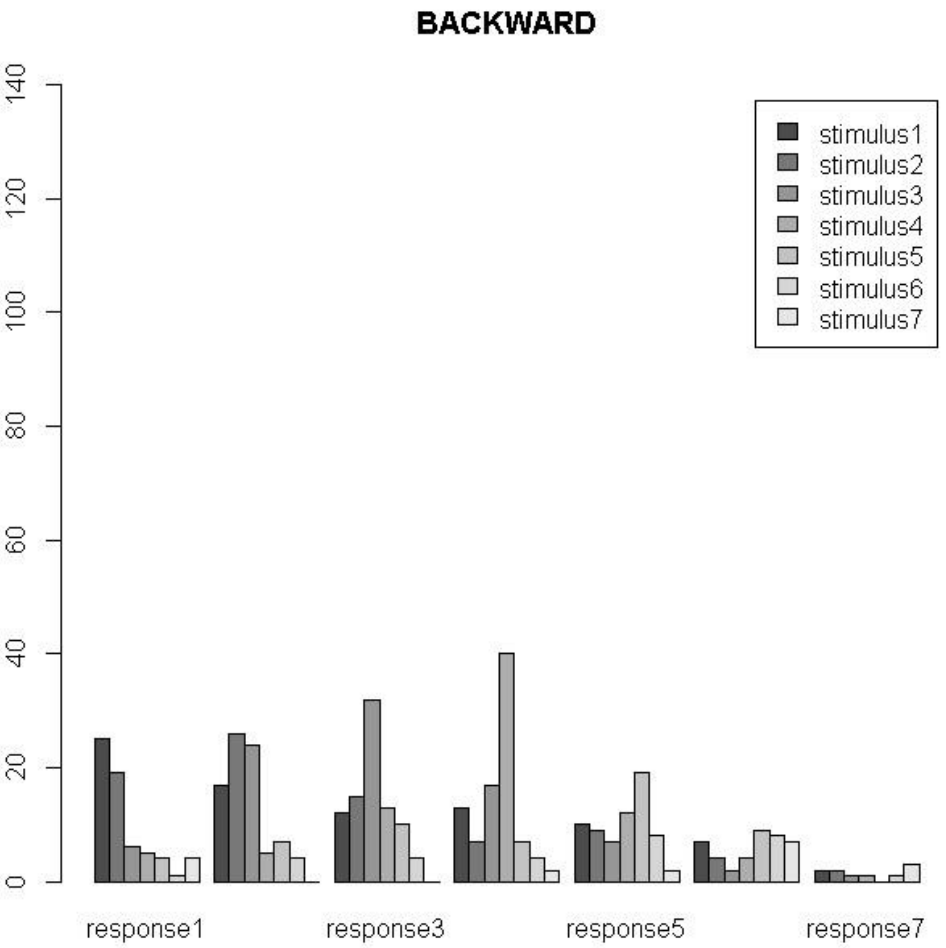


Figure 27. *Backward transposition gradients for deaf in letter stimuli condition*

- for deaf participants in word stimuli condition:

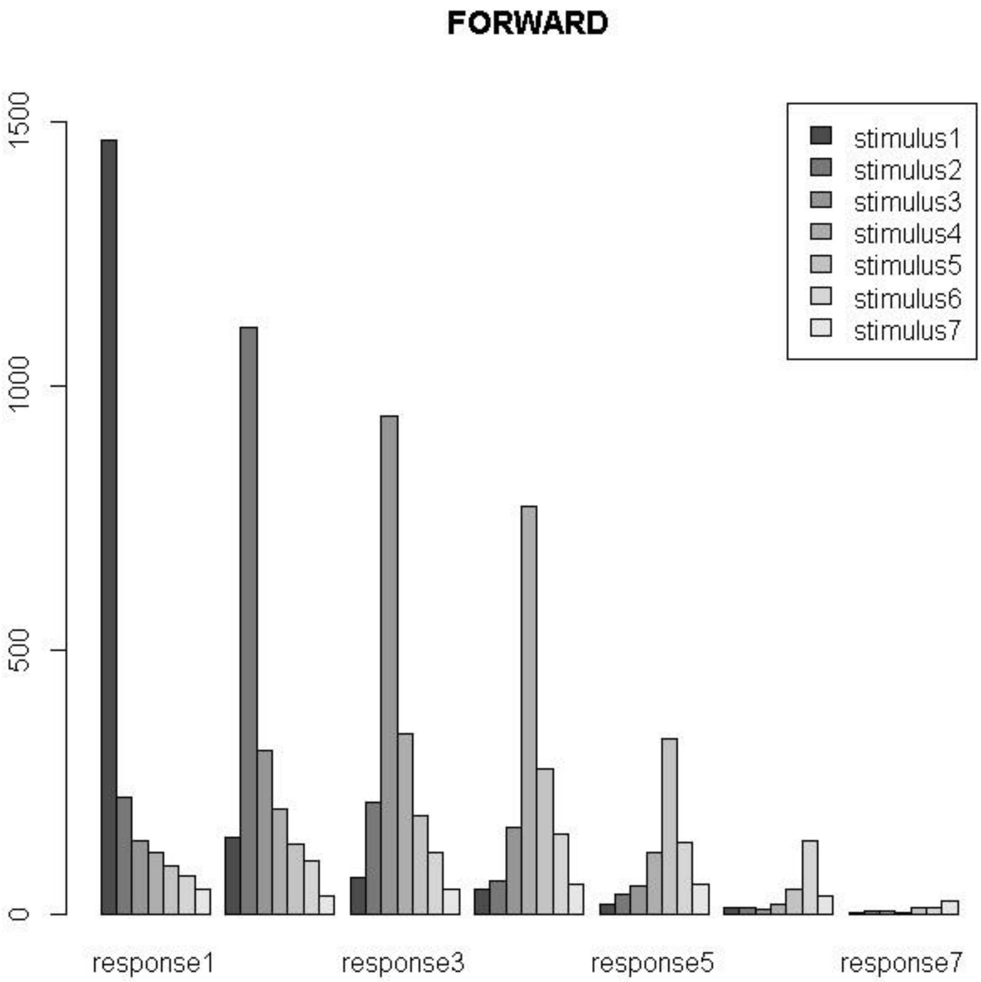


Figure 28. *Forward transposition gradients for deaf in word stimuli condition*

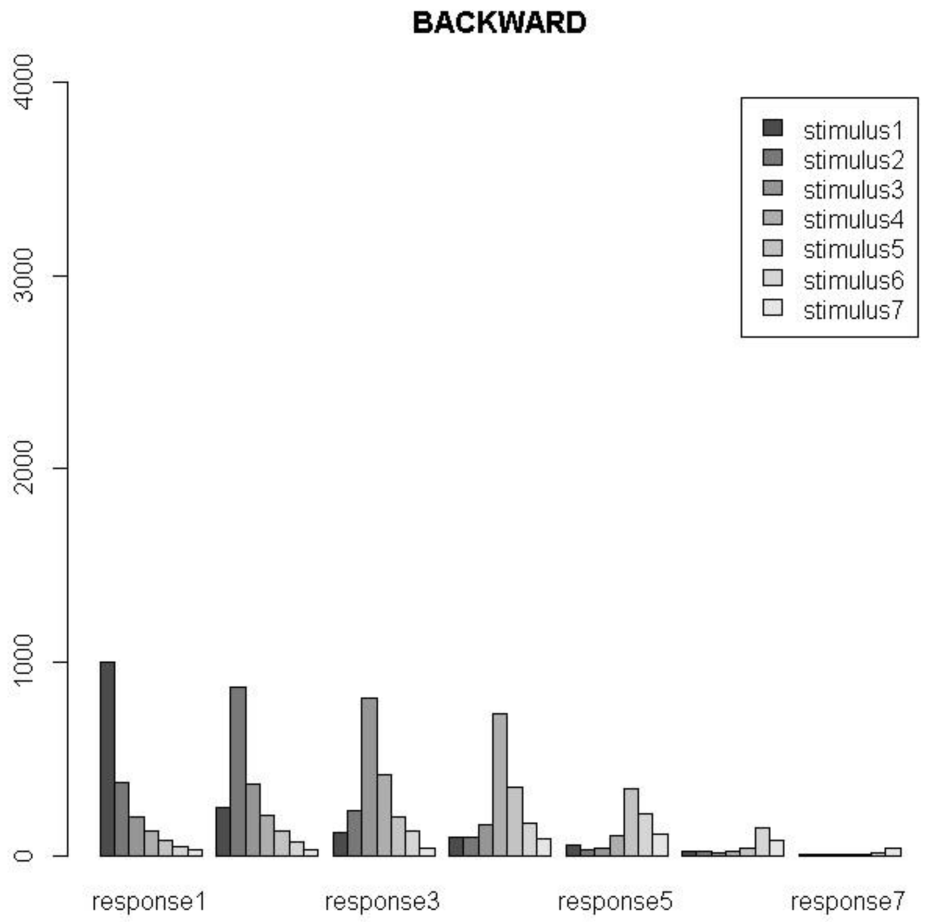


Figure 29. *Backward transposition gradients for deaf in word stimuli condition*

According to the hypothesis of a weaker position binding for signed material, we should expect more transpositions in signed material. To test for this hypothesis we performed a series of statistical analyses to find out whether the gradients for signed material differed significantly from those for spoken material. To this end we constructed transposition gradient matrices for each sequence length separately.. The use of transposition gradient matrices separately for sequence length was motivated by the fact that putting different lengths together could bring in a possible confounding with the length effect: more errors in longer sequences, and, possibly, more transpositions. Separating allows us to see transpositions in a given sequence length and construct the gradients.

An example of transposition matrix can be seen in table 10.

Table 10. *Example of a transposition matrix. Data from hearing control set, matrix for sequence length 5. The matrix represents a correspondence between an item's input position and its output position. The rows are stimuli positions in presentation (first, second, third). The columns are reported positions of the presented items. Thus, along the diagonal of the matrix we have correct responses: an item presented in first position, also reported in first position; an item presented in second position, also reported in second position; etc.*

	Resp1	*Resp2*	*Resp3*	*Resp4*	*Resp5*
Stim1	1287	9	4	2	1
Stim2	8	1224	41	8	3
Stim3	4	30	1197	42	4
Stim4	2	10	44	1197	21
Stim5	1	2	7	13	1226

To analyse the width of the gradient (i.e. how far do the errors spread, and what is the proportion of errors spreading to given positions), we calculated the proportion of errors that are transposed in the immediately adjacent positions (e.g. 2^{nd} to 3^{rd} and vice versa) to the overall quantity of transposition errors.

In table 11 we report the synthetic data on the transposition matrices for all sequence lengths, based on forward position calculation:

Table 11. *Transposition errors overall and from immediately adjacent positions. Proportions across experiments. Note: for hearing/baseline condition we only have lengths 5, 6 and 7, since that was determined by the experimental procedure in Fischer-Baum & McCloskey (in press). In our experiments with signers, conducted later, we added a sequence length of 4, due to a lower span for signs (and we maintained it in the articulatory suppression experiment too, to be able to draw more direct analogies and control).*

HEARING/BASELINE

Length	*Total transposition errors*	*Adjacent transposition errors*	*Proportion*
5	256	208	0,812
6	600	443	0,738
7	978	556	0,568

HEARING/SUPPRESSION

Length	*Total transposition errors*	*Adjacent transposition errors*	*Proportion*
4	313	255	0,815
5	490	357	0,728
6	559	372	0,665
7	445	247	0,555

DEAF/LETTERS

	Total errors	*transposition*	*Adjacent transposition errors*	*Proportion*
Length				
4	214		172	0,804
5	372		264	0,709
6	378		217	0,574
7	299		144	0,482

DEAF/WORDS

	Total errors	*transposition*	*Adjacent transposition errors*	*Proportion*
Length				
4	74		48	0,649
5	240		170	0,708
6	220		126	0,573
7	124		71	0,572

However, comparing the matrices of adjacent error proportions for all sequence lengths from different conditions in a series of t-tests (proportions per length in each condition) did not reveal any significant differences (all *p*s>0.05), so we cannot stick to the hypothesis of a wider transposition gradient in deaf signers: our empirical evidence shows no confirmation for that.

Thus, we cannot affirm the weaker binding hypothesis, since we found no confirmation of a wider transposition gradient that we could expect in case the hypothesis was true.

General Discussion

In the studies reported above we were exploring the possible sources of the differences in short-term memory span between signed and spoken material: it's a fact well confirmed by the literature and our own data, that the span for signs is significantly lower. This data regards not only deaf signers, but also bimodal bilinguals (individuals possessing skills of a spoken and of a signed language), therefore it's not a consequence of deafness itself, but is connected to the nature of the signs.

However, since the previous research has shown equal free recall capacity for signs, and equal working performance with signed material, the problem gets narrowed down to immediate serial recall. What is specific about serial recall as opposed to free recall is the necessity to encode not only the identity of the items, but also their position within a sequence. Several lines of evidence point to serial encoding as critically related to the reduced STM observed with sign (Bavelier et al., 2008; Hanson, 1982; Hirshorn, Fernandez, & Bavelier, 2012; Krakow & Hanson, 1985; Rudner & Rönnberg, 2008; Rudner et al., 2010). Many researchers connected this with the modality-specificity: auditory modality has been thought to suite better for encoding sequential material, and the visuo-spatial modality, in which signs are presented, has a disadvantage in this case.

The studies of position representation (e.g. Henson, 1999; Fischer-Baum, McCloskey & Rapp, 2010) come to a conclusion that hearing speakers using verbal material as stimuli encode the positions according to the both-edges encoding scheme, i.e. when a position of an item is anchored to the start and end points of a sequence. However, when the stimuli material is non-verbal, but rather of a visuospatial nature (sequences of squares in different locations), then another position representation scheme is revealed, namely, the beginning-based scheme, where only the starting point of a sequence serves as anchor for position representation.

Aim of the present work is to investigate whether serial order is comparably represented in signed and verbal codes. This is important in two aspects: one is a better understanding of the functioning of sign language processing, and another one is a more general exploration of the measure of the extent to which the nature of the stimuli can determine processing mechanisms, an additional insight on the contribution of modality-specific mechanisms according to working memory models.

We based our testing method on error analyses carried out on verbal STM that revealed encoding of serial positions specified with respect to both start and end positions (Fischer-Baum & McCloskey, 2014; Henson, 1999). We ran our experiments with immediate serial recall for signs and analyse them in the same manner that the data from hearing speakers has been analysed, drawing conclusions about the position representation scheme.

The first experiment with signers was immediate serial recall task with presentation of sequences of videotaped signs and an instruction afterwards to repeat them by signing. The perseverations in recall (items not present in a given stimulus sequence, but erroneously reported in the response because they were present in one of the preceding stimuli sequences) were analysed through a computation of chance likelihood of the intrusions and comparisons of the chance with the actual perseverations observed. To discern between the contributions of the beginning-based and end-based encoding scheme, residual analyses were conducted. Results from the first experiment with letter stimuli painted a clear picture, demonstrating that aspects of position representation observed in verbal STM extend to sign. We found that signers elaborate the sequential information according to the both-edges positional encoding scheme, i.e. anchoring an element's position with respect to the start and end points of a sequence; with evidence for clear contribution from both the beginning- and end-based components of the scheme. Additionally, the position representations are graded rather than discrete, i.e. the immediately adjacent elements bear more resemblance to the representation of a given position, and the binding decreases gradually.
In order to confirm the same pattern of results even with signs that are inherently related to sign language, we performed the second experiment in which we replaced the signs of the letters with word signs. The results of the second experiment turned out to be much less clear and insufficient to reach conclusions with respect to our hypothesis. This lack of results was due to the fact that participants tended to produce multiple sequences of the same length in a row, therefore, matching the intrusions to both edges of the sequence. It was therefore impossible to distinguish between position schemes. The only way to overcome to this problem would be to collect more data with the same paradigm, to enlarge the pool of sequences of various length to be used in the analyses. We could not pursue this objective, thought, since we were not able to recruit significantly more signers at the moment.

The knowledge our deaf participants have acquired of spoken Italian demands we carefully consider whether the results obtained with letter stimuli are in some way associated with forms of speech-based phonological encoding, analogous to the mechanisms of the hearing individuals use to encode auditorily presented stimuli. In the third experiment we sought evidence of sound-based phonological encoding by examining effects of sound similarity, taking into consideration the accuracy of recall. No evidence of a role of sound emerged from these analyses, showing that sound similarity did not reduce accuracy in deaf signers, while sign similarity creates interference and reduced the recall capacity. For the hearing participants we observed a reverse pattern – interference from sound similarity and no effect of sign similarity (with words presented auditorily). Therefore we can rule out the possible bias of contamination of speech-based phonological knowledge. The effects of sign similarity demonstrated indicate that signs were subject to sign-based phonological similarity, which, as outlined in the introduction, consists of similarities at the level of hand shape, movement and/or position of signs.

To test for the role of the phonological loop in position representation, we conducted our fourth experiment. The starting point was to verify to what extent auditory modality is better suited for encoding sequential order information, and what is the role the phonological loop in the processing of order information. Indeed, the disadvantage for signs can be traced to the fact that the phonological loop is not adapted for processing signed information, while it’s a critical structure for encoding sequential information. In Experiment 4 we explored which was the schema used for position coding putting under stress the phonological loop. Participants were hearing speakers, and they had to perform an immediate serial recall task with visually presented words, while suppressing the articulation (repeating the same syllable). The articulatory suppression is known to disrupt the possibility of rehearsal of the presented material in the phonological loop. If the phonological loop is responsible for order coding, then we should expect a different position-encoding scheme when the loop is suppressed.

The results, however, have shown that while the articulatory suppression leads to a significant reduction in recall accuracy (19% of correctly recalled sequences, versus 57% in an experiment with the same paradigm but no suppression), the position representation scheme remains the same, i.e. a both-edges scheme. This leads us to a conclusion that the phonological loop is not the critical element in the processing of serial order.

Both-edges position scheme for signs

The finding that that both-edges positional scheme also applies to sign helps us to further constrain hypotheses about the causes of sign span disadvantage. The unavailability of the positional scheme used in verbal code could have (at least in part) explained the reduced STM of sign. The finding that both-edges positional scheme is also available with sign, however, rules out an account that identifies the cause of the STM disadvantage in the use of different positional schemes.

Many researchers account for the differences between signs and speech with regard to the different storage units in short-term memory. While spoken material is supposed to be processed through the phonological loop, visuo-spatial material, and also signs, are elaborated through a visuospatial sketchpad that is less suited for storing sequential information. This explanation is not compatible with our results as revealed by the comparing the results we obtained from analyses of perseverations with signs with the pattern obtained in studies of visual STM with non-linguistic material and hearing participants. In tasks that require hearing participants to recall the spatial position and the temporal order in which dots/squares were presented, perseveration errors did not reveal an encoding of serial order based on both start and end positions (Fischer-Baum, 2011), instead supporting a beginning-based representation scheme without any additional contribution of end-based position representations. These results contrast with our findings with signers, suggesting that, at least for deaf signers, sequences of signs are not processed the same way as other types of stimuli retained in visuo-spatial STM.

It is worth considering here that the results obtained in Experiment 4 further foster the ideas that considering that verbal material, encoded through the phonological loop is ordered according to a both edges schema while visual material encoded through the visual sketchpad is ordered according to a beginning-based scheme is not quite accurate. Evidence from Experiment 4 demonstrates, that even under the articulatory suppression hearing speakers maintain the both-edges encoding scheme (while having a drastically reduced recall accuracy). Therefore the both-edges scheme is not provided by the phonological loop itself, but is a modality-independent mechanism.

A possible interpretation of these results is that linguistic experience with a class of stimuli changes how sequences of those stimuli are represented in STM. One universal feature of natural languages is that linguistic elements – whether they be spoken or signed – have to be combined to temporal sequences, at both a sublexical and at a sentence level. For participants who do not know sign language, these sequences of signed letters would be processed like other visual stimuli in the visuo-spatial STM system. But extensive experience using sign language could have induced adaptive changes in the STM system responsible for processing of signs, resulting in a form of serial order representation particularly suitable to the encoding of linguistic elements.

Data from Experiment 1 that shows a both-edges position representation for signs comes from an experiment with fingerspelled letters, which may not be a definite evidence to confirm or reject any hypothesis, since letters are basic elements of verbal (spoken/written) language and refer more to it than to sign language itself. We recognize that a further evidence with signs corresponding to the words of sign language is a critical point for a continuation, since word signs are true elements of sign language, not sharing any feature with spoken language.

We may conclude that serial order encoding is independent of the stimuli nature and modality (signs or speech), but is a general feature of any kind of linguistic material, different from visuospatial (location?) non-verbal stimuli.

Weaker binding hypothesis

We've seen that the span for signs is lower, even if the signers use the same position representation scheme as speakers, therefore it's not the lack of an appropriate position encoding scheme.

An alternative hypothesis to explain the reduction of the span for signs, that seems reasonable to entertain in light of our findings, is that of a weak binding between signs and serial positions. In other words, the problem could be in forming a strong association between the letter sign D and its position in the series ABCDE so that, at retrieval, the letter sign D would appear in the correct serial position. A stronger binding occurs in the verbal domain, and this can explain the greater span of verbal STM.

Maybery, Clissa, Parmentier, Leung, Harsa, Fox, & Jones (2009) in a series of experiments showed evidence of the binding of sound identity and location information for auditorily presented stimuli. While binding tended to be stronger for the more recent items of the sequence, there was consistent evidence of the retention of associations of features for the early sequence items, suggesting durability of binding of auditory features over time (at least 5.5 s) and despite the interpolated processing of other stimuli. conclusions. This may lead to an assumption that memory binding for verbal material is particularly strong, while this may not be the case for signs.

Proposals to explain difference in binding have included longer lasting memory traces in echoic than iconic memory (Boutla et al., 2004) and the greater sensitivity to temporal features acquired by speech processes as an adaptive response to speech stimuli with prominent temporal characteristics (Conrad, 1970; Hamilton & Holzman, 1989; Hanson, 1982; Koo et al., 2008; Krakow & Hanson, 1985; Lichtenstein, 1988; Miller, 2007; Wilson, 2001).

In order to test for this hypothesis we run transposition gradient analyses, calculating the errors within a given sequence (a stimulus presented in a given position is reported in the response in another position). The assumption was that in case of weaker position binding with signs, errors within a sequence will happen more often, and "travel" farther than in an analogous task with spoken material. The results of the transposition gradient analyses did not reveal any significant differences between signed and spoken material in terms of proportions of immediately adjacent errors to the total quantity of errors, i.e. the width of the gradients.

The results seem incongruent with the idea of a weaker binding of the sign with the correspondent position with respect to verbal material. If this were the case, in fact, we should have observed a wider transposition gradient for signed than for spoken material.

Higher Interference hypothesis

Since we did not find a confirmation for a weaker binding hypothesis, we may have to search further for an explanation of sign span reduction.

An alternative explanation, which for now is purely speculative, could be the fact that positional encoding of signs in short-term memory are prone to interference more than spoken verbal material.

Keppel & Underwood (1962), exploring the mechanisms of forgetting in short-term memory, demonstrated that on the first trial of the experiment the decay was always minimal, They suggested an explanation of proactive interference, i.e. that the new information gradually pushes out older items, unless the older items is actively protected against interference by rehearsal. This finding has been confirmed multiple times afterwards (e.g. Oberauer, K. & Kliegl, R., 2006). We might extend this explanation to the coding of positional information. In other words it might be that the coding of older positions might interfere with the coding of new positions in this way reducing the span of signs.

The following step in our research is planned to be a more thorough exploration of this hypothesis, including an experimental testing of the short-term memory span of the signers, changing the classic paradigm of gradually increasing sequence length, and starting instead from long sequences, to see whether the first sequences would be remembered well, which, if observed, would provide evidence in favour of the interference hypothesis.

Summary

The span for signed material is reduced respect to the span for spoken material. We searched for the source of such a discrepancy. We demonstrated a both-edges position encoding scheme for signs, the same one that is used for spoken material, even if signs are presented in a visuospatial modality. Therefore the span difference cannot be attributed to differences in position representations. We controlled for a possible use of sound-related information in signs encoding, and found no evidence of it. We demonstrated that the phonological loop doesn’t play a critical role in position representation (since the both-edges scheme persists under articulatory suppression). The source of the difference in span is not a weaker binding of elements to their positions either, as demonstrated by transposition analyses.

As we have argued, the similarities emerged from our data between sign and verbal STM are important because they help in advancing our understanding of the causes of the reduced STM span observed with signs. Furthermore, because signs are both visual and linguistic in nature, understanding how sign STM relates to verbal and visuo-spatial STM might shed light on the intricate relationship between language (sign and spoken) and short-term memory systems.

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Appendices

Appendix 1. *Questionnaire for the deaf participants*

QUESTIONARIO

Età ______________________ Sesso M F

Dove sei nata/o (Paese):

Se sei nata/o fuori dall'Italia, da quanto tempo sei in Italia: ___________ anni

Da quanto sei sorda/o?

- sono nato sorda/o
- sono diventato sorda/o prima dei 2 anni
- sono diventato sorda/o tra i 2 e gli 6 anni
- sono diventato sorda/o tra i 6 e i 10 anni
- sono diventato sorda/o dopo i 10 anni

Hai un impianto cocleare? SI NO

Se SI, a che età hai fatto l'impianto? : _____________anni

Tua madre è sorda? SI NO

Tuo padre è sordo? SI NO

Hai fratelli sordi? SI NO

Hai fratelli udenti? SI NO

Quando hai imparato la LIS?

- 0-2 anni	-7 anni	-12 anni
- 3 anni	-8 anni	-13 anni
- 4 anni	-9 anni	-14 anni
- 5 anni	-10 anni	-15 anni
- 6 anni	-11 anni	-16 o oltre

Ti consideri un parlante LIS:

- molto esperto - mediamente esperto - poco esperto

Se sei uno studente dell'Istituto Magarotto

A che età sei entrato/a all'Istituto Magarotto? ______________________ anni

Appendix 2. *Informed consent for deaf participants*

MODULO DI CONSENSO INFORMATO

Con la presente dichiaro di aver acconsentito volontariamente di partecipare allo studio intitolato "La mano potente".

Lo scopo della ricerca è quello di studiare le conseguenze dell'uso della Lingua Italiana dei segni (LIS) e i vantaggi derivanti dalla pratica del bilinguismo per i segnanti sordi (leggere e scrivere in Italiano, ma comunicare prevalentemente in LIS).

Sono stato informato/a, prima di partecipare al suddetto studio, del mio diritto di interrompere la mia partecipazione allo studio in qualsiasi momento, senza fornire alcuna motivazione, senza alcuna penalizzazione e ottenendo il non utilizzo dei miei dati. Inoltre, dichiaro di essere stato informato dello scopo del suddetto studio e del fatto che i miei dati (incluse videoregistrazioni, audio registrazioni, foto, ecc) rimarranno anonimi e protetti secondo il Codice in materia di protezione dei dati personali (Dlgs. n. 196/2003). Sono stato informato che solo le persone che conducono la ricerca potranno avere accesso ai miei dati limitatamente ai fini della loro elaborazione e alla pubblicazione anonima dei risultati a fine scientifico.

Autorizzo i responsabili del presente studio di utilizzare i miei dati.

Firma ___________________________

Data ___________________________

Appendix 3. *Informed consent for the parents of underage deaf participants.*

Ai Signori Genitori degli Allievi dell'Istituto Magarotto – Padova

Cari genitori,

in collaborazione con l'Università di Padova, Dipartimento di Psicologia dello Sviluppo e della socializzazione l'Istituto Magarotto sta partecipando ad un progetto di ricerca intitolato "*La mano potente*" (responsabile Prof.ssa Francesca Peressotti). Lo scopo del progetto è quello di studiare le conseguenze dell'uso della Lingua Italiana dei segni (LIS) e i vantaggi derivanti dalla pratica del bilinguismo per i segnanti sordi (leggere e scrivere in Italiano, ma comunicare prevalentemente in LIS).

Alcuni studi pioneristici hanno mostrato vantaggi legati all'uso del codice visuo/spaziale e dei movimenti raffinati delle mani su altre funzioni cognitive. Altri studi, inoltre, mostrano che i processi linguistici sottesi alla LIS e alla lingua italiana sono del tutto analoghi.

Stiamo approfondendo queste ricerche e studiando in particolare la memoria di sequenze di lettere segnate, la denominazione di figure in LIS e i processi focalizzazione dell'attenzione nei sordi che parlano la LIS.

La ricerca prevede la presentazione di figure o lettere sullo schermo al quale è richiesta una semplice risposta (come ripetere lo stimolo presentato, o segnare il nome della figura, o premere un tasto in funzione dell'orientamento o del colore degli stimoli). Le risposte potranno essere riprese con la telecamera centrata sulle mani dei partecipanti. Gli esperimenti proposti hanno una durata di 20-40 minuti, non hanno scopi clinici o valutativi, ma solo di raccolta di dati. Gli studenti non sono obbligati a partecipare e hanno diritto ad interrompere la loro partecipazione allo studio in qualsiasi momento senza alcuna penalizzazione e ottenendo il non utilizzo dei dati. I dati raccolti (inclusi video) rimarranno anonimi e protetti secondo il Codice in materia di protezione dei dati personali (Dlgs. n. 196/2003). Solo le persone che conducono la ricerca potranno avere accesso ai dati limitatamente ai fini della loro elaborazione e alla pubblicazione anonima dei risultati a fine scientifico.

Chiediamo la vostra autorizzazione per la partecipazione di vostra/o figlia/o

(nome e cognome dell'allievo) ____ allo studio.

Firma ___________________________

Data ___________________________

Appendix 4. *stimuli list from Experiment 2.*

borsa – bag

caffe – coffee

cane – dog

curva – curve

donna – woman

freno – brake

mucca – cow

oro – gold

penna – pen

pesce – fish

sete – thirst

soldi – money

spade – sword

tipo – type

vecchio – old man

vita – life

Appendix 5. *Stimuli list from Experiment 3*

SIGN SIMILAR	SIGN CONTROL	SOUND SIMILAR	SOUND CONTROL
albero – tree	sorella – sister	porta – door	gamba – leg
cappello – hat	caldo – warm	borsa – bag	gesto – gesture
pizza – pizza	timbro – stamp	forza - strength	libro – book
vaso – vase	prete – priest	corso – course	mente – mind
citta' – city	nome – name	torta – cake	cella – cell
lago – lake	gatto – cat	torso – torso	tigre – tiger
piatto – plate	treno – train	morso – bite	palmo – palm
ruota – wheel	uovo – egg	dorso – spine	pasta – pasta
sole – sun	moda – fashion	forma – shape	campo – field

Appendix 6. *Stimuli list from Experiment 4*

blink
clash
drown
flask
growl
hitch
joust
khaki,
latch
marsh
noose
punch
queer
rhyme
sting
thorn
vogue
whine
zebra