Cognition 154 (2016) 69–80

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/COGNIT

Original Articles

# Serial position encoding of signs

Michele Miozzo [a,b,*], Anna Petrova [c], Simon Fischer-Baum [d], Francesca Peressotti [c]

[a] The New School, United States
[b] Johns Hopkins University, United States
[c] Universita' di Padova, Italy
[d] Rice University, United States

ARTICLE INFO

*Article history:*
Received 4 September 2014
Revised 29 April 2016
Accepted 15 May 2016

*Keywords:*
Sign language
Deafness
Short-term memory

ABSTRACT

Reduced short-term memory (STM) capacity has been reported for sign as compared to speech when items have to be recalled in a specific order. This difference has been attributed to a more precise and efficient serial position encoding in verbal STM (used for speech) than visuo-spatial STM (used for sign). We tested in the present investigation whether the reduced STM capacity with signs stems from a lack of positional encoding available in verbal STM. Error analyses reported in prior studies have revealed that positions are defined in verbal STM by distance from both the start and the end of the sequence (both-edges positional encoding scheme). Our analyses of the errors made by deaf participants with finger-spelled letters revealed that the both-edges positional encoding scheme underlies the STM representation of signs. These results indicate that the cause of the STM disadvantage is not the type of positional encoding but rather the difficulties in binding an item in visuo-spatial STM to its specific position in the sequence. Both-edges positional encoding scheme could be specific of sign, since it has not been found in visuo-spatial STM tasks conducted with hearing participants.



## 1. Introduction

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 signers as compared to speakers, a robust finding that has been documented in different languages and populations using a variety of experimental paradigms. 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; MacSwinney, Campbell, & Donlan, 1996), Italian Sign Language (Geraci, Gozzi, Papagno, & Cecchetto, 2008), Israeli Sign Language (Miller, 2007), and Swedish Sign Language (Rönnberg, Rudner, & Ingvar, 2004). Shorter STM spans were observed with signs produced both by deaf signers and hearing individuals proficient in sign language (Boutla, Supalla, Newport, & Bavelier, 2004; Hall & Bavelier, 2011). Differences in STM capacities were demonstrated with stimuli as diverse as printed digits, letters and words (e.g., Belmont, Karchmer, & Pilkonis, 1976; Pintner & 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 spoken words (Baddeley, Thomson, & Buchanan, 1975) and signs (Wilson & Emmorey, 1998), possibly reflecting the limited capacity of STM buffer or the functioning of rehearsal mechanisms (Baddeley, 2007). 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. Notwithstanding the relevance of this question, the causes have remained elusive.

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 (Marschark & Mayer, 1998; Wilson, 2001; Wilson & Emmorey, 1997), chiefly the fact that signs tend to be longer in

* Corresponding author at: Department of Psychology, 80 5th Avenue, New York, NY 10011, United States.

*E-mail address:* mm1150@columbia.edu (M. Miozzo).

http://dx.doi.org/10.1016/j.cognition.2016.05.008
0010-0277/

duration (Bellugi & Fischer, 1972). While a few results lent support to accounts assuming differences in duration (Wilson & Emmorey, 2006), findings showing that shorter STM spans persisted even when signs were carefully matched to verbal stimuli in duration (Bavelier, Newport, Hall, Supalla, & Boutla, 2006; Bavelier et al., 2008; Boutla et al., 2004; Geraci et al., 2008) 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 (Boutla et al., 2004; Conrad, 1970; Hamilton & Holzman, 1989; Hanson, 1982; Koo, Crain, LaSasso, & Eden, 2008; Lichtenstein, 1988; Miller, 2007). The critical role these accounts assign to the encoding of temporal order information is justified by findings showing that as soon as instructions of recalling items in a specific order were lifted and items could be recalled in any order, comparable spans appeared across modalities (Bavelier et al., 2008; Hanson, 1982; Krakow & Hanson, 1985; Rudner, Davidsson, & Rönnberg, 2010; Rudner & Rönnberg, 2008). While findings from free order recall demonstrate comparable encoding of sign and speech, disadvantages for signs restricted to serial order recall lend support to hypotheses linking the reduced capacity with signs to temporal order information. Further converging evidence was obtained by Bavelier et al. (2008). Even when instructions allow free order recall, order of presentation is often preserved at recall, as in the example ABCDE → ECDBA where C and D appear next to each other both in the stimulus and the response. 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 (see Gmeindl, Walsh, & Courtney, 2011 for a similar result comparing verbal and spatial STM).

The present study aims to contribute to the investigation of the temporal order hypothesis that associates the reduced span of sign to 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 (Farrell & Lelièvre, 2009; Fischer-Baum & McCloskey, 2015; Henson, 1998). For example, 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). However, Fischer-Baum (2011) found that some spatial STM tasks, like the Matrix Span and Corsi Block Tasks, rely on a different representation of serial order in which position is encoded only relative to the start of the sequence.[1] We investigated whether both-edges positional encoding scheme are computed in the immediate ordered recall of signs, or instead whether position is represented by a start-anchored only scheme. Evidence that favors the start-anchored only scheme over the both-edges scheme would reveal that memory for signs lacks a key component. Such evidence would further indicate that the serial positions of signs are specified as with other visuo-spatial stimuli, for which evidence of both-edges positional encoding was similarly lacking. By contrast, evidence favoring the both-edges positional encoding in sign ordered recall would establish that discrepancies in STM capacity between sign and speech do not reflect differences in the representation of item position within a sequence.

[1] Results reported in Fischer-Baum (2011) indicate that the spatial locations hearing speakers memorized in the Matrix span task were not encoded as part of path-like representations. These results suggest instead that each location was encoded as a distinct unit. In this respect, representations of spatial locations are discrete similar to encoding linguistic elements, such as words and signs.

Critical evidence on the encoding of temporal sequences in verbal STM was garnered from intrusion errors. Intrusion errors arise when an item not included in the original sequence appears in the recalled list. For example, F intrudes in the response ABCDFE produced for the sequence ABCDE. Intruded items were often produced in immediately preceding responses (Conrad, 1960; Estes, 1991; Werner, 1947; Wickelgren, 1966), for example when the intruding letter F in ABCDFE appeared in the immediately preceding response MXBFT. In other words, some of the intrusions appear to be *perseverations* from prior responses. The positions in which intruded items occur would be informative for accounts on serial position encoding if they reflect the positions taken in prior responses rather than being determined by chance. Perseverations produced in verbal serial recall tasks not only differed from distributions expected by chance, but they also conformed to predictions of accounts positing start- and end-anchored positional encoding (Fischer-Baum & McCloskey, 2015; Henson, 1999). Here, we examined the perseverations that signers of Italian Sign Language produced in an immediate serial recall task involving finger-spelled letters (see examples in Fig. 1). Perseverations were analyzed to determine whether their occurrences reflected the encoding of serial positions with respect to both edges that characterizes verbal STM.

### 1.1. Both-edges positional encoding scheme

Let us suppose that F intruded in the response ABCDFE (hereafter called the *perseveration response*) and appeared in a previous response MBFT (hereafter called the *source response*). Does the intruded F appear in the same position in both responses? The answer to that question differs depending on the underlying scheme used to represent serial position (see examples in Fig. 2). According to a start-anchored scheme, F does not match position between the perseveration and the source response, as it appears in position S+5 in the perseveration response and S+3 in the source response. It does, however, match position according to the end-anchored scheme, appearing in position E−2 in both responses. Alternatively, let us consider the perseveration error ABFCDE with the source response MBFT. Here, the perseveration error matches position by the start-anchored scheme (F is in position S+3 in both responses) but not by the end-anchored scheme (F is in position E−4 in the perseveration response, and E−2 in the source response). The hypothesis that a positional encoding scheme that is both start- and end-anchored underlies the STM representation of signs makes the following two predictions: (1) sign perseveration errors should match position defined by the start-anchored position encoding scheme but not the end-anchored position encoding scheme significantly more often than would be expected by chance, and (2) perseveration errors should match position defined by the end-anchored position encoding scheme but not the start-anchored position encoding scheme significantly more often than would be expected by chance. The second prediction is particularly critical for determining whether the representation scheme used to encode position in this task patterns with the scheme used by hearing participants to encode position in verbal STM (both-edges) or visuo-spatial STM (start-anchored only). To test these predictions, we applied methods developed in earlier work, which used perseverations in reading and writing to evaluate theories of letter position representation (Fischer-Baum, McCloskey, & Rapp, 2010; McCloskey, Fischer-Baum, & Schubert, 2013; McCloskey, Macaruso, & Rapp, 2006).

The logic of these methods have a similar rationale to the analyses reported in Henson (1999) on position representation in immediate serial recall, but with a clear advantage over the earlier

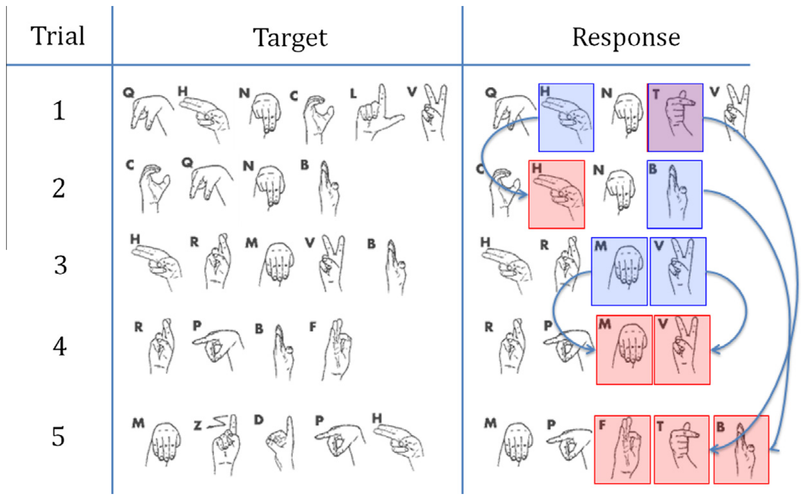



**Fig. 1.** Examples of signs corresponding to letters presented as targets and produced as responses in the immediate serial recall task. Signs produced in previous trials that intruded in later responses (*perseverations*) are highlighted. Arrows relate signs in the source responses that later appeared in the perseveration responses.

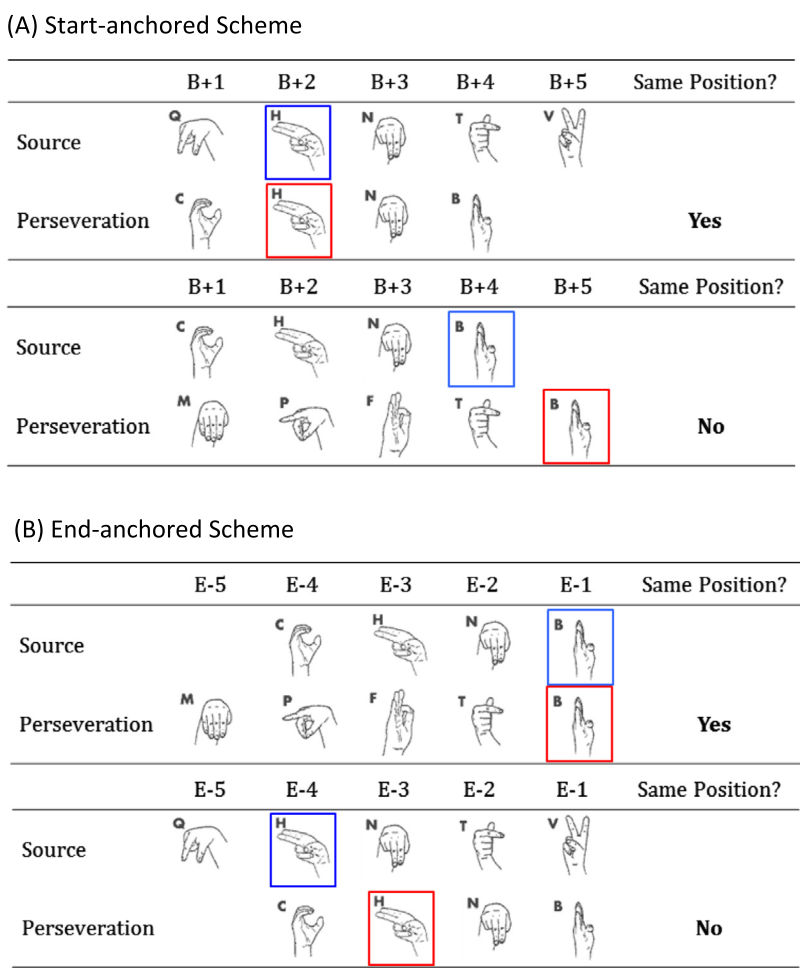



**Fig. 2.** Perseveration errors in the immediate serial recall task in which the sign retains it original position (Same Position? Yes), or it does not preserve it (Same Position? No), according to start-anchored scheme (top) and end-anchored scheme (bottom).

analyses. Henson's analyses of intrusions considered only three response positions, and the analysis for each position examined only one positional scheme (start-anchored for the first and fifth positions; end-anchored for the final position); the current method compares different positional schemes across all positions within a list. This alternative method has been used to analyze perseveration errors in immediate serial recall for visually and auditorily presented lists of words with English speaking participants (Fischer-Baum & McCloskey, 2015). The results of these analyses provide broader-based evidence and stronger support for the start- and end-anchoring encoding of position previously reported by Henson (1999) in verbal STM.

### 1.2. Overview of the present investigation

The analyses of intrusion errors represent the core of our investigation. Four analyses were conducted to determine whether serial positions in sign STM are assigned with respect to the beginning and/or end of the sequence. These analyses are similar in logic and, as explained in detail below, reveal whether the frequencies with which intrusions occurred match the frequencies anticipated by a specific type of position representation (e.g., start-anchoring encoding), while differing from frequencies expected by chance. Specifically, Analysis 1 aims to determine if both start- and end-anchoring encoding underlie serial positions in sign STM, while Analysis 2 examines the individual contribution of these types of encoding. Analyses 3 and 4 clarify how each serial position is represented within start- and end-anchoring schemes, assessing whether positions are specified discretely or in a more graded fashion, so that nearby positions are encoded as similar. Analyses 1–4 were performed on a large pool of signed responses produced in immediate serial recall (see Experimental Task). This large response pool was also used to examine errors in which signs exchanged their positions within a sequence, as in ABCDE → BACDE. These position-exchange errors demonstrate specific patterns in verbal immediate recall that reflect the representation of serial position in verbal STM (Farrell, Hurlstone, & Lewandowsky, 2013; Henson, 1998; Henson, Norris, Page, & Baddeley, 1996; Page & Norris, 1998; Surprenant, Kelley, Farley, & Neath, 2003). Although position-exchange errors are not diagnostic of start- and end-anchoring encoding, establishing that these error patterns occur similarly in signed and spoken sequences strengthens the conclusion that a similar type of encoding of serial position underlies both sign and verbal STM.

We also examined if the deaf participants verbally encoded the items presented for immediate recall. The reason for assessing verbal encoding was twofold: first, the deaf participants possessed knowledge of spoken language in varying degrees; second, we used letters for testing immediate recall. Letters represented ideal stimuli, as they allowed us to create meaningless sequences suitable for our analyses. Furthermore, letters have simple signs and names that facilitate cross-modal comparisons. However, the fact that deaf signers use finger-spelled letters to express spoken/written words in the spatial domain could determine a verbal encoding of finger-spelled letters. To the extent that we can rule out a verbal encoding, our error analyses should shed light specifically on the representation of serial positions in sign-based encoding. The role of verbal encoding was examined with both signs and finger-spelled letters.

### 1.3. Participants

Twenty deaf participants 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. Deaf participants attended a boarding school for deaf students in Northern Italy, where Italian Sign Language is adopted for teaching and used by students for communication. They had some knowledge of spoken Italian, acquired especially for purposes of reading and writing. Two groups of hearing participants were tested – Group 1, which included 15 participants (10 female; mean age = 22.2, SD = 1.6) in the pretest, and Group 2, composed of 20 participants (10 female; mean age = 22.4, SD = 1.7), in the experimental task. Participants in both groups were university students who reported to be native Italian speakers and have no hearing deficits or knowledge of a sign language.

## 2. Modality of encoding

The pretest allowed us to control whether or not deaf participants translated signs into Italian (a speech-based code). Reduced memory span with lists that include similar sounding words is the hallmark characteristic of verbal encoding (Baddeley, 2007). We examined if the deaf participants exhibited parallel disadvantages in recalling signs corresponding to words that sound similar in Italian spoken language. In the pretest, it was also controlled whether or not our participants showed a reduced span when lists included visually-similar signs, a type of evidence that has been taken to demonstrate the encoding of visual characteristics of signs (Hanson, 1982; Poizner, Bellugi, & Tweney, 1981; Shand, 1982; Wilson & Emmorey, 1998).

### 2.1. Materials and procedure

We prepared distinct sets of 60 4-sign-lists to examine sound and sign similarity, respectively. Each list was created from a pool of 36 signs corresponding to Italian words. In the set of lists testing for effects of sound similarity, half of the lists included two sound-related words, differing by only a single phoneme (e.g., *forza*-*forma*, strength-shape), while the other half included only 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 features forming the signs, referred to as parameters in the linguistic literature (Battison, 1978; Liddell, 2003; Mathur & Rathmann, 2014; Sandler & Lillo-Martin, 2006; Stokoe, Casterline, & Croneberg, 1965; Van der Hulst, 1993). The signs included in the sequences testing sound similarity did not share identical parameters in Italian Sign Language. The set of lists testing for effects of sign similarity was similarly structured. For half of the lists, two of the signs included in a sign-related sequence shared 2 parameters (hand-shape and either orientation or movement). The signs in unrelated lists did not share identical parameters. Related and unrelated lists included signs that corresponded to Italian words matched for length, frequency, and neighborhood density ($ts < 1$).

Each sign was videotaped. In the STM test, signs were presented sequentially at 1 s intervals. Deaf participants were instructed to reproduce the signs in the exact order in which they had appeared. Responses were videotaped for scoring purposes. In the replication of the STM test with hearing participants, words were presented at 1 s intervals via audio recordings, while responses were produced verbally.

### 2.2. Results

Data from the pretest were collected from 18 of the 20 deaf participants tested in the Experimental Task, and from the 15 hearing participants of Group 1. Data were entered in a three-way ANOVA with Group (deaf vs. hearing) as between-participants factor, and List (sign vs. sound) and Sequence (similar vs. dissimilar) as within-participants factors. The main effect of Group was significant ($F(1,31) = 14.03$, $p = 0.001$, $\eta^2 = 0.31$; here and elsewhere, significance was set at $\alpha = 0.05$). In line with previous reports, overall deaf participants recalled fewer sequences than hearing participants (53% vs. 78%). Each two-way interaction was significant

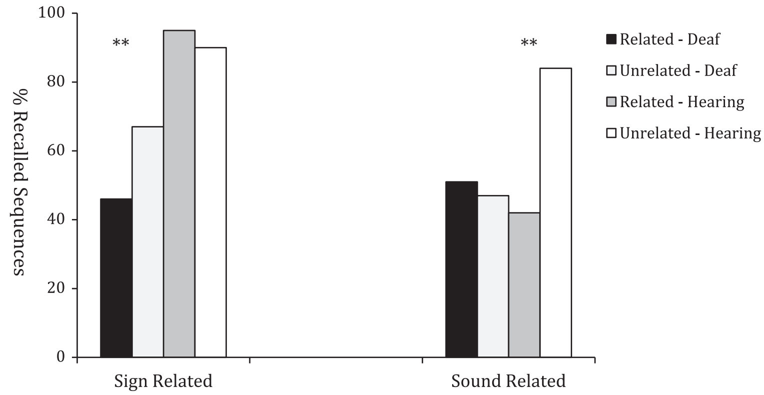



**Fig. 3.** Percentage of sequences correctly recalled by deaf and hearing participants (pretest). Sign similarity affected recall of deaf participants, sound similarity of hearing participants. Asterisks (**) indicate significant differences ($p < 0.0001$) between related and unrelated sequences.

(List × Group, $F(1,31) = 26.14$, $p < 0.001$, $\eta^2 = 0.48$; Sequence × Group, $F(1,31) = 54.26$, $p < 0.001$, $\eta^2 = 0.63$, List × Sequence, $F(1,31) = 50.01$, $p < 0.001$, $\eta^2 = 0.62$). These effects were specified by the three-way interaction ($F(1,31) = 10.84$, $p = 0.002$, $\eta^2 = 0.26$; see Fig. 3). Deaf participants showed reduced span with the 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 instead suggest only a sign-based encoding of the signs presented as stimuli in STM tasks. As revealed by the results we present in the next section, these conclusions hold also for finger-spelled letters, the stimuli tested in our main experiment.

## 3. Experimental task

### 3.1. Methods

#### 3.1.1. Materials

Each letter of the Italian alphabet has a corresponding sign in Italian Sign Language, which is used in fingerspelling and signing (as for example when signing the equivalent of the A in the sentence "A is a letter"). Finger-spelled 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 that are included in the Italian alphabet (B, C, D, F, G, H, L, M, N, P, Q, R, S, T, V, Z). Consonants require one-hand signs in Italian Sign Language. Sequences varying in length from 4 to 7 items were created by randomly selecting the letters 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. Finger-spelled letters were videotaped. Within each sequence, finger-spelled letters appeared at 1 s intervals, the presentation rate used in several prior studies on the STM of signs (e.g., Conrad, 1970, 1972; 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. Like in Fischer-Baum and McCloskey (2015), identical letters were allowed to appear in consecutive sequences.

#### 3.1.2. Procedure

Participants started each memory trial by pressing the space bar of the keyboard, which triggered the presentation of a sequence of finger-spelled letters on the computer monitor. Immediately after the presentation of the last finger-spelled letter in the sequence, the response screen appeared 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 sign-to-print 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 finger-spelled letters in our investigation. Instructions, presented in Italian Sign Language, explicitly required producing the finger-spelled letters in the order in which they were presented. A short practice session preceded the experimental task. Responses were videotaped for scoring purposes. In the replication of the STM test with hearing participants, letters were presented at 1 s intervals via audio recordings while the responses were produced verbally.

### 3.2. Results

#### 3.2.1. Accuracy

In the Experimental Task, deaf participants recalled the entire sequences 19% of the time, significantly less frequently than hearing participants (45%; $t(38) = 6.1$, $p < 0.0001$). Further analyses were conducted on the responses from the deaf participants. Their accuracy declined steadily as sequence length increased (4-letters = 47%; 5-letters = 22%; 6-letters = 6%; 7-letters = 2%; $F(3,57) = 53.3$, $p < 0.0001$; all pair-wise comparisons were significant at $p < 0.01$ by Tukey HSD test except the differences between 6- and 7-letter sequences). Their responses exhibited primacy effects, as shown in Fig. 4, and recency effects were observed for the shorter lists (4- and 5-letters) but not the longer lists (6- and 7-letters).

#### 3.2.2. Type of errors

The errors produced by deaf and hearing participants in the Experimental Task included omissions (FLTR<u>S</u> → FLTR), position-exchange errors (FL<u>TR</u>S → FL<u>RT</u>S), and intrusions. The latter were defined as errors in which finger-spelled letters not present in the stimulus sequence appeared in the response as additions

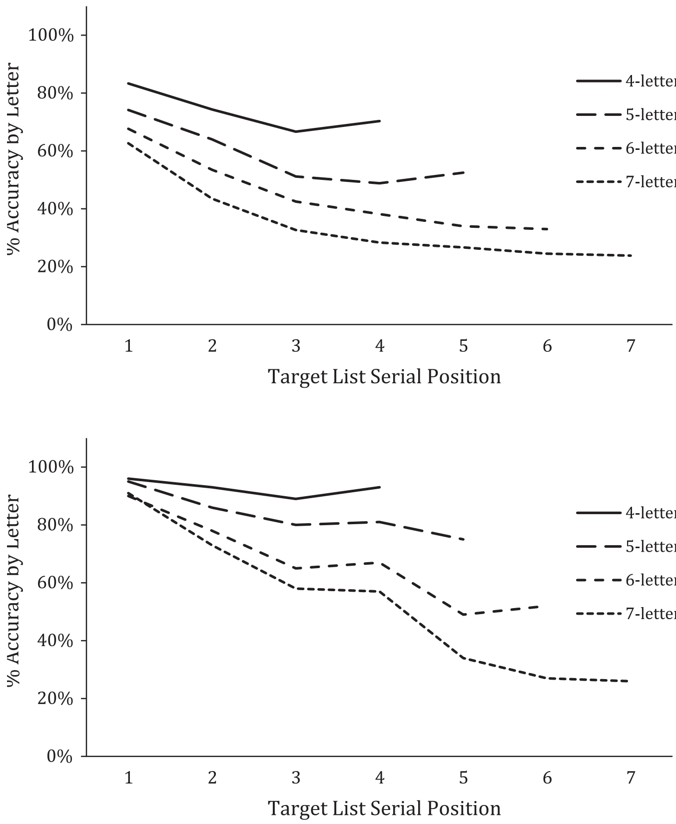



**Fig. 4.** Serial position effects for letter lists of different lengths. Top: signed letters; bottom: spoken letter names. Accuracy was greater with spoken vs. signed letters. However, responses patterned alike across modalities, with primacy effects appearing with all lists, and recency effects appearing most clearly in the shortest lists.

(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.

#### 3.2.3. Effects of visual and sound similarities

The results from the pretest showed that immediate serial recall was affected in deaf participants by the visual similarity of signs, not by the verbal similarity of the corresponding words. Converging evidence was sought from the substitution errors deaf participants produced in the Experimental Task. If we were to find evidence that substitution errors occur more frequently between consonants with similar sounding names than between those with different sounding names, this would suggest that deaf participants relied (at least to a certain extent) on verbal encoding. 14 of the consonants tested in the Experimental Task have names that sound similar in Italian – an example is B (/bI/) and C (/tʃI/), which share a vowel (/I/). 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. 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.), a result providing no evidence of verbal encoding. However, in line with previous results from Bellugi et al. (1975), we anticipated substitution errors to be especially common between consonants with similar hand configurations if deaf participants relied on visual encoding. 15 of the consonants tested in the Experimental Task have similar hand configurations in Italian Sign Language, sharing one parameter (e.g., orientation with B–F) or two parameters. The greater occurrence of substitution errors among consonants with similar relative to different hand configurations (mean errors: 7.8 vs. 6.4; $t(14) = 2.75$, $p = 0.01$) confirmed sensitivity to visual similarity.

### 3.3. Position-exchange errors

An error like ABCDE → BACDE involves items from the same trial and results from incorrect position encoding, causing B and C to trade positions. Errors determined by position exchange exhibit recurrent patterns in verbal STM. In particular, they show a 'locality effect:' the misplaced items tend to be recalled in positions close to their correct positions (e.g., Henson, 1998; Henson et al., 1996). Accordingly, given B in the sequence ABCDE, B is more likely to be misplaced as in ACBDE than ACDEB. Other patterns relate to items that are retrieved too soon and the fate of the misplaced items. An error of this kind occurs when, given the sequence ABCDE, B is incorrectly produced as the first item in the sequence. Two types of errors have been examined when B occupies this incorrect position. In a 'fill-in' error, B is followed by A (BACDE); here, A was misplaced by B and fills in. In a 'infill' error, B is followed by C (BCDE); here, C retains its original relative position (next-to-B). Several studies on verbal STM have reported a predominance of fill-in errors over infill errors (Farrell et al., 2013; Henson, 1998; Henson et al., 1996; Page & Norris, 1998; Surprenant et al., 2003). To determine whether the locality effect and the predominance of infill errors are also characteristic of sign STM, we analyzed the responses of deaf participants in the Experimental Task.

#### 3.3.1. Locality effect

These effects were analyzed considering responses in the Experimental Task that preserved target length (47% of all trials for the deaf participants, 71% for the hearing participants). Within these responses, we identified letters produced in incorrect positions, coding either movements to adjacent positions (e.g., ABCDE → BACDE or ACBDE) or to more distant positions (e.g., ABCDE → ACDBE or ACDEB). Responses in which a letter was repeated were excluded. There were more adjacent movement errors than non-adjacent movement errors produced by both deaf participants (mean: 39.1 vs. 17.9) and hearing participants (mean: 34.2 vs. 8.2). An ANOVA with Participants (deaf vs. hearing) and Error Position (adjacent vs. non-adjacent) as variables, revealed a significant effect of Error ($F(1,38) = 118.58$, $p < 0.0001$), which reflected a greater incidence of adjacent movement errors than non-adjacent movement errors, replicating the locality effect described above. The effect of participant group was marginally significant ($F(1,39) = 3.54$, $p < 0.07$), as deaf participants produced more movement errors overall, even in this relatively constrained set of target-response pairs, consistent with their much poorer performance on the task. Importantly, the lack of a significant interaction ($F(1,39) = 1.25$, $p > 0.25$), demonstrates comparable locality effects in sign and verbal STM.

#### 3.3.2. Fill-in vs. infill errors

These errors were analyzed using the strict scoring criteria described in previous studies (Farrell et al., 2013; Solway, Murdock, & Kahana, 2012). Accordingly, the sign that is recalled too soon is considered the first error in the sequence. This scoring applies to signs recalled too soon in each of the possible positions in the sequence. More fill-in errors than infill errors were produced in the Experimental Task by both deaf participants (mean: 9.8 vs. 4.1) and hearing participants (mean: 9.7 vs. 2.8). An ANOVA with Participants (deaf vs. hearing) and Error (fill-in vs. infill) as variables, only revealed a significant effect of Error ($F(1,38) = 93.94$, $p < 0.0001$), which reflected a greater incidence of fill-in errors. Importantly, the lack of a significant interaction ($F < 1$) demonstrates a similar predominance of fill-in errors in deaf and hearing participants. In sum, results from fill-in and infill errors converge with those from the locality effect in showing that the pattern of serial order errors deaf participants demonstrate in STM is comparable the pattern observed with hearing participants.

### 3.4. Intrusion errors

Many of the errors produced in our STM task by deaf and hearing participants were intrusions, with approximately half of the erroneous responses including at least one intruded finger-spelled letter (or letter name). Intruded finger-spelled letters (or letter names) 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 letter H that also appears in the response QHNTV produced on trial T-1, immediately prior to the response intrusion. Conceivably, then, the letter 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 finger-spelled letters (or letter names) appeared in the prior responses more often than expected by chance. We establish this point in the analyses presented below. In the following section, we report on analyses aimed at elucidating the nature of the position encoding used with signs.

#### 3.4.1. Perseveration analysis

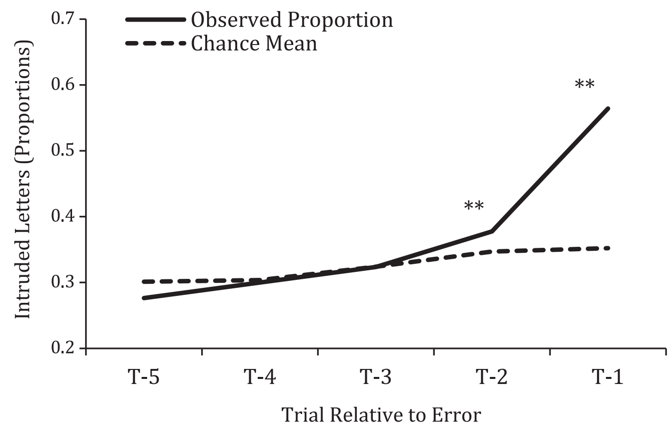
We analyzed the intrusions of finger-spelled letters – 1742 in total – pooled across all 20 deaf participants. A computer program first tabulated whether an intruded letter was produced in the response on trial T-1. Based on these tabulations, the program calculated the percentage (%) of intruded letters produced in the corresponding T-1 responses. Next, the program computed the % of intruded letters that did not appear in T-1 responses but did appear in T-2 responses.

The program then computed the % 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 finger-spelled letters repeated in trials 1–5 are shown in Fig. 5 (solid line). These results reveal that, for example, 56% of the intruded finger-spelled letters (985/1746) were previously produced on trial T-1.

The computer program also estimated the likelihood of an intruded letter 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 letters—whether or not the actual T-1 response contained the intruded letter—a *control response* was selected at random 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 and 39 control responses were identified (e.g., PNGTV, BQMDV, VPNHD) that matched the T-1 response QHNTV for length and that were outside the vicinity of the intrusion error. By chance, the intruded letter could be included in the control response, an event that in our example could have happened in the response VPNHD. 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 letters forming the control responses matched the intruded letters. The result of each run of the Monte Carlo analysis is a single estimate of the percentage of perseverated letters for which a match between perseveration and source is expected by chance. The entire process was carried out 10,000 times, yielding

**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 | CHNB |



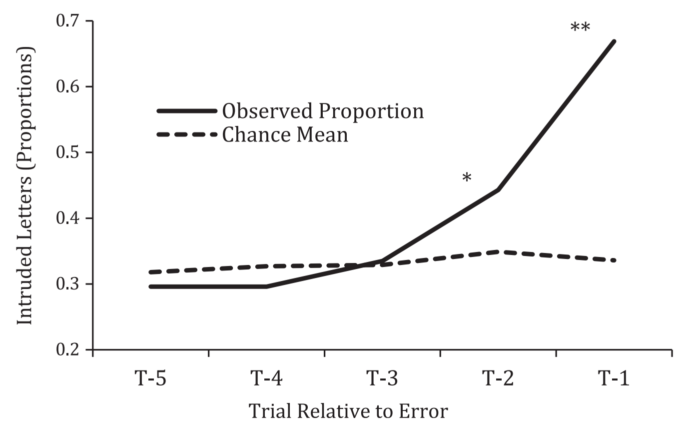




**Fig. 5.** Distribution of perseverated finger-spelled letters on the five immediately preceding trials: observed responses (solid line); mean proportion expected by chance based on Monte Carlo chance analyses (dashed line). Top: deaf participants; bottom: hearing participants. Reliable differences from chance appeared with both groups of participants on T-1 and T-2 (** indicates $p < 0.0001$, * indicates $p < 0.001$).

a distribution of chance percentages for T-1 responses. This distribution can be used to derive *p*-values – that is, the proportion of the 10,000 trials in which a chance value as high or higher than the observed value is found. The same procedure was independently applied to the other prior responses (T-2 to T-5).

Results of the chance analysis are presented in the dotted line on Fig. 5. Averaging across the 10,000 runs of the chance analysis program for the T-1 response, 35% of the intruded finger-spelled letters matched a finger-spelled letter in the control responses. In none of the 10,000 runs was a value as high as or higher than the observed value for T-1 responses (56%) found, indicating that the observed proportion differs reliably from chance.[2] Reliable differences from chance also appeared in trials T-2 ($p < 0.05$), but not in trials T-3 through T-5 ($ps > 0.5$). In short, there appears to be genuine perseverations of finger-spelled letters 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 finger-spelled letters, appears to span two trials. Monte Carlo analyses were also conducted on the 966 intrusion errors produced by the hearing participants. As shown in Fig. 5, the window of perseveration was similarly restricted to T-1 and T-2 with hearing participants. Those were the only preceding trials in which reliable differences from chance appeared.

### 3.4.2. Position analyses

The analyses presented in this section aimed to shed light on how positions are encoded in representations held during the immediate recall of finger-spelled letters. They were conducted on potential perseveration-source pairs in which the intruded finger-spelled letter 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 deaf 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 perseverated finger-spelled 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 determined if the observed distributions differed from the distributions expected by chance. These analyses were conducted on signed responses and replicated on spoken responses in order to establish whether or not serial positions were similarly encoded by signers and speakers.

*Analysis 1: Observed* vs. *chance position matches*. This analysis represents a first attempt to determine whether positions of finger-spelled letters are specified with respect to both edges (start 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 start- or end-anchored 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. We illustrate this point returning to the example in Table 1 of the letter H appearing in the perseveration response CHNB as well as in the T-1 response QHNTV. 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 start-anchored 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 (see Fischer-Baum et al., 2010 and McCloskey et al., 2013 for a detailed description of the methods). The chance analysis program was run 10,000 times.

Intruded finger-spelled letters appeared in the same start-anchored position in 24% of the perseveration-source pairs (421/1742), a higher rate than the chance baseline (19%; $p < 0.0001$). 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-anchored scheme, the observed rate was 23%, while the chance rate was 20%, and in none of the 10,000 runs ($p < 0.0001$) was a rate as high or higher than the observed one. These results fully replicated those of hearing participants that demonstrated significant differences from chance rates, both with the start-anchored scheme (21% (199/966) vs. 17%; $p = 0.001$) and the end-anchored scheme (22% (208/966) vs. 19%; $p = 0.008$).

While Analysis 1 suggests that both schemes contribute to the representation of positions with finger-spelled letters, 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 letter (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 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 procedure that permits an accurate characterization of the independent contribution of each scheme. Analyses examined both schemes and are illustrated here with respect to the start-anchored scheme. To assess whether the start-anchored scheme makes systematic contribution above and beyond the end-anchored scheme, we analyzed *residual pairs*, which are potential perseveration-source pairs for which the end-anchored scheme failed to predict the source position of the intruded letter. The pair CHNB-QHNTV represents an example,

[2] As in prior studies (e.g., Estes, 1991), position analyses were carried out using results pooled across participants. However, enough data were collected for individual deaf participants to allow by-participant position analyses. For each deaf participant, we computed (a) the observed proportion of position matches for the graded both-edges scheme, and (b) the proportion expected by chance. The mean observed proportion of position matches was significantly higher than the mean proportion expected by chance ($t(19) = 6.13$, $p < 0.0001$). This result argues against the possibility that the findings from the pooled-data analyses were driven by a small subset of the participants.

since the intruded letter H occurs at position E−3 and E−4, respectively. It was then determined whether the start-anchored scheme was more successful than the end-anchor scheme in predicting the source position of the intruded letters with residual pairs.

The end-anchored scheme correctly predicted the source position of the intruded finger-spelled letters for 400/1742 pairs. The residuals analysis was therefore carried out over the remaining 1342 pairs for which the end-anchored scheme failed to predict the source position. The start-anchored 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. Results from Analysis 2 are presented in Table 2. The observed proportion of residual pairs that matched start-anchored position was significantly greater than the proportion expected by chance (16%; $p < 0.0001$). Complementary residuals analyses revealed that the end-based scheme also performed above chance ($p < 0.0001$). Although the proportions expected by chance differed from the observed proportions by only ∼3%, they were invariably smaller compared to the observed proportions, as illustrated in Fig. 6. Significant differences were also found for hearing participants for both anchored-schemes, as shown by the results in Table 2. In sum, residuals analyses provide strong evidence that both start- and end-anchored coding contribute independently to the representation of the position in STM not only with spoken letter names but also finger-spelled letters.

*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 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, 2015; 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.

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 starting 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 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 ($p < 0.0001$). The same discrepancy was found with spoken verbal responses (69% (665/966) vs. 64%; $p = 0.005$).

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

| Position scheme | Residual PS pairs | Observed position matches | Matches expected by chance | *p*-Value |
|---|---|---|---|---|
| *Deaf participants* | | | | |
| Start-anchored | 1342 | 273 (20%) | 209 (16%) | <0.0001 |
| End-anchored | 1321 | 252 (19%) | 213 (16%) | <0.0001 |
| *Hearing participants* | | | | |
| Start-anchored | 758 | 141 (19%) | 118 (16%) | 0.003 |
| End-anchored | 767 | 150 (20%) | 127 (17%) | 0.005 |

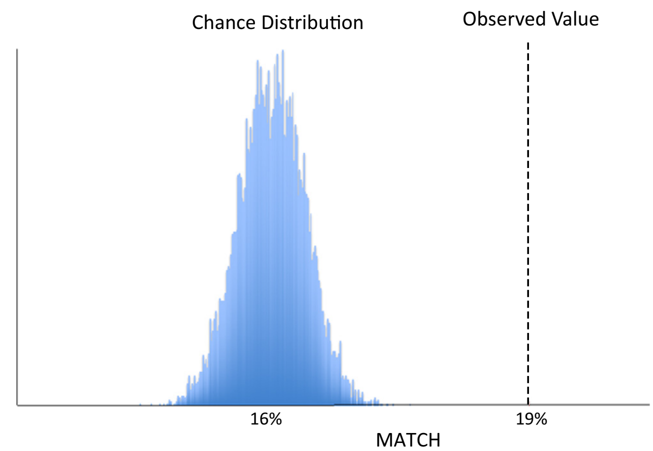



**Fig. 6.** Proportion of residual pairs that matched end-anchored positions, either expected by chance or observed. Proportions expected by chance were invariably smaller than 19% (observed proportion).

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. These representational differences lead to contrasting predictions, with a systematic contribution of adjacent positions anticipated by adjacent both-edges scheme not by discrete both-edges scheme. 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. As reported in detail in Table 3, the adjacent both-edges scheme performed significantly better than chance at predicting source position with deaf participants ($p < 0.0001$), as well as with hearing participants ($p = 0.02$). These findings indicate that serial positions are represented by both signers and speakers in a graded rather than discrete fashion.

*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 start- and end-anchored component of this graded both-edges

**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 |
|---|---|---|---|---|
| *Deaf participants* | | | | |
| Adjacent both edges/discrete both-edges | 1069 | 607 (57%) | 528 (49%) | <0.0001 |
| Graded start-anchored/graded end-anchored | 732 | 270 (37%) | 226 (31%) | <0.0001 |
| Graded end anchored/graded start-anchored | 704 | 242 (34%) | 207 (29%) | <0.0001 |
| *Hearing participants* | | | | |
| Adjacent both edges/discrete both-edges | 617 | 316 (51%) | 296 (48%) | 0.02 |
| Graded start-anchored/graded end-anchored | 473 | 172 (36%) | 154 (33%) | 0.005 |
| Graded end anchored/graded start-anchored | 434 | 133 (31%) | 131 (30%) | 0.422 |

scheme contribute to position encoding. Residuals analyses were again carried out to determine whether the graded start-anchored component of the graded both-edges scheme contributes above and beyond the graded end-anchored component, and vice versa. The results of the residuals analyses, reported in Table 3, show that with deaf participants positions were predicted above chance both by the start-anchored scheme (37% vs. 31%, $p < 0.0001$) and the end-anchored scheme (34% vs. 29%, $p < 0.0001$). These results were partially replicated with hearing participants (see Table 3). Significant differences from chance were found with the start-anchored scheme (36% vs. 33%, $p = 0.005$), but not with the end-anchored scheme. The lack of a significant difference with the end-anchored scheme might have resulted from the relatively small error corpus available for this analysis – with a larger corpus, a significant difference was found by Fischer-Baum & McCloskey, 2015. The results with hearing participants indicate that both components contribute significantly and independently to the graded both-edges position encoding of finger-spelled letters. As shown with each of the other analyses of perseveration errors reported thus far, the results of deaf participants converged with those from hearing participants.

#### 3.4.3. Summary

Taken together, the result of the four 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 start- and end-anchored position representations. The results from deaf signers paralleled closely those we obtained with hearing participants, which in turn replicated previous findings that revealed graded both-edges representations of serial positions (e.g., Henson, 1998). Although our results suggest strong similarities between the encoding of serial positions with signers and hearing participants, it would be premature to conclude that there are no differences between these groups – e.g., in terms of strength of position effects. The size of group participants was probably too small to reach a conclusion of this kind. On the other hand, the results from deaf signers contrast with previous work in visuo-spatial STM that have revealed start-anchored position representations, with no contribution from an end-anchored scheme (Fischer-Baum, 2011).

## 4. General discussion

While several lines of evidence point to serial encoding as critically related to the reduced STM observed with sign (Bavelier et al., 2008; Hanson, 1982; Hirshon, Fernandez, & Bavelier, 2012; Krakow & Hanson, 1985; Rudner & Rönnberg, 2008; Rudner et al., 2010), we sought to determine if serial order is comparably represented in sign and verbal codes. We took advantage of 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, 2015; Henson, 1999). Results from our error analyses were clear-cut, demonstrating that aspects of position representation observed in verbal STM extend to finger-spelled letters: (1) both-edges positional encoding with evidence for clear contribution from both the start- and end-anchored components of the scheme and (2) graded rather than discrete representations of position.

In addition to perseveration errors, which result from exchanges across trials, we also examined errors occurring within a trial and involving position exchanges, as in <u>AB</u>CDE → <u>BA</u>CDE where A and B trade their positions. The patterns revealed by position-exchange errors in sign STM completely replicated the patterns this type of error demonstrated in verbal STM. We found that items were most likely to be incorrectly recalled in immediately adjacent positions in sign immediate recall similar to what has been found for verbal immediate recall (e.g., Healy, 1974; Nairne, 1991; Surprenant et al., 2003). Furthermore, the predominance of fill-in errors over infill errors that we and others (Farrell et al., 2013; Henson, 1998; Henson et al., 1996; Page & Norris, 1998; Surprenant et al., 2003) found in verbal STM also appeared with signs. Therefore, if the letter B was misplaced in first position when the expected sequence was ABCDE, the letter B was more likely to be followed by the letter A (<u>BA</u>CDE; fill-in error) than the letter C (<u>BC</u>DE; infill error). Although position-exchange errors are not diagnostic of start- and end-anchoring encoding, they nevertheless reflect underlying representations of serial positions (Henson, 1998; Page & Norris, 1998; Surprenant et al., 2003). In this respect they are informative for the account of serial position encoding. The similarities we found between position-exchange errors in verbal and sign STM converge with the results from perseveration errors in demonstrating a common type of encoding of serial positions across modalities.

The knowledge our deaf participants have acquired of spoken Italian demands we carefully consider whether our results are associated with forms of verbal encoding. We sought evidence of verbal encoding by examining effects of sound similarity on both accuracy (with signs) and errors at recall (with finger-spelled letters). As no evidence of verbal encoding emerged from these analyses, we can rule out that our findings reflect the contamination of verbal knowledge. By contrast, the effects of sign similarity demonstrated in analyses of both accuracy and errors indicate that signs were subjected to sign-based encoding.

The finding that that both-edges positional scheme also applies to sign helps us to clarify the causes of the STM disadvantage with sign. 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. In this respect, our results constrain hypotheses about the causes of sign disadvantage; however, the causes of the STM disadvantage remain unclear. One cause could relate to specifications of serial positions with respect to start- and end-sequences that are less precise with signers. Alternatively, the disadvantage could reflect distortions during encoding that lead to underspecified and less discriminable memory traces, similar to what Surprenant, Neath, and Brown (2006) demonstrated in simulations of memory decline in aging. Another hypothesis is that of a weak binding between signs and serial positions. The problem could be in forming a strong association between D and its position in the series ABCDE so that, at retrieval, the 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. This hypothesis of a weak binding echoes a number of proposals that also highlighted weak binding as a possible cause of memory failures with signers. Naturally, the critical question concerns what would determine these differences in binding. Proposals 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). Advances in the understanding of the neurocognitive processing of the temporal aspects of speech will hopefully result in more refined accounts of what makes serial position so precisely encoded in verbal STM.

An intriguing discrepancy appears when we compare the representation of serial order that emerged from analyses of perseverations with finger-spelled letters and in visual STM. In tasks that require hearing participants to recall the spatial position and the temporal order in which dots 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 start-anchored scheme without any additional contribution of end-anchored position representations. These results contrast with our findings with finger-spelled letters, 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, and instead pattern with verbal stimuli. 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 sign, resulting in a form of serial order representation particularly suitable to the encoding of linguistic elements. More research is necessary to investigate this claim. Sequences of different types of visuo-spatial stimuli may rely on different position representations schemes. Evidence that visuo-spatial STM relies on a different position representation scheme comes from tasks in which participants have to recall a sequence of locations, and there is reason to believe that spatial STM, such as memory for locations, differs from object STM, such as memory for hand shapes (Courtney, Ungerleider, Keil, & Haxby, 1996). If so, object STM may rely on the both-edges scheme, and individuals with no knowledge of signs would make errors consistent with the both-edges scheme if given the lists from the experiment reported above. However, these results raise an intriguing question: how much malleable are short-term memory processes to linguistic demands and, more generally, to experience-based change?

The accounts of serial position encoding we have examined up to this point assume a specification based on both edges. Alternative accounts have been proposed that assume context-dependent representations (e.g., Lewandowsky & Murdock, 1989; Wickelgren, 1965). Under these accounts, referred to as chaining or item-to-item association accounts, a position is coded relative to other items in the sequence, so that C in ABCDE is represented as following B and preceding D (position B_D). Various results have provided empirical support to these accounts (e.g., Baddeley, Conrad, & Hull, 1965; Botvinick & Bylsma, 2005; Wickelgren, 1966). Crucially, some of the results consistent with context-dependent representations are not compatible with accounts assuming both-edges schemes. To resolve these discrepancies, hybrid accounts have been proposed that incorporate context-dependent and both-edges representations (Botvinick & Plaut, 2006; Solway et al., 2012). Using a residual analysis of perseverations produced in verbal STM, Fischer-Baum and McCloskey (2015) assessed the contribution of each of these types of position representations, finding significant contributions for both, although comparatively more substantial for both-edges representations. The residual analysis carried out by Fischer-Baum & McCloskey (Position Analysis 2) was replicated on our data. Only a significant contribution of both-edges representations was found with finger-spelled letters. While this finding suggests cross-modality differences in position encoding, the small contribution of context-dependent representations observed in verbal STM demands a cautious interpretation, as it is possible that our negative findings reflected limited power in our analysis.[3] In this respect, both-edges representations offer a more convincing test of cross-modal similarities, and the convergence of finding between sign and verbal STM provide solid grounds on which basing the conclusion that positions are similarly encoded.

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.

## Acknowledgements

We are grateful to the personnel of the Istituto Magarotto, and particularly to Arianna Caccaro, for having facilitated the testing of the deaf participants. We also want to acknowledge the help of Eduardo Navarrete with experiment preparation, Daniela Di Menza with data collection, and Elena Toscano with response coding.

## References

Baddeley, A. D. (2007). *Working memory, thought and action*.Oxford: Oxford University Press.

Baddeley, A. D., Conrad, R., & Hull, A. J. (1965). Predictability and immediate memory for consonant sequences. *Quarterly Journal of Experimental Psychology, 17*, 175–177.

Baddeley, A. D., Thomson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14*, 575–589.

Battison, R. (1978). *Lexical borrowing in American sign language*.Silver Spring, MD: Linstok Press.

Bavelier, D., Newport, E. L., Hall, M. L., Supalla, T., & Boutla, M. (2006). Persistent difference in short-term memory span between sign and speech: Implications for cross-linguistic comparisons. *Psychological Science, 17*, 1090–1092.

[3] Chaining models of serial order represent a type of accounts that assumes context-dependent representation. Within chaining models, strong item-item associations are formed between adjacent items (e.g., between B and C in the sequence ABC). As argued by Henson et al. (1996; see also Surprenant et al., 2003), the greater occurrence of fill-in errors relative to infill errors is inconsistent with chaining models. In fact, when B is incorrectly recalled first, the strong item-item association between B and C would lead C to be recalled next, and therefore an infill error to occur. By contrast, recalling A next to B – a fill-in error – should be observed less frequently. The predominance of fill-in errors over infill errors that we found in the immediate recall of finger-spelled letters appears to exclude the type of context-dependent representation assumed within chaining models.

Bavelier, D., Newport, E. L., Hall, M., Supalla, T., & Boutla, M. (2008). Ordered short-term memory differs in signers and speakers: Implications for models of short-term memory. *Cognition, 107*, 433–459.

Bellugi, U., & Fischer, S. (1972). A comparison of sign language and spoken language. *Cognition, 1*, 173–200.

Bellugi, U., Klima, E. S., & Siple, P. (1975). Remembering in signs. *Cognition, 3*, 93–125.

Belmont, J. M., Karchmer, M. A., & Pilkonis, P. A. (1976). Instructed rehearsal strategies' influence on deaf memory processing. *Journal of Speech and Hearing Research, 19*, 36–47.

Bonvillain, J. D., Rea, C. A., Orlansky, M. D., & Slade, L. A. (1987). The effect of sign language rehearsal on deaf's subjects immediate and delayed recall of English word lists. *Applied Psycholinguistics, 8*, 33–54.

Botvinick, M., & Bylsma, L. M. (2005). Regularization in short-term memory for serial order. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 31*, 351–358.

Botvinick, M. M., & Plaut, D. C. (2006). Short-term memory for serial order: A recurrent neural network model. *Psychological Review, 113*, 201–233.

Boutla, M., Supalla, T., Newport, E. L., & Bavelier, D. (2004). Short-term memory span: Insights from sign language. *Nature Neuroscience, 7*, 997–1002.

Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological loop and its timing. *Psychological Review, 106*, 551–581.

Conrad, R. (1960). Serial order intrusions in immediate memory. *British Journal of Psychology, 51*, 45–48.

Conrad, R. (1970). Short-term memory processes in the deaf. *British Journal of Psychology, 61*, 179–195.

Conrad, R. (1972). Short-term memory in the deaf: A test for speech coding. *British Journal of Psychology, 63*, 173–180.

Courtney, S. M., Ungerleider, L. G., Keil, K., & Haxby, J. V. (1996). Object and spatial visual working memory activate separate neural systems in human cortex. *Cerebral Cortex, 6*, 39–49.

Estes, W. K. (1991). On types of item coding and sources of recall in short-term memory. In W. E. Hockley & S. Lewandowsky (Eds.), *Relating theory and data: Essays on human memory in honor of bennet B. Murdock* (pp. 155–173). Hillsdale, NJ: Lawrence Erlbaum Associates.

Farrell, S., Hurlstone, M. J., & Lewandowsky, S. (2013). Sequential dependencies in recall of sequences: Filling in the blanks. *Memory & Cognition, 41*, 938–952.

Farrell, S., & Lelièvre, A. (2009). End anchoring in short-term order memory. *Journal of Memory and Language, 60*, 209–227.

Fischer-Baum, S. J. (2011). *Position representation: General principles or domain-specificity?* ProQuest Dissertations and Theses (3463614).

Fischer-Baum, S., & McCloskey, M. (2015). Representation of item position in immediate serial recall: Evidence from intrusion errors. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 41*, 1426.

Fischer-Baum, S., McCloskey, M., & Rapp, B. (2010). Representation of letter position in spelling: Evidence from acquired dysgraphia. *Cognition, 115*, 466–490.

Geraci, C., Gozzi, M., Papagno, C., & Cecchetto, C. (2008). How grammar can cope with limited short-term memory: Simultaneity and seriality in sign languages. *Cognition, 106*, 780–804.

Gmeindl, L., Walsh, M., & Courtney, S. M. (2011). Binding serial order to representations in working memory: A spatial/verbal dissociation. *Memory & Cognition, 39*, 37–46.

Goslin, J., Galluzzi, C., & Romani, C. (2014). Phonitalia: A phonological lexicon for Italian. *Behavior Research Methods, 46*, 872–886.

Hall, M. L., & Bavelier, D. (2011). Short-term memory stages in sign vs. speech: The source of the serial span discrepancy. *Cognition, 120*, 54–66.

Hamilton, H., & Holzman, T. G. (1989). Linguistic encoding in short-term memory as a function of stimulus type. *Memory & Cognition, 17*, 541–550.

Hanson, V. L. (1982). Short-term recall by deaf signers of American Sign Language: Implications of encoding strategy for order recall. *Journal of Experimental Psychology: Learning, Memory and Cognition, 8*, 572–583.

Healy, A. F. (1974). Separating item from order information in short-term memory. *Journal of Verbal Learning and Verbal Behavior, 13*, 644–655.

Henson, R. N. (1998). Short-term memory for serial order: The start-end model. *Cognitive Psychology, 36*, 73–137.

Henson, R. N. (1999). Positional information in short-term memory: Relative or absolute? *Memory & Cognition, 27*, 915–927.

Henson, R. N., Norris, D. G., Page, M., & Baddeley, A. D. (1996). Unchained memory: Error patterns rule out chaining models of immediate serial recall. *The Quarterly Journal of Experimental Psychology A, 49*, 80–115.

Hirshon, E. A., Fernandez, N. M., & Bavelier, D. (2012). Routes to short-term memory indexing: Lesson from deaf native users of American Sign Language. *Cognitive Neuropsychology, 29*, 85–103.

Koo, D., Crain, K., LaSasso, C., & Eden, G. F. (2008). Phonological awareness and short-term memory in hearing and deaf individuals of different communication backgrounds. *Annals of the New York Academy of Sciences, 1145*, 83–99.

Krakow, R. A., & Hanson, V. L. (1985). Deaf signers and serial recall in the visual modality: Memory for signs, fingerspelling, and print. *Memory & Cognition, 13*, 265–272.

Laudanna, A., Thornton, A. M., Brown, G., Burani, C., & Marconi, L. (1995). Un corpus dell'italiano scritto contemporaneo dalla parte del ricevente. In S. Bolasco, L. Lebart, & A. Salem (Eds.). *III Giornate internazionali di Analisi Statistica dei Dati Testuali* (Vol. I, pp. 103–109). Roma: Cisu.

Lewandowsky, S., & Murdock, B. B. Jr., (1989). Memory for serial order. *Psychological Review, 96*, 25–57.

Liben, L. S., & Drury, A. M. (1977). Short-term memory in deaf and hearing children in relation to stimulus characteristics. *Journal of Experimental Child Psychology, 24*, 60–73.

Lichtenstein, E. H. (1998). The relationships between reading processes and English skills of Deaf college students. *Journal of Deaf Studies and Deaf Education, 3*, 80–134.

Liddell, S. (2003). *Grammar, gesture and meaning in American Sign Language*. Cambridge: Cambridge University Press.

Logan, K., Mayberry, M., & Fletcher, J. (1996). The short-term memory of profoundly deaf people for words, signs, and abstract spatial stimuli. *Applied Cognitive Psychology, 10*, 105–119.

MacSwinney, D. S., Campbell, R., & Donlan, C. (1996). Varieties of short-term memory coding in deaf signers. *Journal of Deaf Studies and Deaf Education, 1*, 249–262.

Marschark, M., & Mayer, T. S. (1998). Interactions of language and memory in deaf children and adults. *Scandinavian Journal of Psychology, 39*, 145–148.

Mathur, G., & Rathmann, C. (2014). The structure of sign languages. In M. Goldrick, V. Ferreira, & M. Miozzo (Eds.), *The Oxford handbook of language production*. New York: Oxford University Press.

McCloskey, M., Fischer-Baum, S., & Schubert, T. (2013). Representation of letter position in single-word reading: Evidence from acquired dyslexia. *Cognitive Neuropsychology, 30*, 396–428.

McCloskey, M., Macaruso, P., & Rapp, B. (2006). Grapheme-to-lexeme feedback in the spelling system: Evidence from a dysgraphic patient. *Cognitive Neuropsychology, 23*, 278–307.

Miller, P. (2007). The role of spoken and sign languages in the retention of written words by prelingually deafened native signers. *Journal of Deaf Studies and Deaf Education, 12*, 184–208.

Nairne, J. S. (1991). Positional uncertainty in long-term memory. *Memory & Cognition, 19*, 332–340.

Page, M., & Norris, D. (1998). The primacy model: A new model of immediate serial recall. *Psychological Review, 105*, 761–781.

Pintner, R., & Paterson, D. G. (1917). A comparison of deaf and hearing children in visual memory for digits. *Journal of Experimental Psychology, 2*, 76–88.

Poizner, H., Bellugi, U., & Tweney, R. D. (1981). Processing formational, semantic, and iconic information in American Sign Language. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 1146–1159.

Rönnberg, J., Rudner, M., & Ingvar, M. (2004). Neural correlates of working memory for sign language. *Cognitive Brain Research, 20*, 165–182.

Rudner, M., Davidsson, L., & Rönnberg, J. (2010). Effects of age on the temporal organization of working memory in deaf signers. *Aging Neuropsychology & Cognition, 17*, 360–383.

Rudner, M., & Rönnberg, J. (2008). Explicit processing demands reveals language modality-specific organization of working memory. *Journal of Deaf Studies and Deaf Education, 13*, 465–484.

Sandler, W., & Lillo-Martin, D. (2006). *Sign language and linguistic universals*. Cambridge: Cambridge University Press.

Shand, M. A. (1982). Signed based short-term coding of American Sign Language signs and printed English words by congenitally deaf signers. *Cognitive Psychology, 14*, 1–12.

Solway, A., Murdock, B. B., & Kahana, M. J. (2012). Positional and temporal clustering in serial order memory. *Memory & Cognition, 40*, 177–190.

Stokoe, W. C., Casterline, D. C., & Croneberg, C. (1965). *A dictionary of American Sign Language on linguistic principles.*Washington, DC: Gallaudet Press.

Surprenant, A. M., Kelley, M. R., Farley, L. A., & Neath, I. (2003). Fill-in and infill errors in order memory. *Memory, 13*, 267–273.

Surprenant, A. M., Neath, I., & Brown, D. A. (2006). Modeling age-related differences in immediate memory using SIMPLE. *Journal of Memory and Language, 55*, 572–586.

Van der Hulst, H. (1993). Units in the analysis of signs. *Phonology, 10*, 209–241.

Wallace, G., & Corballis, M. C. (1973). Short-term memory and coding strategies in the deaf. *Journal of Experimental Psychology, 99*, 334–348.

Werner, H. (1947). The effect of boundary strength on interference and retention. *American Journal of Psychology, 60*, 598–607.

Wickelgren, W. A. (1965). Short-term memory for repeated and non-repeated items. *The Quarterly Journal of Experimental Psychology, 17*, 14–25.

Wickelgren, W. A. (1966). Associative intrusions in short-term recall. *Journal of Experimental Psychology, 72*, 852–858.

Wilson, M. (2001). The case for sensorimotor coding in working memory. *Psychonomic Bulletin & Review, 8*, 44–57.

Wilson, M., & Emmorey, K. (1997). A visuospatial "phonological loop" in working memory: Evidence from American Sign Language. *Memory & Cognition, 25*, 313–320.

Wilson, M., & Emmorey, K. (1998). A "word length effect" for sign language: Further evidence for the role of language in structuring working memory. *Memory & Cognition, 26*, 584–590.

Wilson, M., & Emmorey, K. (2006). Comparing sign language and speech reveals a universal limit on short-term memory capacity. *Psychological Science, 17*, 682–683.