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Routes to short term memory indexing: Lessons from deaf native users of American Sign Language

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Abstract

Models of working memory (WM) have been instrumental in understanding foundational cognitive processes and sources of individual differences. However, current models cannot conclusively explain the consistent group differences between deaf signers and hearing speakers on a number of short-term memory (STM) tasks. Here we take the perspective that these results are not due to a temporal order-processing deficit in deaf individuals, but rather reflect different biases in how different types of memory cues are used to do a given task. We further argue that the main driving force behind the shifts in relative biasing is a consequence of language modality (sign vs. speech) and the processing they afford, and not deafness, per se.

Keywords

short-term memory; deafness; sign language; phonological coding; spatial-temporal coding

Working memory (WM) supports the ability to maintain and manipulate representations in the service of cognition. One would be hard pressed to name any higher-level cognitive ability that does not foundationally depend on holding information in memory and being able to manipulate and integrate it with knowledge from long-term memory. Cognitive constructs as varied as spatial navigation, mathematical calculations or language processing, to name a few, all critically engage WM. 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). Here we consider a group difference consistently documented in the literature, the root of which has yet to be conclusively understood: lower serial span in deaf individuals.

The serial span in deaf populations

The extant literature since the early 1900s demonstrate that deaf individuals under-perform compared to their hearing peers on serial recall of linguistic material (Ursula Bellugi, Klima, & Siple, 1974–1975; Boutla, Supalla, Newport, & Bavelier, 2004; Conrad, 1970, 1972; Hall & Bavelier, 2011; Pintner & Patterson, 1917). In such tasks, participants are asked to recall a list of items in the exact order of presentation; the span is defined as the highest list length subjects can recall in the correct order. A typical example is the digit span task in which hearing English speakers exhibit a span of about 7 ± 2 whereas deaf individuals only reach about 5 ± 1 items. Although in early studies the lists to recall were presented in English print, and thus relied on a language that may not have been native for many deaf individuals, the discrepancy in span was confirmed when testing deaf native signers in their native

language, sign language. Lower span using signed stimuli has been demonstrated in American Sign Language (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), as well as Swedish Sign Language (Rönnberg, Rudner, & Ingvar, 2004). Crucially, deaf participants in these studies were native users of the sign language used in the test. As it is known that deaf individuals raised in a signing community undergo the typical stages of language development (Mayberry & Squires, 2006; Newport & Meier, 1985; Schick, Marschark, & Spencer, 2005), their lower short-term memory (STM) performance cannot be easily attributed to poor language skills or lack of familiarity with the materials used. A role of poor language skills or deficient cognitive skills in the source of the span discrepancy has been further ruled out by the demonstration that *hearing* native signers also show a shorter span when tested in sign language (Boutla et al., 2004; Hall & Bavelier, 2011). Studies of hearing individuals fluent in both English and ASL demonstrate that the very same individuals show a normal span when tested in English but a reduced span when tested in ASL. Given the prevalence of the serial span in school settings and in clinical evaluations, the question arises of how to interpret lower serial span in deaf individuals. The current paper aims to gain understanding of these issues and in doing so, reevaluate in a new light some of the foundational conceptions about WM and its underlying STM buffers.

Working Memory and Short-term Memory Buffers

A model of WM that has gained much traction over the last 40 years is the multicomponent model of Baddeley and Hitch (A. Baddeley & Hitch, 1974). This model describes two ‘slave STM buffers’ that hold respectively visual/spatial (visuospatial sketchpad) and temporal/phonological (phonological loop) information for a limited amount of time, as well as a central executive that integrates and manipulates information available in these buffers along with that retrieved from long-term memory (Burgess & Hitch, 2005; Cowan, 2008). The visual-spatial sketchpad allows for the maintenance of visual-spatial information with a typical span of 4. The underlying mechanism involved with the visual-spatial sketchpad has been thought of as holding a mental imagery representation of the identity and the location of an object in memory (Kosslyn, 1981). The phonological loop, commonly compared to a ‘tape recorder in your head’, has a span of about 7+–2 and is perhaps the most studied and well-understood component. It supports recoding of auditory and linguistic information and is especially efficient at maintaining verbal information, like remembering a phone number. The processes at play within the phonological loop have been characterized through a number of trademark effects including phonological similarity, word length, and articulatory suppression effects (A. Baddeley, 1992; A. Baddeley, Thomson, & Buchanan, 1975) that have shown how verbal STM can be affected (lowered) when items are phonologically similar, word length is longer, and when articulation is suppressed by repeating an unrelated sound.

Evaluation in signers of the three landmark effects of the phonological loop has led Wilson and Emmorey to propose a sign language-based rehearsal mechanism which parallels in many respects the phonological loop in speakers (Wilson, Bettger, Niculae, & Klima, 1997; Wilson & Emmorey, 1997, 1998). These studies document an elegant parallel between phonological loop processes in sign language and spoken language. However, since they assume fundamentally similar underlying processing, phonological loop function in sign vs. spoken language cannot explain the precise source of the performance differences in signers and speakers when using speech versus sign in STM tasks.

Over the years, two main classes of explanation have been put forward in the literature for this span discrepancy. First, we will review explanations targeting the phonological loop and

the possibility that sign language characteristics result in shorter spans within that buffer. Second, we will consider explanations focused on the key role of auditory information and effects of deafness in shaping up temporal processing and the brain's ability at processing information serially.

Structural Differences between Speech and Sign

An early explanation of the span difference between signers and speakers proposed that it could be due to fundamental properties of the different languages themselves. This was based on the observation that signs typically take longer to articulate than speech, either because of their complexity or the use of manual articulator that tend to be slower (U. Bellugi & Fischer, 1972). The serial span in speakers is known to get shorter as words get longer or more complex, and thus this explanation seemed quite coherent with the available pattern of data at the time. However, in 2004 Boutla et al. demonstrated that the discrepancy in span between signers and speakers fully remains even when the signed material is carefully matched in articulation length and complexity to speech materials (for further discussion, see D. Bavelier, Newport, Hall, Supalla, & Boutla, 2006; Wilson & Emmorey, 2006a, 2006b). Furthermore, individual differences in articulation are a good positive predictor of STM span in English, whereas there is no correlation between articulation rate and STM span in native signers (see Hall & Bavelier, 2010, Figure 30.2). Thus, a direct account of the span discrepancy in terms of articulation time differences or unequal phonological complexity across languages seemed unlikely.

A more recent proposal focuses on the internal structure of signs, and argues that unlike speech, signs contain both simultaneous and sequential components that may result in "heavier" phonological units (Geraci et al., 2008; Gozzi, Geraci, Cecchetto, Perugini, & Papagno, 2011). Under this view, STM for sign material is hampered as compared to speech because the memory load associated with even the simplest syllable is likely to be higher in sign. In a recent work, Mann et al. (2010) noted that greater memory load in sign could stem from 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). Indeed, it is well accepted that signers are faced with a much wider signing register than English speakers, having to adapt their comprehension and production of signs as the skill level of their interlocutor changes widely. Greater variability in sign does predict greater difficulty when encoding signs, especially rare items; however, it remains unclear how such views can explain lower STM span in signers when using signs as simple and over-learned as digits or letters, where hand-shape alone is sufficient to represent each item. In addition, these explanations do not align well with the finding that sign language use hampers serial span performance at *presentation* and during memory *encoding*, but if anything *enhances* span when used at recall time (Hall & Bavelier, 2011). Such differences across memory stages calls for more nuanced models.

A newer model of WM has argued that serial ordering processes in language *production* are a likely candidate for a maintenance mechanism in verbal WM, with particular emphasis placed on the process of phonological *encoding* (Acheson & MacDonald, 2009). Although a promising framework worth pursuing for future research, this proposal has not yet been fleshed out to consider possible differences in speech and sign production that are relevant for the current discussion. Another model, termed the Ease of Language Understanding (ELU), proposed by Rudner and Rönnerberg (Rudner & Rönnerberg, 2008) also addresses working memory processes in the larger context of language production *and* comprehension. It acknowledges language specific storage networks for speech and sign respectively, as well as common phonological and semantic networks between speech and sign. It does not directly address the difference in serial spans between signers and speakers, but by

considering the importance of multiple WM codes in the service of language processing, it provides a broader perspective on the importance and role of not only phonological representations in WM, but also semantic representations. It places a special emphasis on an episodic buffer, whose main role is to bind together information from different sources within a representation that uniquely refers to the item to be remembered. We will return to the potential role of such episodic buffer after considering the alternate view that span discrepancy in hearing and deaf individuals can be understood as a consequence of auditory deprivation.

Temporal order deficits following auditory deprivation

The second class of explanation for shorter serial spans in deaf populations holds that early deafness hinders temporal processing. This view is driven by the fact that (i) most studies showing a smaller serial span have tested deaf individuals that were not necessarily signers, and (ii) these studies used primarily English print rather than sign. The proposal that deafness may hinder temporal processing goes back to the early 1900s, largely stemming from studies comparing the short-term memory capacity of deaf individuals to that of hearing individuals (Ursula Bellugi et al., 1974–1975; Conrad, 1970, 1972; Pintner & Patterson, 1917). These results have often been understood in the context of the *deficiency theory of deafness*, which holds that integrative processes, such as multi-sensory integration, are essential for normal development. Previous research suggested a consistent sequence of development along sensory processes, starting with cutaneous, then vestibular, olfactory, auditory and finally visual senses (Gottlieb, 1971). Such developmental scaffolding was seen as critical for ‘normal’ development, with earlier senses creating a framework upon which senses with later onset could be built and incorporated (Radell & Gottlieb, 1992; Turkewitz & Kenny, 1982). Given the recognized role of audition in the processing of fine temporal distinction, this view predicted that deaf individuals would be at a disadvantage on tasks – especially visual ones – that require temporal ordering. This view is still prevalent, although often revised to contrast a disadvantage following auditory deprivation for memory tasks requiring temporal order but an advantage for those requiring spatial order (D. Bavelier, Newport, Hall, Supalla, & Boutla, 2008; Hanson, 1990; Wilson, 2001).

The contrast between spatial and temporal processing in the auditory versus visual modality finds support in studies showing that the auditory modality is better suited to process temporal order, whereas the visual modality is better equipped to process spatial information (e.g., Penney, 1989). For example, the auditory advantage in short-term memory recall tasks is typically attributed to such factors as a longer decay period for auditorily as compared to visually presented items, and to the automaticity of processing in the phonological loop (A. D. Baddeley, Lewis, & Vallar, 1984). The literature on STM and deafness reinforces this view as it documents a disadvantage for temporal order but better visuo-spatial memory in deaf individuals. In particular, several studies show better visuo-spatial skills in deaf signers than in hearing speakers (K. D. Emmorey, Kosslyn, S.M., Bellugi, U., 1993). Tests of mental rotation (K. Emmorey & McCullough, 1998; McKee, 1988), memory for number in spatial arrays (Zarfaty, Nunes, & Bryant, 2004) and face recognition (Ursula Bellugi & Hickok, 1993) all reveal significant advantages in deaf signers. In addition, a strong preference for spatial coding has been reported in deaf children. When deaf and hearing children are asked 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 children choose the spatially-middle digit whereas hearing children choose the temporally-middle one (Hermelin & O’Connor, 1975; O’Connor & Hermelin, 1973). Additional evidence, albeit indirect, comes from a Concentration/Memory game study where subjects had to remember the spatial locations of pictures of faces or shoes and then find their matches in a matrix of cards (Arnold & Mills, 2001). When the use of a within-category set

(all shoes or all faces) prevented efficient verbal tagging of the objects, deaf signers needed fewer attempts to find the matches than hearing non-signers. Together, these results are suggestive of a visuo-spatial processing advantage in the deaf group, and a temporal one in the hearing group.

However, in this case, evidence suggests that the visuo-spatial advantage may be due to sign language experience and not deafness, per se. For example, the Corsi Block task, a paradigm often used to assess the spatial span, reveals higher spatial span in deaf than hearing (Wilson et al., 1997). Interestingly, sign language experience (and not deafness) appears necessary and sufficient for this effect. Deaf children who have no exposure to sign language perform as well as, but not better than, hearing children on the Corsi Blocks Task (Parasnis, Samar, Bettger, & Sathe, 1996). Additionally, hearing adults or children (age 6 years) with non-native experience with sign languages exhibit increased spatial memory span on the Corsi Blocks Task as compared to their peers with no sign experience (Capirci, Cattani, Rossini, & Volterra, 1998; Keehner & Gathercole, 2007).

Nonetheless, the observation of a dichotomy between temporal and spatial memory in deaf and hearing individuals has led to two rather different claims about deafness and cognition. In line with the idea that temporal order and sequential processing is inherently facilitated in the auditory modality, the ‘Auditory Scaffolding Hypothesis’ proposes that experience with sound provides the proper foundation for the development of more general cognitive abilities related to representing temporal patterns (C. M. Conway, Pisoni, D.B., & Kronenberger, W.G., 2009). Under this hypothesis, deafness may lead to altered development of sequential or temporal order processing which in turn may result in the decrease in learning, recalling and producing temporal information that are observed in deaf individuals. As temporal order processing is often acknowledged to be at the core of many cognitive abilities such as working memory, planning, language processing, and executive functioning, the ‘Auditory Scaffolding Hypothesis’ predicts that the decreased performance observed in deaf individuals on serial STM tasks will extend to a broad spectrum of cognitive tasks. In line with the claim that the auditory modality is inherently more suited to temporal order processing, there is some evidence from studies in hearing individuals that the auditory modality shows a quantitative advantage over visual and tactile modalities in statistical learning designs testing implicit sequence learning (C. M. Conway, & Christiansen, M.H., 2005). Furthermore, Conway and colleagues also found that deaf children with cochlear implants, who have had degraded auditory input, showed disturbances in sequence learning abilities in the visual domain (C. M. Conway, Pisoni, Anaya, Karpicke, & Henning, 2011) and in motor sequencing (C. M. Conway, Karpicke, et al., 2011; C. M. Conway, Karpicke, J., Anaya, E.M., Henning, S.C., Kronenberger, W.G., & Pisoni, D.B., 2011), relative to the typically-developing normal-hearing children. Data supporting the Auditory Scaffolding Hypothesis should be qualified by pointing out that they mostly included *hearing impaired* individuals learning speech (with the aid of cochlear implants or hearing aids). These individuals are likely to have suffered from language delays and associated psychosocial challenges during development (P.C. Hauser, Lukomski, & Hillman, 2008; P. C. Hauser, Wills, & Isquith, 2006). Developmental delays, rather than auditory deprivation, per se, could be one major source of lower span in these populations. This concerns calls for a more systematic inclusion in future studies of deaf native signers.

The alternative view that we propose here is also consistent with the idea that the auditory modality affords direct access to temporal order information. However, unlike the ‘Auditory Scaffolding Hypothesis’, it entertains the possibility that the lesser serial STM span noted in deaf individuals is not the result of a generalized impairment of temporal order processes with consequences for many aspects of cognition, but rather results from a lesser reliance in deaf populations on one form of temporal order information – that afforded by the rehearsal

of phonologically-encoded unit in the phonological loop. This view holds that differences between deaf and hearing are specific to tasks that require serial order recall of linguistic material, with little to no consequences for cognition at large. Accordingly, this view predicts that differences in memory between deaf and hearing individuals should be restricted to serial span tasks that rely heavily on rehearsal of linguistic materials. Working memory tasks, which diminish the contribution of rehearsal by requiring manipulation, rather than just maintenance of information, should alleviate the differences between deaf and hearing individuals. There is some evidence for this proposal. Boutla and collaborators (2004 Experiment 3) reported equivalent performance in deaf signers and hearing speakers on a Working Memory production span task, in which lists of words have to be recalled in a self-generated sentence. Temporal order is irrelevant in this task. Similarly, deaf and hearing individuals have been found to perform equally well when tested on free recall tasks that typically exceed the capacity of the phonological buffer and its rehearsal process (D. Bavelier, Newport, et al., 2008; Cumming & Rodda, 1985; Hanson, 1982, 1990; Krakow & Hanson, 1985). Thus, both the 'Auditory Scaffolding Hypothesis' and this latter view predict lesser performance in deaf than hearing individuals on tasks that require serial order recall of verbal material. However, whereas the 'Auditory Scaffolding Hypothesis' predicts such a deficit will have widespread effects throughout cognition, the latter view predicts differences only in tasks that actively engage the phonological loop and its rehearsal processes.

These alternative points of view have important implications for possible cognitive repercussions stemming from lack of audition. In addition, they pose a central question concerning cognition at large by forcing us to characterize the origins of temporal order processing. The ability to maintain temporal order may stem from various levels of representations. For example, the temporal order information afforded by verbal rehearsal does not encompass the same information as that afforded by motor movement or the visualization of a trajectory of a moving object. We consider below how these different types of information contribute to and alter the nature of sequential processing, as this issue remains largely unknown.

The case for an episodic buffer

A major contribution of several recent advances in modeling WM and language processing has been to acknowledge the importance of an episodic buffer, above and beyond the visuo-spatial and phonological buffer initially posited by Baddeley and Hitch. The concept of episodic traces in memory was initially championed by Tulving (Tulving, 1983), based on the observation that in most cognitive task, whether sentence processing or scene understanding, the context of occurrence is necessary to uniquely qualify a memory trace (Mary C. Potter, 1993; Tulving, 2002). One of the main roles of the episodic buffer is to integrate information across various encoding dimensions, including phonology, orthography, visual shape or semantics into a unique memory trace that refers to the to-be-memorized event (Bavlier, 1999; Kahneman, Treisman, & Gibbs, 1992; Zenon W. Pylyshyn, 1989). Thus a distinctive feature of the episodic buffer is to afford unique representations of the information in the outside world by providing a temporal, spatial and semantic context in which the event occurred (Kahneman et al., 1992; Zenon W. Pylyshyn, 1989).

The importance of an episodic buffer during sentence processing is now recognized in several different models. To only cite a few, the model of Baddeley and Hitch considered earlier was revised in 2000 by Baddeley to include such a buffer on the grounds that some neuropsychological patients can recall a story despite an impaired phonological loop (A. Baddeley & Wilson, 2002; A. D. Baddeley, 2000). Similarly the ELU argues for an episodic

buffer that automatically combines multi-modal information allowing for more efficient phonological processing and promoting language understanding.

Overall, neuropsychological data as well as work on language processing makes it clear that language comprehension requires representations that go beyond those of the phonological loop. The episodic short-term memory buffer plays a key role in binding words to their context of occurrence and developing a rich sentence structure as sentence comprehension unfolds. Such a complex structure is not properly captured by serially sequencing words over time as the phonological loop does (Mary C. Potter, 1983; M.C. Potter, 1999). Episodic memory traces are, thus, necessary to account for solving local ambiguity or re-evaluation of meaning. In support of this view, recent work indicates that the type of order information necessary during sentence processing is different from serial order processing that mediates list recall (D. Bavelier, Newport, E.L., Hall, M.L., Supalla, T., & Boutla, M., 2008b; Lewis, Vasishth, & Van Dyke, 2006; McElree, Foraker, & Dyer, 2003; Van Dyke & McElree, 2006). Reports that a semantic span measure is a better predictor of reading comprehension than the traditional serial span measures also highlights the greater role of conceptual representations in short-term memory than suggested by research on serial span (Haarman, Davelaar, & Usher, 2003).

The importance of an episodic buffer holds not only for language processing but also when considering cognition at large. The need for memory traces that uniquely refer to events in the world is acknowledged throughout cognition. Spatio-temporal indexing has been proposed to support visual tracking over time as illustrated by the Multiple Object Tracking paradigm where subjects are asked to track several moving objects amongst objects appearing identical (Zenon W. Pylyshyn, 1989). This proposed indexing also allows objects of attention to be represented as separate, enabling one to perceive two occurrences of the same object type as two entities rather than one (Kahneman et al., 1992; Kanwisher, 1987). Accordingly, such memory indexing has been proposed to provide the stepping stone for several aspects of cognitive development including object identification, knowledge of numerosity, and the understanding of causality (Carey & Xu, 2002). In the case of visual objects, this indexing mechanism has been proposed to engage the inferior intra-parietal sulcus (Xu, 2005). Indexing events uniquely through their context of occurrence in space and time is therefore one of the main routes to WM.

The contribution of the episodic buffer to deaf/hearing differences in STM: an illustration of spatiotemporal individuation

With this background in place, we consider again the hearing/deaf differences for serial span tasks such as the digit span. We first illustrate how the deaf/hearing difference in serial span task may be understood in the context of WM models that not only posit a phonological loop and a visuo-spatial buffer, but also an episodic buffer (Figure 1). The view developed here is that deaf signers prefer episodic encoding and the spatio-temporal indexing it naturally embodies, whereas hearing speakers prefer the phonological loop and thus ordered phonological representations. We first assessed the possibility that deaf signers would outperform hearing speakers in memory tasks that requires recall of temporal order information. In particular, our view proposes that deaf signers should excel on serial STM tasks that disable the contribution of ordered phonological representations but can be achieved through the spatial-temporal indexing afforded by the episodic buffer. We tested this prediction by asking participants to view a sequence of identical squares presented at different locations and to tell us about the temporal order of two of them at probe time (Figure 2). Importantly, the timing and presentation of the squares did not suggest one square moving from one location to another but rather implied several identical squares appearing one after the other at different locations. The presentation of the full array of

squares at probe time was meant to reinforce such an interpretation of the display. These design features were carefully chosen to prevent the use of trajectories for the encoding of temporal information, unlike what is typically the case in Corsi block tasks. Thus, in this first version of this task (Experiment A), once the sequence of squares had been presented, the probe display appeared containing all the squares at the spatial location they had appeared during the initial presentation phase. Two squares were linked by an arrow and subjects had to decide whether the two squares had been presented in the temporal order suggested by the arrow (see Figure 2). As this task requires linking each square with its appropriate spatial and temporal index while reducing possible contributions from the phonological loop, we predicted that deaf signers would outperform hearing speakers.

In the second version of this task (Experiment B, Figure 3), English and ASL letters were added on each of the squares respectively for the hearing and deaf groups (see Supplemental Figure for ASL handshake letters). By providing each square with a separate, nameable label, we predicted improved performance in both populations as two different routes to STM indexing, rather than one, became available. In addition, we predicted a disproportional benefit to hearing as their preferred route of phonological encoding was enabled.

Finally, in a third version of this task (Experiment C, Figure 4), the efficiency of spatio-temporal indexing was weakened allowing us to test its relative contribution in deaf and hearing participants. Lettered squares were presented one at a time as in Experiment B; however, at probe time, rather than presenting all the letters in their correct spatial position, only two letters were presented in the center of the screen. Participants were to judge whether the letter on the left preceded that on the right; the two letters were linked by a corresponding arrow as in previous experiments. Because at probe time, the tested letters are presented at incongruent spatial locations with what was previously seen, this task renders spatio-temporal indexing inefficient and the task is now best carried out by relying on ordered phonological representations (as in standard linguistic span tasks). By reducing the number of efficient memory codes that can be tapped, the task should be harder for both groups. However, it should be disproportionately so for the deaf signer group, as their preferred mode of STM coding is weakened. For all experimental conditions, the longest sequence length at which subjects performed at 67% was found for each subject. The span was defined as that length minus 1 in an analogy to the WAIS scoring procedure. The same congenitally deaf native signers and non-signing hearing participants were run in all three versions of this task (see Methods).

An omnibus 3×2 ANOVA with within-factor of Experiment (A vs. B vs. C) and between-factor of group (deaf vs. hearing) revealed a significant main effect of Experiment [$F(2,40)=11.733$, $p<.001$, $\eta^2=.370$], no significant main effect of group [$F(1,20)=.002$, $p=.968$, $\eta^2=.00$], but importantly a significant interaction between Experiment and Group [$F(2,40)=5.367$, $p=.007$, $\eta^2=.221$] (see Figure 5). Separate 2×2 ANOVAs show that when comparing Exp. A vs. B, there was a marginal interaction [$F(1,20)=2.27$, $p=.096$] such that there was a deaf advantage in Exp. A, which only allowed episodic/spatiotemporal coding [Exp. A: $\text{Mean}_{\text{deaf}}=5.23 \pm .32$, $\text{Mean}_{\text{hearing}}=4.32 \pm .42$; $t(20)=1.732$, $p<.05$ (one-tailed), $d=.750$]. The deaf advantage went away and there was no group difference in B [Exp. B: $\text{Mean}_{\text{deaf}}=6.23 \pm .18$, $\text{Mean}_{\text{hearing}}=6.05 \pm .45$; $t(20)=.371$, $p=.714$, $d=.157$], when the additional cue of letter/phonological information was added. A 2×2 ANOVA comparing Exp. B and C also had a significant interaction [$F(1,20)=3.55$, $p<.05$] such that when spatial-temporal information was no longer relevant at the time of the probe in Exp. C, there was greater decrease in span in the deaf signers than hearing speakers compared to Exp. B [Exp. C: $\text{Mean}_{\text{deaf}}=4.59 \pm .43$, $\text{Mean}_{\text{hearing}}=5.64 \pm .24$; $t(20)=-2.11$, $p<.025$ (one-tailed), $d=.899$]. When comparing Exp. A vs. C (the 2 tasks with just one memory code

available), there was a significant interaction [$F(1,20)=10.15$, $p<.005$], such that deaf signers performed better when just spatiotemporal information was available (Exp. A) and hearing speakers performed better when just phonological/verbal information was available (Exp. C).

The main effect of Experiment seemed attributable to greater spans when episodic and phonological codes both contributed useful memory information as compared to only when one of them was available. Accordingly, the comparison of A and B showed that performance did improve from A to B, as the use of the phonological loop was enabled [$\text{Mean}_A=4.77 \pm .27$, $\text{Mean}_B=6.14 \pm .24$ $t(21)=-4.81$, $p<.001$, $d=1.13$]. The comparison of B and C allows us to examine the effect of disabling spatial-temporal indexing as the spatio-temporal congruity between presentation and probe was destroyed. As expected by weakening the efficiency of episodic coding, overall performance was worse in C as compared to B [$\text{Mean}_B=6.14 \pm .24$, $\text{Mean}_C=5.11 \pm .27$ $t(21)=3.58$, $p=.002$, $d=.859$].

Taken together, Experiments A, B, and C support the view of dissociable routes to STM—spatio-temporal indexing and ordered phonological representations – that both coexist in deaf signers and hearing speakers, but with each population expressing a bias for one type of coding over the other. Each of these codes supports the processing of temporal order information, despite relying on rather different processes to do so. While the phonological store supports maintenance of ordered phonological representations, the episodic buffer is believed to be the main player when it comes to integrating spatial and temporal information into a richer STM trace including semantics and context of occurrence to uniquely refer to the event coded.

A weakness of this series of experiments is that it cannot cleanly distinguish between contributions of the episodic buffer versus the visuo-spatial sketchpad. The Corsi Blocks task has a clear spatial component as the blocks are laid out in front of the subjects and remain in view throughout the task, and arguably can be solved through the encoding of trajectories rather than temporal order per se. The design features of the first experiment presented above were carefully chosen to weaken the potential use of trajectories for the encoding of temporal information. Yet, we acknowledge that these experiments cannot rule out the proposal that deaf signers more readily rely on the visuo-spatial sketchpad rather than the episodic buffer, recognizing that such a view would require to entertain the possibility of greater temporal information in the visuo-spatial sketchpad than is often assumed.

We would like to argue that a greater reliance on the episodic buffer in deaf signers affords a more parsimonious explanation as it captures data from experiments requiring just spatio-temporal indexing as shown here, as well as those manipulating sign language materials. The view here is that deaf signers and hearing speakers share a similar WM architecture, but that spoken language use readily entrains the phonological loop, making it a dominant device during most tasks, whereas sign language use readily entrains the episodic buffer, resulting in a rather weak signed phonological loop. Given the dominant role of the phonological loop in language acquisition (A. Baddeley, Gathercole, & Papagno, 1998) one could expect signers to exhibit language delays. Yet this is not the case (Mayberry & Squires, 2006; Meier, 1991), a result that we argue could be naturally explained by greater reliance on the episodic buffer in deaf signers.

Lastly, this work does not definitively distinguish between effects of deafness versus effects of sign language use in biasing preferred encoding in STM. Our view is that both signing and deafness may conspire to a weaker phonological loop, a weakness that would be compensated by greater reliance on the episodic buffer. This view predicts that

strengthening the phonological loop as oral training may do, would lead to higher spans, despite the individuals being profoundly deaf, whereas hearing signers would more readily rely on episodic coding during sign processing, despite a normal phonological loop for spoken materials. Future research that more systematically includes hearing signers and deaf orally trained, in addition to hearing speakers and deaf signers would allow a finer evaluation of this view.

Discussion

In closing, this paper argues for a greater consideration of the episodic buffer and its various roles when considering WM phenomenon. This is especially the case in clinical literatures, such as the deaf one, where the dominant model of WM typically only considers the phonological loop and the visuo-spatial sketchpad. It would seem a worthwhile path for WM research at large to consider the role of episodic STM in the development of executive skills and language processes. This conclusion rests on several observations outlined below.

Deaf signers' decreased STM span is isolated to a very specific subset of situations: serial order recall of linguistic material or that, which can be recoded phonologically. Critically the presented experiments show that deaf signers can perform equally (Exp. B) or even better (Exp. A) in serial span tasks than their hearing speakers peers. Thus, deaf signers are not poor at temporal order coding in general. In addition, this work highlights that equal performance on a given STM task does not mean equal processes at play. In Exp. B, deaf signers and hearing speakers reached equal span performance. However, their spans were differentially affected by removing one memory cue versus another (in Exps. A & C). Together, these results highlight two points. 1) There is a need to differentiate between different mechanisms capable of supporting temporal order coding in WM. On the one hand, the phonological loop certainly provides a very robust trace of the exact order of how the phonological information unfolds; on the other hand, the episodic buffer appears to allow for a richer contextual coding, binding together time and place of occurrence with multimodal information about the realization of the item and its meaning. The role of such richer, more contextually anchored representations in WM has been highlighted by research on sentence processing or scene understanding. 2) This set of results argues for a WM model that takes into account relative biasing in STM processing that can be weighted by one's individual differences.

This is not the first study to document a bias in hearing speakers for phonological encoding and relying on ordered phonological representations in the context of a serial STM task (Hollingworth, Richard, & Luck, 2008; Jiang, Olson, & Chun, 2000) (Baddeley, 2003; Jiang, Olson, & Chun, 2000). This type of indexing into STM maintains the relative temporal order of the different phonemes in the memory trace and is extremely efficient for items that can contact with existing representations in long-term memory. The present results are more surprising in that they identify one population, deaf signers, in which such a strong bias for ordered phonological representations may not exist, and rather a bias for spatiotemporal indexing appears to be present. Although still quite speculative, a bias for such spatiotemporal indexing is likely to go hand in hand with a greater role for semantic information during memory tasks in deaf signers. Indeed, spatiotemporal indexing in most theoretical framework is seen as a way to individuate conceptual information in the support of action and cognition (Leslie, Xu, Tremoulet, & Scholl, 1998; Z.W. Pylyshyn, 2001). This work should open new avenues of research as the role of spatiotemporal indexing and conceptual information in support of STM, at least in signers, gets better characterized.

Recent neuroimaging studies provide converging evidence for understanding working memory and the different STM buffers associated with it. STM tasks using spatial vs. verbal

stimuli have been contrasted to identify respectively the neural bases of the visual-spatial sketchpad and the phonological loop (E. Smith & Jonides, 1997; E. Smith, Jonides, & Koeppe, 1996; E. E. Smith et al., 1995). However, characterization of the episodic buffer and its possible neural bases has been hampered by the pervasiveness of verbal codes, and therefore the phonological loop, during any STM task that uses potentially nameable stimuli, whether pseudo-words or new objects, in hearing individuals (Postle, D'Esposito, & Corkin, 2005). Thus, the notion that deaf signers are less reliant on phonological coding opens the possibility of studying deaf native signers for identifying unique neural underpinnings of STM components like the episodic buffer. Already, studies of the neural correlates of verbal working memory in signers versus speakers suggest important differences. Thus, although sign and spoken languages are linguistically similar by most accounts (U. Bellugi & Fischer, 1972; Ursula Bellugi, Poizner, & Klima, 1989) and both are proposed to similarly engage a linguistic-based phonological loop (Wilson & Emmorey, 1997), greater parietal activation has been systematically reported for sign than speech. This was the case when considering hearing signers (Rönnberg et al., 2004), but also deaf signers (Bavelier, Newman, et al., 2008). Interestingly, recent work indicates a greater role for parietal areas in semantic processing and possibly episodic memory (Binder, Desai, Graves, & Conant, 2009; Wagner, Shannon, Kahn, & Buckner, 2005). Although only suggestive, further assessment of the parietal cortex and its subdivision as possible nodes within the episodic buffer should be a fruitful path for future work. Lastly, recent work highlights the advantage of examining separately the different phases of STM processing such as encoding, maintenance, and recall to refine our understanding of STM processes in deaf signers versus hearing speakers (D. Bavelier, Newman, et al., 2008; Hall & Bavelier, 2010, 2011). In one such study, while both groups engaged the same front-parietal network thought to be involved in working memory (Wager & Smith, 2003), deaf signers relied to a greater extent than hearing speakers on passive memory storage areas during encoding and maintenance, but relied more on executive process areas during recall (D. Bavelier, Newman, et al., 2008). Neuroimaging therefore affords a unique opportunity in further testing the relative contribution of distinguishable networks known to be involved in different components of working memory. Such an approach holds the promise of determining the relative engagement of one network vs. another in each group despite equal STM performance, as in Experiment B, where multiple codes are available for solving the task.

The current paper brings up important implications for future research on cognitive development, and clinical and education practice. First, when studying effects of deafness on any cognitive processing, it is important to include deaf native signers, as to not conflate possible cognitive differences that are not due to deafness, such as language delays, or abnormal psycho-social development. Second, and most, relevant to clinical or educational assessment of deaf children, the digit span may not be an appropriate or representative assessment of WM/STM ability in deaf individuals. More generally, standard views derived from studies of hearing participants may not equally apply to deaf individuals. This is especially relevant when considering the development of literacy, as verbal STM is one of the main determinants of reading acquisition in hearing individuals (see Ramus and Ahissar in this volume). To the extent that the deaf child also relies on phonological representations of English to bootstrap reading, one may expect the work from hearing children to be relevant. Yet, when considering deaf native signers, the present work indicates that such assumptions may not hold, calling for a reevaluation anew of the factors that may foster reading in this population.

MATERIALS AND METHODS

The same subjects were run on all three experimental conditions during the same session. Condition order was counterbalanced between subjects, and did not affect the main results and therefore will not be reported further.

1. Participants

Deaf group—Twelve adult congenitally deaf native signers were recruited from the National Technical Institute for the Deaf at the Rochester Institute of Technology, Rochester, NY (mean age = 24.08 years, SEM = 1.40, 7 females). All subjects reported having two deaf parents, and 11 subjects reported learning American Sign Language (ASL) from birth and using it daily. One subject reported learning German Sign Language at birth and learning ASL in school. For those subjects who knew their audiological information (7 out of 12 subjects), the average hearing loss was 90 dB (better-ear average, range = 65–105 dB). Ten subjects were undergraduates, 1 subject was in graduate school, and 1 subject had completed a graduate degree. None of the subjects reported having any neurological impairment.

Hearing group—Twelve adult hearing speakers were recruited from the University of Rochester, Rochester, NY (mean age = 20.14 years, SEM = 0.90, 8 females). All subjects reported having normal hearing and no experience with signing (i.e. had not taken any classes in ASL and had no deaf friends or relatives). Ten subjects were undergraduates, 1 was in graduate school, and 1 had a graduate degree. None of the subjects reported having any neurological impairment.

Two outliers were identified, one in the hearing group and one in the deaf group and were discarded. Both outliers were more than 2 standard deviations from their respective group's mean. Thus, the reported results are from 11 deaf subjects and 11 hearing subjects. All subjects were treated in accordance with the University of Rochester's Research Subjects Review Board guidelines and were paid for their participation in the study.

1. Stimuli, Design, and Procedure

Experiment A—Experimental trials were composed of a display sequence and a probe. The display sequence consisted of white squares flashed sequentially at different locations on a black background. Each square subtended approximately 2.1 degrees of visual angle. The display sequence began with a fixation cross presented in the middle of the computer screen, followed by a 500ms wait time and then a sequence of squares presented at a rate of 1 square per second as in other STM span studies (Figure 2). Each square was presented in a unique location on the computer screen so that no two squares touched or overlapped. The minimum distance allowed between squares was 1.25 degrees. The to-be-encoded sequence of squares was then followed by a probe display containing all of the squares at the location they had appeared during the presentation sequence. An arrow linked two of the squares on the screen. One of the two squares was randomly chosen by the program and the other one was temporally consecutive to the randomly chosen one. The two squares were then linked by an arrow, and the subjects' task was to decide whether the arrow indicated the correct temporal order between the two squares. In a "yes" trial, the square being pointed to came immediately after the square that the arrow was extending from. In a "no" trial, the direction of the arrow was reversed. In this way, the arrow always linked temporally consecutive squares, but either indicated the correct temporal order or the reverse order.

Experiment B—Experiment B is identical to Experiment A except that a distinct printed or fingerspelled letter was printed on each square (Figure 3). Thus, during the presentation

phase, subjects viewed letters in a square frame presented one after the other at different locations, and then during the probe phase, subjects viewed each letter where it had been presented before (Figure 3). An arrow linked two consecutive square-framed letters and subjects had to decide whether the direction suggested by the arrow corresponded to the temporal order of presentation or not. Because each square can be uniquely individuated by its letter name, the task can now be carried out by relying on either spatio-temporal indexing or ordered phonological representations. As a result, the task should be easier for both groups, but disproportionately so for the hearing group.

The letter stimuli set consisted of 16 uppercase English letters, printed in Arial font, and 16 ASL handshape letters. The ASL handshape letters were made from high-quality photos of a deaf model's hand forming each hand shape (see supplementary information for the full set of handshape letters used). To minimize effects of phonological similarity, different letter sets were used for each language while keeping the letter set as close as possible. The English letters for this task were 'B, C, D, F, G, H, J, K, L, M, Q, R, S, X, Y, Z' and the ASL handshape letters were 'B, C, D, F, G, H, K, L, M, R, S, T, V, W, X, Y' (see Supplementary Figure). Vowels were not included in either language's letter sets, in an attempt to minimize the production of words during the computer program's random presentation of the letters. In addition, polysyllabic English letters and ASL handshape letters that contained movement were also eliminated from the letter sets.

Experiment C—Stimuli and task were identical to that of Experiment A and B, except the probe display. In Experiment C, the probe display contained only 2 letters presented around the center of the screen (Figure 4). The letters were consecutive ones and subjects had to decide whether the arrow which was always left-to-right indicated the correct temporal order of presentation or not. The design and procedure was otherwise identical to Experiment B.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

The multiple component working memory model adapted from Baddeley (2000) which accounts for relative group biases. Incoming information first activates long-term memory (LTM) representations. This system permits the accumulation of long-term knowledge. In contrast, the short-term memory buffers represent dedicated temporary workspace, all under the control of the central executive (not shown here). The episodic buffer binds information from multiple codes and provide the richest input to the central executive, whereas the two slave systems are highly specialized for phonological versus visuo-spatial information respectively. More over, the episodic system uniquely labels events with respect to their time and place of occurrence allowing individuation of “episode” or temporary memory trace that uniquely refer to one event in the world. In contrast, temporal information in the phonological loop is conveyed through the chaining of phonological units, and in the visual spatial sketchpad through trajectory through space. Experiment A was designed to require precise tagging of when/where as supported by the episodic buffer and favored 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 coding and favored hearing speakers.

Figure 2.

In Experiment A participants had to perform a spatial STM task and decide whether the two squares in the probe display were presented in the same location as squares in the sequence (Yes) or whether one of them was in a different location (No). The use of squares diminishes the contribution of the ordered phonological representations and insures greater reliance on spatio-temporal indexing, predicting higher performance in deaf than hearing.

Figure 3.

The sequence of stimuli and types of probe displays used in Experiment B were identical to those in Experiment A, except that each square was now labeled with a separate letter. As a result, spatio-temporal indexing and ordered phonological representations could both be efficiently used to encode and maintain information in STM in Experiment B.

Figure 4.

The sequences of stimuli used in Experiment C were identical to those in Experiment B. The only difference was in the probe displays in which the two probes were always displayed centrally reducing the contribution of spatio-temporal indexing to the STM task.

Figure 5.

Group differences in each experiment demonstrate different biases in deaf signers and hearing speakers. There was a deaf advantage in Experiment A, when only spatial-temporal coding could be used [$*=p<.05$, one-tailed]. When both spatial-temporal and phonological coding could be used in Experiment B, deaf and hearing spans did not differ. When spatial-temporal coding at recall was disabled in Experiment C, there was a hearing advantage [$**=p<.05$, two-tailed].