Modality of Language Shapes Working Memory: Evidence From Digit Span and Spatial Span in ASL Signers

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Deaf children who are native users of American Sign Language (ASL) and hearing children who are native English speakers performed three working memory tasks. Results indicate that language modality shapes the architecture of working memory. Digit span with forward and backward report, performed by each group in their native language, suggests that the language rehearsal mechanisms for spoken language and for sign language differ in their processing constraints. Unlike hearing children, deaf children who are native signers of ASL were as good at backward recall of digits as at forward recall, suggesting that serial order information for ASL is stored in a form that does not have a preferred directionality. Data from a group of deaf children who were not native signers of ASL rule out explanations in terms of a floor effect or a nonlinguistic visual strategy. Further, deaf children who were native signers outperformed hearing children on a nonlinguistic spatial memory task, suggesting that language expertise in a particular modality exerts an influence on nonlinguistic working memory within that modality. Thus, language modality has consequences for the structure of working memory, both within and outside the linguistic domain.

Working memory, or short-term memory, has long been held to represent information in separate verbal and spatial codes (e.g., Paivio & Csapo, 1969). In the context of Baddeley's model of working memory, these forms of representation have been explored in more detail (see Baddeley, 1986; Baddeley & Hitch, 1994, for reviews; see also Allport, 1980; Martin & Romani, 1994; Carpenter, Miyake, & Just, 1994, for alternative views of the nature of working memory). In particular, there is considerable evidence that verbal working memory, or the "phonological loop," makes use of phonological and articulatory representations in order to rehearse and maintain speech stimuli.

Furthermore, for deaf users of American Sign Language (ASL), working memory appears to contain a sign language–based rehearsal mechanism that is parallel in many respects to the phonological loop for speech (e.g., Hanson, 1982; Klima & Bellugi, 1979; Wilson & Emmorey, in press-a, in press-b). This line of research suggests that both the sign-based and speech-based rehearsal mechanisms are shaped by linguistic properties common to all human languages. However, these two rehearsal mechanisms are based in different sensori-motor modalities, each with its own processing constraints, which may affect the form that these mechanisms can take. We know, for example, that audition and vision differ in their ability to process spatial and temporal information. Do these constraints have consequences for linguistic working memory? Should we expect to find differences between speech-based working memory and sign-based working memory in terms of their spatio-temporal processing abilities, due to the differences between audition and vision?

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Further, modality of language may have consequences for *nonlinguistic* working memory as well. That is, language expertise may interact with nonlinguistic working memory within the same sensory modality. For example, we can ask whether expertise in a spoken language exerts an influence on nonlinguistic auditory memory, and similarly whether expertise in a sign language exerts an influence on nonlinguistic visuo-spatial memory. This question is difficult to address in the auditory domain, because exposure to speech is essentially universal among people with intact auditory abilities. We can, however, study the nature of visuo-spatial working memory in subjects who do or do not have expertise in a visuo-spatial language. This allows us to explore how language can affect the broader working memory system.

Thus, by studying the structure of working memory in native signers of ASL, we can explore the impact of language modality on working memory. Our study compares deaf and hearing subjects on a linguistic working memory task (experiment 1) and on a nonlinguistic visuo-spatial working memory task (experiment 2), to determine the impact of language modality in each of these domains of working memory.

Linguistic Working Memory

We begin by addressing how the structure of linguistic working memory may be influenced by the differences between auditory and visual processing. One important difference is in how spatio-temporal information is coded (e.g., Kubovy 1988). Vision excels at processing information presented simultaneously in which items are distinguished from one another by spatial location, but is relatively poor at linking successively presented items across time. Conversely, audition excels at temporal sequencing, but is extremely poor at spatial resolution and at processing many simultaneously presented items. These differences suggest that working memory for visual stimuli and for auditory stimuli may differ in how serial order information is processed.

There are in fact systematic differences between working memory for speech and working memory for print (see Penney, 1989, for review) and also between working memory for language materials and working memory for nonlinguistic visuo-spatial materials (Anderson, 1976; Logie, 1995, pp. 52–56; Paivio & Csapo, 1971). However, these results are difficult to interpret in terms of modality differences. Data on linguistic working memory in hearing subjects make it clear that sensory modality of the input is of less importance for subsequent processing than is the phonological status of the input. Thus, lipread stimuli, although visual, nevertheless conform to the pattern for speech stimuli and not the pattern for print stimuli (Campbell & Dodd, 1980; Gardiner, Gathercole, & Gregg, 1983). Shand and Klima (1981) argue that speech and sign are both primary language codes, while print is a derived code, and that this distinction has important consequences for how materials are treated in working memory. One common interpretation for these differences is that print stimuli must be translated into phonology before they can be rehearsed in the phonological loop (e.g., Baddeley, Lewis, & Vallar, 1984). Nonlinguistic visual stimuli such as nonsense shapes, of course, differ from speech even more dramatically than does print.

In contrast to print and nonlinguistic visual stimuli, sign language bears several important similarities to speech. Like speech, sign language is a dynamically expressed form of language that depends upon temporal structure at both the phonological[1] and syntactic levels. These similarities between speech and sign in their temporal structuring of the perceptual stream may serve to mitigate the inherent differences between audition and vision in terms of how sequential information is represented in working memory. A further parallel between sign and speech is in their articulatory properties. Both sign and speech have a motorically expressed productive form, which is closely mapped to the perceived form of the language and which allows the possibility of articulatory rehearsal. It may be that automatized rehearsability plays an overriding role in structuring linguistic working memory, in which case we would expect a minimal influence of sensory modality.

Indeed, previous work indicates strong similarities between speech-based working memory and sign-based working memory (Wilson & Emmorey, in press-a, in press-b). Immediate serial recall of signs in deaf signers shows effects and interactions that are characteristic of the phonological loop for spoken language (e.g., effects of phonological similarity, item length, competing movement of the relevant articulators, and characteristic interactions between these effects). The fact that the same pattern of effects is found for sign as for spoken language suggests the existence of a sign-based phonological loop in deaf signers that closely parallels the phonological loop in hearing subjects. Furthermore, the pattern of data for memory for signs parallels that of memory for *speech*, and not memory for print (Krakow & Hanson, 1985; Shand & Klima, 1981; Wilson & Emmorey, in press-a, in press-b). Thus, despite shared modality between sign and print, it appears that the dynamic, articulatory, or primary language–code properties common to speech and sign are critical in determining the structure of sign-based working memory.

The question, then, is whether the memory mechanisms for speech and sign are identical, or whether we can find ways in which the differing characteristics of audition and vision do play a role. The differences in how the two modalities code spatio-temporal information suggest that, if the sign-based and speech-based rehearsal mechanisms are indeed shaped by the perceptual properties of vision and audition respectively, then we might find differences in the coding of serial order information. Two pieces of evidence might be taken as indicating better temporal coding for speech than for sign. First, deaf native signers of ASL use an English-based phonetic code when temporal order recall is required, but not when spatial order recall is required (Hanson, 1990), which indicates that a speech code is particularly well suited to maintenance of temporal information. However, it is difficult to contrast this to a sign code, since no evidence for sign coding was found for either type of recall in Hanson's experiment (perhaps due to choice of stimulus materials—cf. Krakow & Hanson, 1985). The second piece of evidence is the well-established finding of better serial recall for spoken language than for sign language (e.g., Bellugi, Klima, & Siple, 1975; Hanson, 1982). However, this difference may be due to the difference in articulation rate between the two languages, rather than a difference in ability to code temporal information. ASL signs take longer to articulate on average than do English words (Bellugi & Fischer, 1972), and such differences are known to cause differences in memory span across spoken languages (Baddeley, Thomson, & Buchanan, 1975; Ellis & Henelly, 1980; Hoosain, 1979; Stigler, Lee, & Stevenson, 1986). Similarly, differences in articulation rate may account for the difference in memory span between ASL and English (Marschark, 1996).

A better test of spatio-temporal coding of sign and speech might be the ability to reverse a given serial order. A long-established finding for hearing subjects is that recalling a list of spoken items in reverse order is substantially more difficult than recalling a list in the order received (e.g., Ebbinghaus, 1885/1964). This suggests that the representation of spoken language in working memory makes use of a temporally based sequencing, a form of coding that is unidirectional. In contrast to temporally based representations, spatial representations do not entail a necessary directionality. Items arranged spatially can be selected left-to-right or right-to-left with approximately equal ease. Thus, a representation that captures serial order information in a spatial form rather than a temporal form ought to be well suited to reporting a sequence of items backward.

Indeed, it has been shown that when subjects are biased towards visuo-spatial coding, the difference between forward and backward report diminishes. One line of evidence is the performance of hearing subjects shown items distributed across space. This type of presentation has been shown to bias subjects towards visual coding (Hanson, 1990; Healy, 1984; Metcalfe, Glavanov, & Murdock, 1981), and also has been shown to reduce the size of the difference between forward and backward recall in hearing subjects (e.g., Hermelin & O'Connor, 1975). A second line of evidence is the performance of deaf children who have had inadequate language exposure.[2] Such children might be expected to use a nonlinguistic visuo-spatial strategy, and indeed several studies show that they do rely more heavily on visual coding in short-term memory than do hearing children (e.g., O'Connor & Hermelin, 1973; Wallace & Corballis, 1973). Further, such children have been reported to perform equally, or even better, on backward recall than forward recall (e.g., Blair, 1957; Hermelin & O'Connor, 1975; O'Connor & Hermelin, 1976). Finally, there is evidence that even hearing subjects given central presentation of printed words show less of a difference between forward and backward report than they do with spoken words, suggesting that visuo-spatial representation is coming into play (Powell & Hiatt, 1996; but see Hermelin & O'Connor, 1975, for a large difference in hearing subjects between forward and backward report with central visual presentation).

Thus, if the visuo-spatial nature of sign language plays a critical role in the representation of ASL in working memory, then we might expect less difference between forward and backward recall of sign than is found for speech. But if instead working memory for ASL is based on a more abstract phonological code that carries little visuo-spatial information, or if its structure is largely or entirely determined by properties of the language that resemble speech, such as linear ordering across time or articulatory processes, then we might expect similar patterns of performance for sign and speech. As mentioned above, several findings suggest that working memory for sign resembles working memory for speech, and not working memory for visual materials such as print (Krakow & Hanson, 1985; Shand & Klima, 1981; Wilson & Emmorey, in press-a). If this pattern holds, then we might expect that backward report should be difficult for both sign and speech.

In the first experiment of our study, we compare memory for speech and memory for sign with forward and backward recall. We do so by comparing deaf children who are native signers of ASL (that is, deaf children of deaf parents) and hearing children who are native speakers of English. As a control, we also test a group of deaf children being educated in ASL but who were born to hearing parents and did not receive exposure to ASL from birth. If the performance we observe in the deaf native group indeed reflects sign-based rehearsal, and not a nonlinguistic visuo-spatial strategy, then we should expect overall performance to be better in subjects who have been exposed to ASL from birth.

Experiment 1: Method

Subjects. Three groups of subjects were compared: hearing children, deaf children who were native signers of ASL, and deaf children who were not native signers of ASL. The hearing group consisted of 31 hearing children who were native English speakers with no deaf family members, attending public school in San Diego, California. They ranged in age from 8;0 to 10;11 years, with an average age of 9;3. The deaf native group consisted of 16 prelingually deaf children who were native ASL signers, each with two deaf parents, attending the California School for the Deaf in Fremont, California. They ranged in age from 8;1 to 10;4 years, with an average age of 9;2.[3] The deaf nonnative group consisted of 22 prelingually deaf children with no deaf family members, attending the California School for the Deaf in Fremont, California. They ranged in age from 8;7 to 10;11 years, with an average age of 9;7. All had been using ASL or another signing system for a minimum of 3 years and had been exposed to signing by age 6 at the latest.

Stimuli. Digit sequences were taken from the WAIS-R (Wechsler, 1981) and WISC-R (Wechsler, 1974). Separate sets of sequences were used for the forward report and backward report conditions. The hearing subjects received the digit stimuli in spoken English, presented by a hearing experimenter. The deaf subjects received the digit stimuli in ASL, presented by a deaf experimenter. The sequences were spoken or signed at a rate of approximately one digit per second.

Procedure. Each subject was tested first in the forward recall condition and then in the backward recall condition. For forward recall, subjects were told to repeat each sequence exactly as the experimenter had done. For backward recall, subjects were told to repeat each sequence in reverse order. Instructions were given in spoken English by a hearing experimenter for the hearing group, and in ASL by a deaf experimenter for the deaf group.

Immediately before each condition, subjects were given two practice trials with feedback. During the main test, subjects were given two trials at each sequence length, starting at length 3 for the forward recall condition and length 2 for the backward recall condition. If the subject correctly answered one or both sequences of the same length, the length was increased by one. The experimenter stopped the test when the subject answered incorrectly on both sequences of a

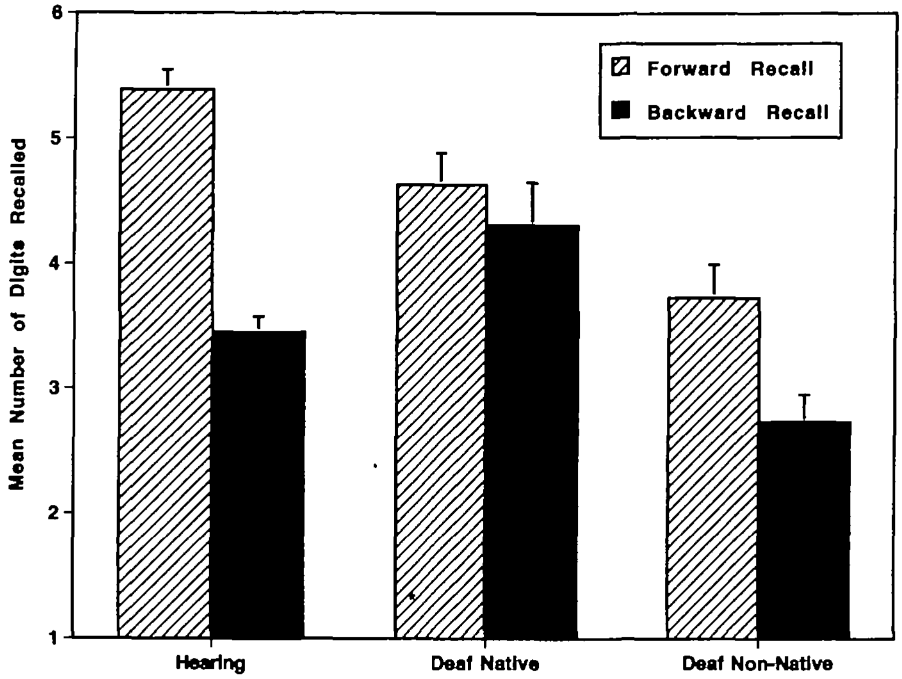

Figure 1 Digit span with forward and backward report for hearing children, deaf children who are native signers of ASL, and deaf children who are nonnative signers of ASL. The hearing and nonnative groups show lower performance on backward report than forward report. The deaf native group shows no difference. The deaf native group scored lower than the hearing group on forward report, but higher than the hearing group on backward report.

given length. All testing sessions were videotaped for purposes of scoring. The score for each task was the length of the longest sequence with at least one completely correct response.

Experiment 1: Results

Performance of the two groups for the recall orders is shown in Figure 1. An analysis of variance (ANOVA) found a main effect of group [$F(2, 66) = 14.01$, $p < .01$], a main effect of recall order [$F(1, 66) = 107.56$, $p < .01$], and an interaction [$F(2, 66) = 14.71$, $p < .01$]. To determine the source of the interaction, the effect of recall order was analyzed separately for each group. Better performance with forward recall than backward recall was found for the hearing group [$F(1, 66) = 113.85$, $p < .01$] and also for the deaf nonnative group [$F(1, 66) = 21.57$, $p < .01$], but not for the deaf native group [$F(1, 66) = 1.53$, not significant, or NS].

Planned comparisons were conducted to compare the deaf native group to the hearing group. There was no main effect of group [$F(1, 45) = .04$, NS], but there was a significant effect of recall condition [$F(1,45) = 82.04$, $p < .01$] and a significant interaction [$F(1,45) = 25.37$, $p < .01$]. The deaf native group scored lower than the hearing group on forward recall [$F(1,90) = 6.71$, $p < .05$], but higher than the hearing group on backward recall [$F(1,90) = 8.56$, $p < .01$]. Planned comparisons were also conducted to compare the deaf native group to the deaf nonnative group. There was a main effect of group [$F(1,36) = 12.98$, $p < .01$], a main effect of task [$F(1,36) = 18.45$, $p < .01$], and an interaction [$F(1,36) = 4.21$, $p < .05$]. The deaf native group scored higher than the deaf nonnative group on both forward recall [$F(1,72) = 5.49$, $p < .05$] and backward recall [$F(1,72) = 17.12$, $p < .05$].

Experiment 1: Discussion

Deaf children who are native signers of ASL showed no difference between forward recall and backward recall for language materials, exhibiting essentially no cost of the requirement to transform the order of stimulus input. In contrast, hearing children are substantially worse at backward recall than at forward recall, a replication of the standard finding. While the deaf native group performed below the hearing group on forward recall—also a standard finding, possibly due to articulation rate differences between speech and sign—the deaf native group nevertheless performed above the hearing group on backward recall. Should this pattern of results be explained in terms of the differing spatio-temporal processing characteristics involved in spoken versus signed language? First, we must consider several alternative explanations.

We can immediately rule out two such explanations. One is that the lack of difference between forward and backward recall in the deaf native group is a floor effect. This is clearly not the case, first because the deaf native group outperformed the hearing group on backward recall; and second because the deaf nonnative group showed a difference between conditions, in spite of lower performance than the deaf native group. A somewhat more subtle explanation is that, even when performance is not at floor, low forward scores in general might co-occur with relatively good backward scores, perhaps due to differences in prefered strategy. Again, the deaf nonnative data argue against this explanation. Further, we compared forward and backward scores for those hearing subjects who scored below the mean on forward recall. This group of 20 subjects showed a substantial difference between forward and backward scores [4.85 versus 3.35, $F(1,19) = 57.00$, $p > .01$]. For these reasons, the equal performance on forward and backward recall in the deaf native group cannot be explained in terms of a general effect of low forward scores.

The data from the deaf nonnative group also argue against another set of possible explanations, which would attribute the data pattern of the deaf native group to various factors other than the structure of sign-based rehearsal. First, the results for the deaf native subjects might be due to deafness itself—that is, to auditory deprivation and a resulting reorganization of cognitive architecture, or greater dependence on visual strategies in general. A second possibility is that the time-course of development of the sign-based rehearsal loop is different from that for the speech-based rehearsal loop, and that the deaf native subjects were not yet relying on the sign loop. In such a case, their data might be due to the use of a nonlinguistic visual strategy. A final (somewhat unlikely) possibility is that the deaf native subjects, despite their normal language exposure from birth, are in some way developmentally delayed, and their pattern of performance represents an earlier developmental stage.

If any of these three proposals is correct, then deaf children who receive delayed exposure to sign language should be even more likely to show no difference between forward and backward recall. Instead, deaf children with delayed exposure to ASL do not show this pattern. Thus, the differences between the hearing and the deaf native groups cannot be accounted for on the basis of auditory deprivation, preference for a nonlinguistic visual strategy over a sign-based strategy, or some developmental delay of unknown source specific to deaf children.

The best explanation, then, seems to be that the performance of the deaf native group reflects the operation of the sign-based rehearsal loop in working memory, which suggests that both the sign-based loop and the speech-based loop are influenced by the distinct spatio-temporal processing characteristics of the sensory modality in which they are based.

However, if this is the correct explanation, we are left with an unsolved puzzle. Why does the deaf nonnative group show a difference between forward and backward recall? And how do we reconcile these data with the data found by previous investigators, in which deaf children (presumably nonnative, since the large majority of deaf children are nonnative) showed equal performance on forward and backward recall? Data from previous studies have been interpreted by their authors in terms of a nonlinguistic visuo-spatial strategy (e.g., Hermelin & O'Connor, 1975). Indeed, their subjects may well have had little exposure to sign language, as well as (apparently) insufficient speech skills to induce a speech-based strategy. In contrast, the deaf nonnative subjects of our experiment were immersed in an ASL environment both in and outside the classroom. It is possible that the data from the present nonnative subjects represents the effects of delayed acquisition of ASL, perhaps showing the influence of a linearly structured, articulatory linguistic system, but not yet showing the influence of linguistic functions of space. Clearly, any explanation at this point is necessarily speculative, and further research is called for to address this question. Nevertheless, the data from the deaf nonnative group serve to rule out a variety of competing accounts for the deaf native results.

The data from experiment 1 therefore suggest that the sign-based rehearsal loop in the working memory of deaf native signers is not entirely parallel to the speech-based rehearsal mechanism in terms of how it codes information. Speech-based rehearsal appears to be unidirectional, in the same way that time is unidirectional (cf. Penney, 1989). In contrast, deaf signers showed essentially no cost of the requirement to report the items in reverse order. That is, sign-based rehearsal does not appear to have this constraint of unidirectionality. This pattern of findings is in fact just what we would expect to see if working memory for ASL uses space, rather than time, to code serial order. We should note that this does not necessarily imply explicit use of visual imagery, but it does suggest a form of mental representation that preserves some of the informational properties of vision.

Inspection of the means in experiment 1 shows that performance for the deaf native signers was in fact slightly lower for backward span than forward span, although the difference was not statistically significant. It is important to note that the tasks used here do not necessarily represent the operation of a single process, and it is possible that there is some time-based coding operating for ASL as well. For instance, if subjects are using manual articulatory rehearsal (Wilson & Emmorey, in press-a, in press-b), this rehearsal presumably occurs in a particular order, which could introduce a directional bias. Nevertheless, these results suggest that ASL is coded in working memory in a form that takes advantage of the properties of vision, just as speech is coded in a form that takes advantage of the properties of audition. Thus, the linguistic domain of working memory, while apparently structured by properties common across languages, nevertheless appears also to be constrained by the sensory processing characteristics of the modality in which the language is based.

Experiment 2: Nonlinguistic Working Memory

We now turn our attention to the second question we have asked, namely, whether the modality of one's language influences nonlinguistic working memory. There are several reasons for thinking that language might influence nonlinguistic aspects of working memory. We know that expertise in sign language produces systematic effects on visual processing (e.g., Emmorey & Kosslyn, 1996; Klima, Tzeng, Fok, Bellugi, Corina, & Bettger, in press; Poizner, Fok, & Bellugi, 1989; Neville & Lawson, 1987; Parasnis & Samar, 1985), suggesting that language can influence nonlinguistic perceptual processing within the same modality. These effects of language might be expected to extend beyond the perceptual system to working memory, perhaps influencing nonlinguistic components of working memory. Further evidence in favor of this hypothesis comes from the fact that, in hearing subjects, nonlinguistic auditory working memory (e.g., memory for musical pitch and timbre) may make use of speech production mechanisms (Smith, Reisberg, & Wilson, 1992, citing Hespos, 1989). This suggests that mechanisms or skills developed in the context of language may be borrowed to assist with ostensibly nonlinguistic tasks. The same may occur in the visuo-spatial domain, in which case ASL signers will possess resources for visuo-spatial memory unavailable to nonsigners.

One way in which we might expect to see an influence of ASL on visuo-spatial memory is in the representation of spatial relationships. Spatial locations and spatial relationships are used to convey information in ASL. In discourse, referents are often associated with particular loci in space, and this information must be remembered over the course of the conversation. These uses of space in ASL might be expected to exert an influence on spatial working memory, even for nonlinguistic materials.

Previous studies have compared deaf and hearing subjects on various visuo-spatial memory tasks (Carey & Blake, 1974; Das, 1983; Hanson, 1990; McDaniel, 1980; Tomlinson-Keasey & Smith-Winberry, 1990), but none of these experiments strictly addresses spatial memory. For example, Hanson (1990) asked subjects to recall either the temporal order or the spatial order of a sequence of words. This experiment was not designed to address visuo-spatial memory per se, but rather to address the efficacy of temporal ordering versus spatial ordering in linguistic working memory. Tasks used in various other studies also allow for nonvisuo-spatial strategies. For example, the task used by

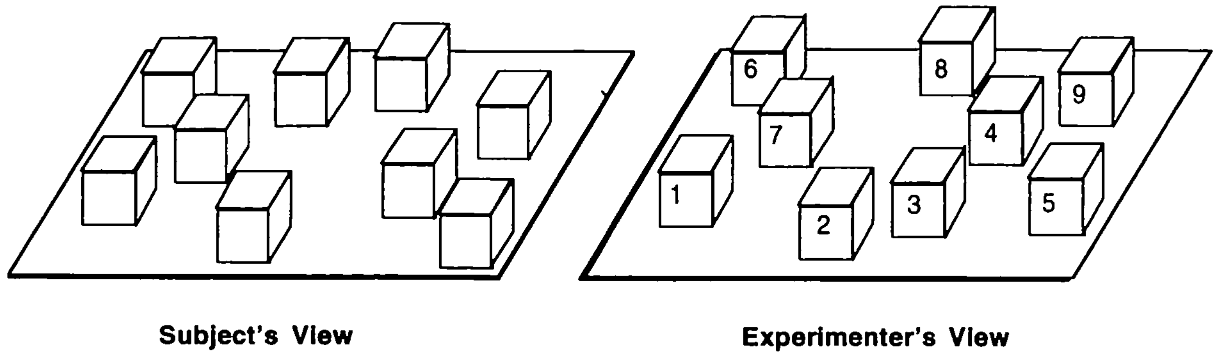

Figure 2 The Corsi blocks arrangement used for the spatial task.

Tomlinson-Keasey & Smith-Winberry is the game "Simon," in which four colored panels light up in a random sequence. The fact that the locations have distinct namable colors allows a subject to remember the names of the colors, rather than being forced to remember the locations. Further, with the exception of Hanson (1990), who tested native signers of ASL, the studies cited above do not report the language history of their subjects and cannot be interpreted in terms of the impact of sign language.

A purer measure of spatial working memory is the Corsi blocks task (Milner, 1971), in which the subject must remember and reproduce a sequence of identically marked spatial locations. One recent study used the Corsi blocks taks and found no difference between adult hearing subjects and adult deaf signers (Logan, Maybery, & Fletcher, 1996). However, apparently none of the deaf subjects had received early exposure to a natural sign language. How will deaf subjects who are native users of a natural sign language perform on the Corsi blocks task?

Experiment 2: Method

Subjects were the hearing and deaf native groups tested in experiment 1. Stimuli consisted of nine irregularly spaced identical blocks, a subset of which were touched in a sequence by the experimenter on each trial (see Figure 2). The blocks were labeled with the numbers 1–9 visible only to the experimenter, and the sequences of locations were determined by the same digit sequences as were used in experiment 1. The experimenter presented each sequence of locations by touching the blocks at a rate of approximately one block per second. Each subject's score was assessed as the length of the longest sequence correctly produced. Instructions were given in spoken English by a hearing experimenter for the hearing group, and in ASL by a deaf experimenter for the deaf group.

Experiment 2: Discussion

Mean spatial span for the deaf group was 5.56 (standard error [*SE*] = .30) and for the hearing group was 5.00 (*SE* = .12), a statistically significant difference [$F(1,45) = 4.18$, $p < .05$). This finding of enhanced performance on the Corsi task in deaf children is complemented by a finding from Parasnis, Samar, Bettger, & Sathe (1996). That study found that deaf children who were educated in a spoken language setting and had received no exposure to sign language performed the same as hearing children on the Corsi blocks task. That is, deafness per se, and any consequent compensation in the visual modality for the absence of auditory input, does not result in enhanced spatial memory. This suggests that our finding of a spatial memory advantage for deaf subjects is due to early exposure to ASL. The use of spatial locations and spatial relationships in ASL for coding information may give deaf subjects an enhanced ability to represent space.

What might this enhancement consist of? One possibility is that the enhancement is due to linguistic representations of space coopted for nonlinguistic purposes. Deaf signers may use linguistic representations of spatial locations or of paths between spatial locations as a strategy for the spatial span task. This would be similar to a hearing person inventing new onomatopoeic words to encode nonlinguistic sounds (cf. Smith, Reisberg, & Wilson, 1992). Alternatively, use of ASL may enhance spatial abilities in a more general way. The extensive use of spatial abilities needed for processing ASL might result in a general enhancement of spatial processing not specific to language.

The spatial span task joins a growing list of spatial and visual tasks for which experience with sign language appears to affect performance (e.g., Emmorey & Kosslyn, 1996; Klima, Tzeng, Fok, Bellugi, Corina, & Bettger, in press; Poizner, Fok, & Bellugi, 1989; Neville & Lawson, 1987; Parasnis & Samar, 1985). Our finding indicates that the modality of one's language can influence the functioning of working memory beyond the domain of language.

Conclusion

The experiments in this article explored how modality of language influences the structure of working memory. Experiment 1 asked whether the processing requirements of a particular sensory modality place constraints upon the structure of working memory for a language within that modality. We found that deaf subjects were essentially equal on forward and backward report of linguistic stimuli, while hearing subjects were substantially worse on backward than forward report, as is typically found. This suggests that working memory for speech and working memory for sign differ in how they represent serial order information. Experiment 2 asked whether expertise in a language within a particular modality influences nonlinguistic working memory within that same modality. We found that deaf subjects were better than hearing subjects on spatial memory, indicating that expertise in a visuo-spatial language can influence nonlinguistic visuo-spatial memory.

These findings bear upon theoretical models of how working memory is structured. Wilson & Emmorey (in press-a, in press-b) argue for the existence of a sign-based "phonological loop" in deaf signers, which closely parallels the phonological loop in hearing subjects. Our findings indicate important differences in how information is represented in these two forms of the phonological loop, and that those differences are the result of differences between the auditory and visual modalities. Taken together, the results of Wilson and Emmorey and these results indicate the extent to which the structure of working memory is flexible in response to experience, allowing a rehearsal loop structure to develop in whichever modality receives the appropriate input; but indicate also that there are limitations on this flexibility, as seen by how modality plays a role in determining how that rehearsal loop will code information. In addition, our results show that language can influence nonlinguistic working memory. This has potential implications for auditory as well as visual working memory. Just as sign language appears to exert an influence on visuo-spatial working memory, spoken language may play an important role in the functioning of ostensibly nonlinguistic auditory working memory.

The picture emerging from this line of research is one in which working memory exploits the sensory and language resources available to it in order to devise rehearsal mechanisms or to augment existing mechanisms (cf. Reisberg, Rappaport, & O'Shaughnessy, 1984, on devising novel motoric rehearsal strategies; Pechmann & Mohr, 1992, on musicians' memory). Our study indicates some of the ways in which both language expertise and sensory modality contribute to the architecture of working memory.

Notes

1. ASL and other sign languages possess sublexical grammatical structure with properties similar to the phonology of spoken languages (e.g., hierarchically organized feature classes, autosegmental representatioons, deletion and segmentation rules, a sonority hierarchy; see Corina and Sandler, 1993, for review). For this reason, linguists have broadened the term "phonology" to refer to the "patterning of the formational units" of any natural language (Coulter & Anderson, 1993, p. 5).

2. The studies cited here either do not report the early language history of their subjects or else specify children of hearing parents or "orally trained" children. If native signers were not specifically selected, then, given the demographics of the deaf population, the large majority of subjects most likely had hearing parents and were not given early exposure to sign language. In addition, we can assume that, for the majority of these deaf subjects, exposure to and training in spoken language did not constitute normal language exposure.

3. Subjects were not explicitly matched for IQ, but other studies have found equivalent cognitive development in random samples of hearing children and deaf children of deaf parents (see Mayberry, 1992, for review). Indeed, there is no reason to

expect any such differences. Children with inherited deafness are not at risk for neurological disorders that can accompany deafness from other causes. Further, such children receive normal language exposure from birth and throughout early childhood, and in this sample were attending a school where their natiive language is used both for instruction and among their peers outside the classroom. In this respect, comparing deaf native signers to hearing children is no more problematic than, for example, comparing groups of randomly selected English speakers and Chinese speaker.

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