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Visual imagery and visual–spatial language: Enhanced imagery abilities in deaf and hearing ASL signers*

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Abstract

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The ability to generate visual mental images, to maintain them, and to rotate them was studied in deaf signers of American Sign Language (ASL), hearing signers who have deaf parents, and hearing non-signers. These abilities are hypothesized to be integral to the production and comprehension of ASL. Results indicate that both deaf and hearing ASL signers have an enhanced ability to generate relatively complex images and to detect mirror image reversals. In contrast, there were no group differences in ability to maintain information in images for brief periods or to imagine objects rotating. Signers' enhanced visual imagery abilities may be tied to specific linguistic requirements of ASL (referent visualization, topological classifiers, perspective shift, and reversals during sign perception).

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Introduction

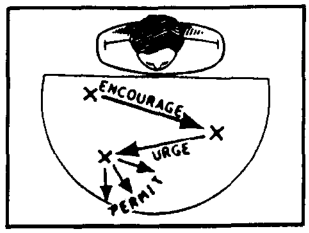
American Sign Language (ASL), the language of deaf communities in the United States, exploits visual–spatial mechanisms to express grammatical structure and function. Visual–spatial perception, memory, and mental transformations are prerequisites to grammatical processing in ASL (Emmorey & Corina, 1990; Emmorey, Norman, & O'Grady, 1991; Hanson & Lichtenstein, 1990), and also are central to visual mental imagery (Farah, 1988; Finke & Shepard, 1986; Kosslyn, 1980; Shepard & Cooper, 1982). Hence, it is of interest to examine the relation between the use of ASL and spatial imagery abilities. In this article we report a series of experiments in which we compare various aspects of visual mental imagery in deaf signers of ASL, hearing signers who learned ASL from their deaf parents, and hearing non-signers. We investigate whether signers are more adept at imagery abilities that apparently are recruited to produce and comprehend ASL.

The hypothesis that deaf ASL signers are especially adept at certain aspects of visual imagery is plausible because ASL makes use of visual–spatial distinctions at all linguistic levels (Bellugi, 1980; Klima & Bellugi, 1979; Lillo-Martin & Klima, 1990). The most striking surface difference between English and ASL is in the latter's reliance on explicitly marked spatial contrasts at all linguistic levels. This is particularly evident in the complex spatial organization underlying ASL syntax and discourse. Referents introduced into the discourse can be associated with arbitrary points in a specific plane of signing space, and direction of movement of verb signs between these spatial endpoints indicates the grammatical role (subject or object) of the referents (Figure 1a). Pronominal signs directed toward previously established loci function to refer back to their associated nominals. The referential system of ASL is further complicated by shifts in point of view that are expressing by spatially shifting the frame of reference (Figure 1b). This is particularly evident in narrative mode (van Hoek, in press). Thus tracking reference in ASL requires coordination and integration of several different linguistic subsystems that are spatially expressed. In general, signers are faced with the dual task of spatial perception, spatial memory and spatial transformation, on the one hand, and processing grammatical structure on the other – in one and the same visual event.

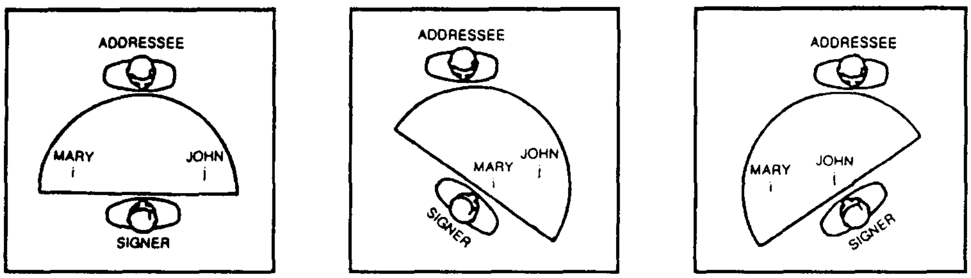
Bellugi et al. (1990) provide evidence that experience with a visual language can affect some non-language visual abilities. As illustrated in Figure 2a, they found that deaf signing children can discriminate faces under different conditions of spatial orientation and lighting better than hearing children. In ASL, the face conveys not only emotional information but also linguistic structure; specific facial expressions serve to signal relative clauses, conditionals, topicalization, as well as several adverbial forms (Coulter, 1979; Liddell, 1980). The fact that deaf signing children discriminate faces better than hearing children suggests not only that acquiring the ability to detect grammatical distinctions expressed on the face enhances other (non-linguistic) aspects of face recognition, but also that some aspects of visual processing may subserve both linguistic and non-linguistic functions.

In addition, Klima, Tzeng, Fok, Bellugi, and Corina (1992) and Bettger (1992) found that deaf signers can detect and interpret moving light displays better than hearing non-signers. In this experiment, Chinese pseudo-characters were written in the air with a light-emitting diode, which created a continuous stream of movement. Deaf signers (both Chinese and American) were significantly better than their hearing counterparts at perceiving the underlying segments of these pseudo-characters. Figure 2b shows the contrast between first-grade Chinese hearing and deaf children on this task. Furthermore, Neville has shown that deaf signers have a heightened ability to detect the direction of movement in the periphery of vision (Neville, 1988). Enhanced movement interpretation and detection in deaf subjects can be tied to their linguistic experience because recognition of dynamic movement is integral to morpholexical recognition in ASL (see Emmorey & Corina, 1990; Poizner, 1983).

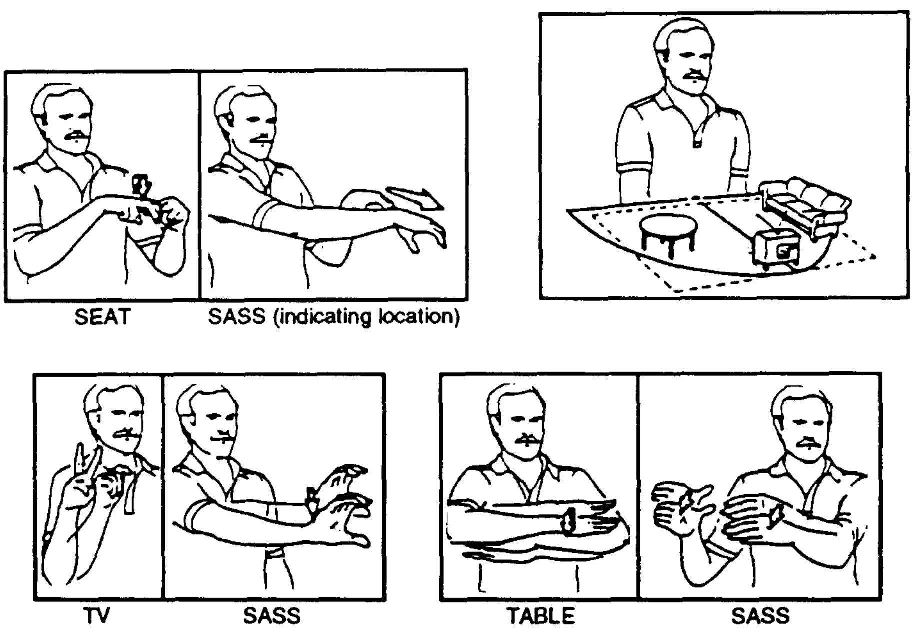
In the experiments reported here, we investigate three visual mental imagery abilities that we hypothesize are integral to ASL production and comprehension: image generation, maintenance, and transformation. These abilities also reflect the typical progression of processing when imagery is used in cognition: an image is first generated, and it must be maintained in short-term memory in order to be manipulated. If ASL does in fact recruit these abilities, and thus signers practice them frequently, then we might expect signers to be better at these aspects of imagery than non-signers. Image generation is the process whereby an image (i.e., a short-term visual memory representation) is created on the basis of information stored in long-term memory. That is, a visual mental image is not stored as a whole; rather it must be constructed either actively or passively, and this process itself becomes more efficient with practice (see Kosslyn, Brunn, Cave, & Wallach, 1985). In ASL, image generation may be an important process underlying not only the spatially organized syntax but also the expression of real-world spatial relations represented in the language. As opposed to its syntactic use, space in ASL also functions in a topographic way. The space within which signs are articulated can be used to describe the layout of objects in space. In such mapping, spatial relations among signs correspond topographically to actual spatial relations among objects described (Bellugi, Poizner, & Klima, 1989; Supalla, 1986, in press). Spatial mapping uses ASL predicates of location and motion, including size and shape specifiers (SASSes), termed "classifier signs", to represent external real-world space (see Figure 1c). Classifier constructions indicate the movement and location of objects in space, and often require precise representation of visual–spatial relationships within a scene; such explicit linguistic encoding may necessitate the generation of detailed visual images. Unlike



A) Spatially Organized Syntax in ASL



B) Fixed and Shifting Frames of Reference



C) Sign Space to Represent Real World Space spoken languages which contain classifier morphemes that encode spatial properties, ASL uses space itself to encode spatial relations. The interaction between direct spatial encoding and the richness of the linguistic marking may lead to an increased use of imagery in signers. Moreover, Liddell (1990) has argued that a visual image of a referent is generated for certain syntactic constructions utilizing agreement verbs. Thus, the ability to generate visual mental images of referents and spatial scenes may play a role in the production of ASL.

Second, nominals and their associated loci in space must be remembered throughout the discourse, and we hypothesize that the signer/perceiver must therefore maintain a visual–spatial representation of these loci during discourse production and comprehension. This linguistic requirement may heighten the deaf signer's ability to maintain non-linguistic mental images in short-term memory. We will discuss the details of this aspect of ASL in relation to visual imagery when we introduce Experiment 2.

Finally, once spatial loci have been established, there are syntactic and discourse rules that allow a signer to shift these loci to convey perspective shift or a change in location (van Hoek, 1989). Moreover, during sign perception the perceiver must mentally transform these spatial arrays to reflect the signer's perspective in order to process shifts in reference. Spatial and referential perspectives are normally understood from the signer's (not the addressee's) perspective in that spatial relationships are mentally represented as the reverse of what the addressee actually observes. For example, to describe a visual scene, the signer uses linguistic constructions in space to indicate the location, orientation and layout of objects in that scene. An object that the signer locates on his or her right is on the addressee's *left* (assuming face-to-face conversation). Therefore, to understand the scene from the viewpoint of the signer, the addressee must mentally reverse the spatial locations he or she actually observes. We hypothesize that these linguistic requirements may enhance deaf signers' ability to mentally shift or rotate non-linguistic visual images.

In short, it is plausible that at least three imagery abilities – image generation, maintenance, and rotation – play crucial roles in sign language. If so, then it is of interest to discover whether signers are relatively adept at these abilities, even if they are recruited in tasks that have no relation to sign language. To distinguish between effects of using ASL from effects of being deaf from birth, we also tested

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Figure 1. *A. Spatially Organized Syntax in ASL. Nominals are associated with arbitrary spatial loci in a plane of signing space (signified here with 'x'); verb signs move between spatial endpoints indicating grammatical role (arrows indicate verb movement between loci). B. Fixed and shifting frames of reference. The system is complicated by devices for reassigning loci, expressed by spatially shifting frames of reference. C. Sign space to represent real world space. ASL uses predicates of location and motion, including size and shape specifiers (SASSes) to represent external real-world space. This is a very simple example of spatial description in ASL.*

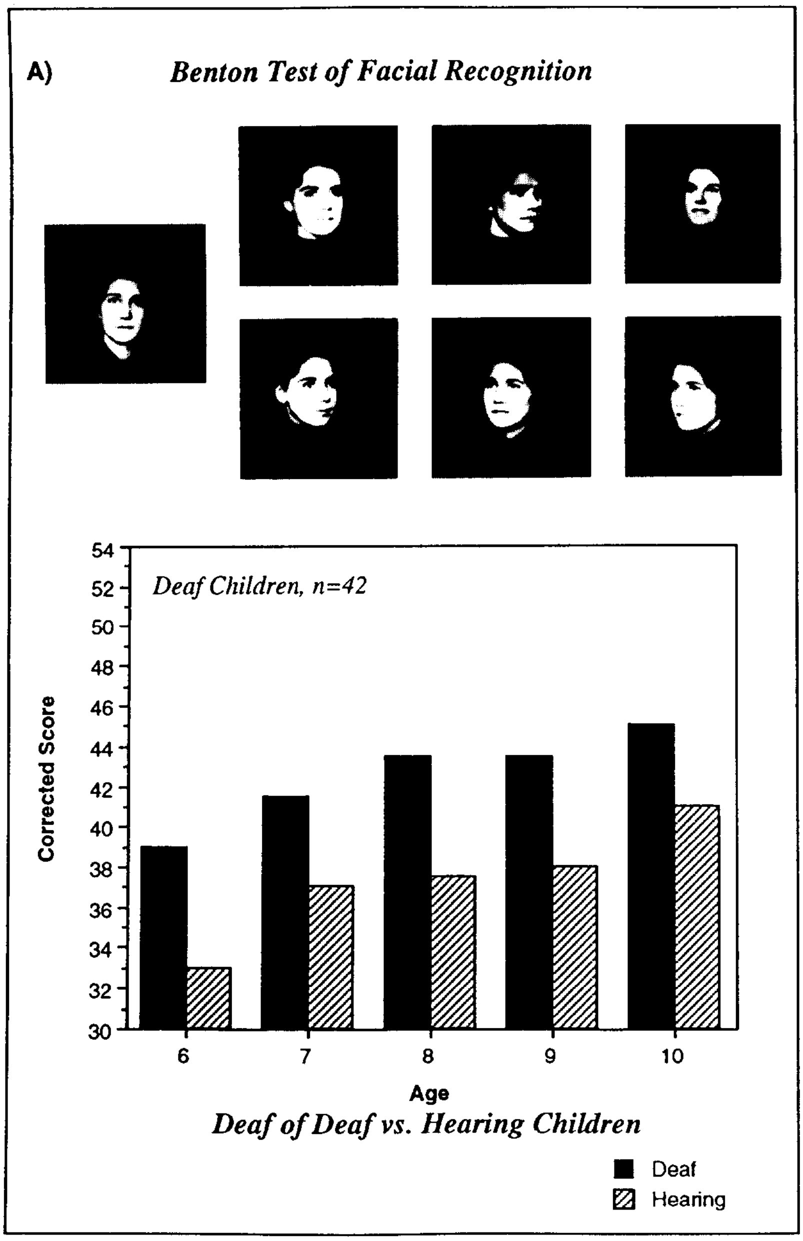

Figure 2a. *Deaf signing children show an enhanced ability to discriminate faces.*

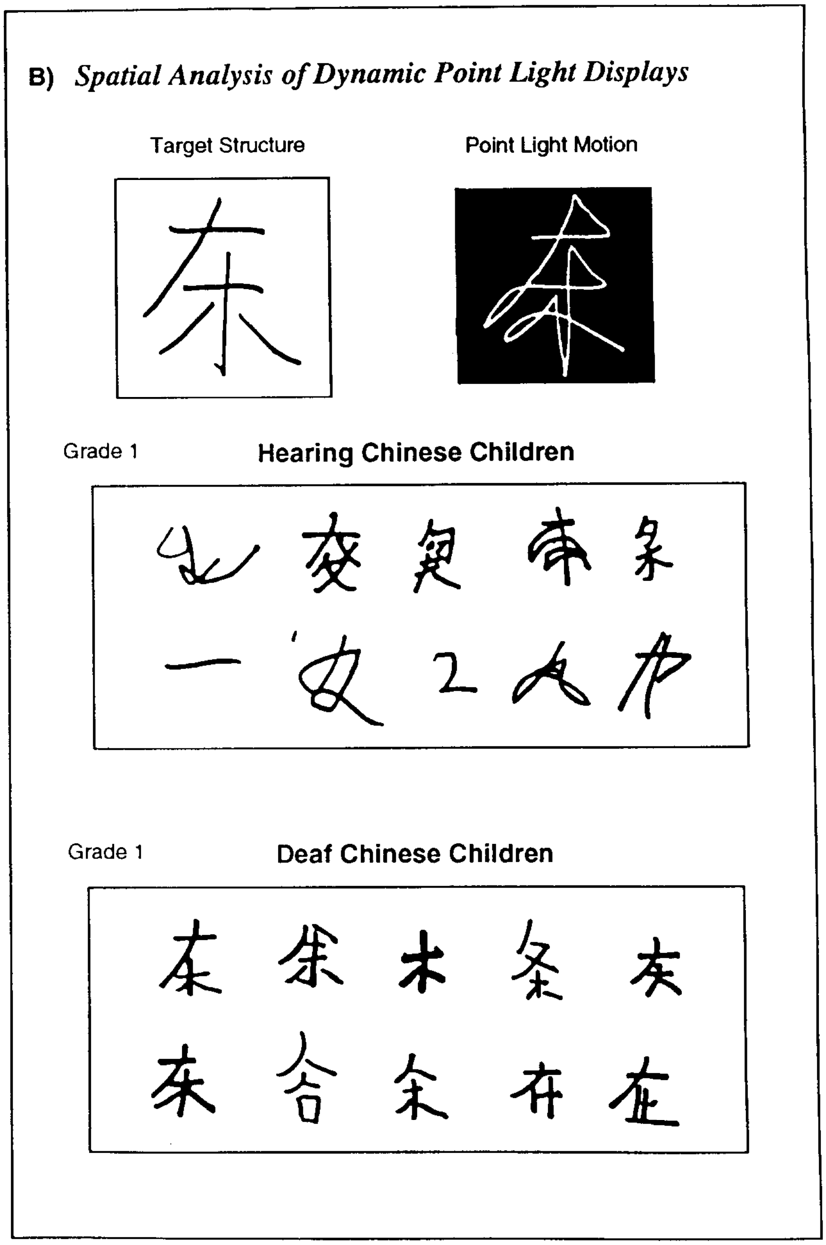

Figure 2b. *Deaf signers show an enhanced ability to analyze dynamic point light displays. Note the contrast between deaf and hearing first grade children.*

a group of subjects who are hearing and were born to deaf parents. These "hearing-of-deaf" (HD) subjects learned ASL as their first language and continue to use ASL in their daily lives. If the HD signers have abilities like those found for the deaf signers, this would suggest that differences in visual imagery arise from the use of a visual language. On the other hand, if HD signers have abilities like those found for the hearing subjects, this would suggest that differences in imagery may be due to auditory deprivation from birth, and it would be difficult to claim that using ASL *per se* affects imagery.

In addition, it is important to note that the deaf population in the United States is not linguistically homogeneous. Although most deaf people use ASL as their primary language, only a small percentage are actually native signers. Native signers are deaf people who have deaf parents; these people acquired sign language starting from infancy in a parallel manner to hearing children acquiring a spoken language (Bellugi, 1988; Newport & Meier, 1985). However, only about 3–8% of deaf people have deaf parents, and thus the majority were born into families who did not sign and had no language exposure in infancy and early childhood (Brown, 1986; Schein & Delk, 1974). Deaf individuals with hearing parents typically learn ASL when they enter a residential school and become immersed in the language, using it to converse with other deaf children and adults. In the experiments reported here, we compare native deaf signers to "non-native" deaf signers, who acquired ASL later in childhood. This comparison will allow us to determine whether any observed differences in visual imagery might depend upon very early exposure to sign language.

GENERAL METHOD

Subjects

Forty deaf signers (mean age = 27 years) and 34 hearing non-signers (mean age = 23 years) volunteered to participate as subjects. Nineteen of the deaf were native signers of ASL (9 male, 10 female) and 21 were non-native signers (10 male, 11 female). The non-native signers learned ASL between age 2 and 16 (the mean age of sign acquisition was 8 years), and had been signing for an average of 20 years. The non-native signers were further divided into two groups: "early" signers ($N = 14$) who learned ASL between ages 2 and 8 (mean = 4.9 years), and "late" signers ($N = 7$) who learned ASL between ages 12 and 16 (mean = 14.5 years). Thirty-four of the 40 deaf signers were deaf from birth, 5 were prelingually deaf (before age 2), and one became deaf at age 4. Deaf subjects had an average hearing loss of 95 dB in the better ear; a loss of 90 dB or more indicates profound deafness, and even shouted speech cannot be heard (American National Standards Institute, 1969). ASL was the preferred means of communication for all deaf signers. Almost all subjects in both groups were right handed, as determined by self report (35 in the deaf group and 32 in the hearing group).[1] The deaf subjects were tested either at The Salk Institute or Gallaudet University. The hearing subjects (6 male, 28 female) participated as part of a class project and were tested at San Diego State University. According to self report, the hearing subjects had no experience with a signed language and had normal hearing. All subjects were volunteers, and all were either paid for their participation or received course credit.

We also included a group of 10 hearing subjects who have deaf parents (HD signers). These subjects were matched as closely as possible with 10 deaf and 10 hearing subjects for age, education, handedness, and gender. However, although we were able to match the ages of the HD group (mean age = 33 years) and the 10 deaf signers (mean age = 32.8 years), the HD group tended to be older than the 10 matched hearing subjects (mean age = 25.4 years). All of the HD signers learned ASL as their first language, although they were also bilingual in English. All of the HD signers continue to use ASL in their daily lives either as interpreters for the deaf or through daily contact with their deaf family and friends.

Most subjects were able to participate in all tasks, but in some cases a subject only participated in part of the study or was excluded from a task because of a computer error. For example, several subjects did not perform the image generation task because of time constraints (the full testing session required over 2 hours). Thus, we report the number of subjects who participated in each of the tasks. The 10 HD signers participated in all tasks, as did the matched comparison samples of deaf and hearing subjects.

General method and procedure

The tasks we used have been shown previously to tap different subcomponents of mental imagery in hearing subjects (Kosslyn, Cave, Provost, & Von Gierke, 1988; Kosslyn & Dror, 1992; Kosslyn, Margolis, Barrett, Goldknopf, & Daly, 1990). These tasks not only allow us to assess specific imagery processes, but they also allow us to tease apart differences in perceptual ability and true differences in imagery ability. All tasks were presented using a Macintosh computer with MacLab software (Costin, 1988), and all subjects received the tasks in the same

[1]All statistical analyses were also conducted using only the right-handed subjects; the results from these analyses did not differ from the results reported here.

order: practice with making yes/no responses, shape memory task, image maintenance (short delay and then long delay), perceptual baseline, image generation, and mental rotation. We present these tasks in the following three sections: image generation, image maintenance, and mental rotation.

The practice yes/no task required subjects simply to push a key marked "Y" or "N" on the keyboard in response to the words "yes" and "no", which appeared in the center of the screen. Each word appeared 16 times, in a random order. This short task familiarized subjects with the computer response keys (b and n) that would be used for all tasks. The response hand (left/right) and response key (whether the b key was yes or no) were constant for all tasks, and were counterbalanced across subjects.

For each task, feedback about accuracy was given only for the practice trials; a wrong response was signaled auditorily for hearing subjects and visually for deaf and HD signers. Each task was preceded by 12 practice trials, unless otherwise noted below. The instructions were given in ASL or English, whichever was the preferred language of the subject group. For all tasks, the subjects were asked to respond as quickly as possible while remaining as accurate as possible.

Finally, the trials were presented in a pseudo-random order, with the constraint that no more than three consecutive trials could have the same response or value on any of the independent variables (e.g., no more than three trials in a row could have stimuli at the greatest level of complexity, the least amount of tilt, and so on). In addition, the same stimulus could not appear twice within four consecutive trials. Each task except rotation was presented twice: once with stimuli in grids and once with stimuli in brackets; each set of stimuli was presented in a separate block of trials, and the blocks were counterbalanced such that an equal number of subjects from each group received the grids first or the brackets first. Detailed descriptions of the remaining aspects of the method and procedure are provided within each section below.

IMAGE GENERATION

When one creates a visual mental image, a common introspection is that the object appears as a whole and all at once. In fact, however, the results from several studies have shown that this is a misconception: visual mental images are constructed serially from parts (e.g, Kosslyn et al., 1988; Roth & Kosslyn, 1988). For example, Kosslyn et al. (1988) modified a task developed by Podgorny and Shepard (1978) so that they could measure the relative time to form images. Subjects first memorized upper-case block letters that were formed by blackening sets of cells in 4×5 grids, and then were shown a series of grids that contained only two X marks. A lower-case letter was beneath each of these grids, and the subjects were asked to decide as quickly as possible whether the corresponding upper-case block letter would cover both of the X marks if it were in the grid. The crucial aspect of the experiment was that the two probe marks appeared in the grid only 500 ms after the lower-case cue letter was presented. This was enough time for subjects to read the cue letter and move their eyes up to the grid, but was not enough time for the subjects to complete forming the image. Thus, the response times reflected in part the time to generate the image.

Kosslyn et al. (1988) found that subjects required more time to image shapes that were composed of more segments in the grid, such as "J" or "G" compared to "L" or "C". In addition, by varying the locations of the probe X marks, Kosslyn et al. discovered that subjects imaged segments in the same order in which they are drawn. This inference was based on the finding that subjects required more time to evaluate probes that were located on segments that are drawn later in the sequence. This result only occurred when the probe marks were presented before subjects could finish forming the image; if the subjects were allowed to form the image first, and then the probes were presented, the location of the probe marks did not affect response times. Thus, the effect of probe location appears to tap the processes that build up the image a segment at a time, and not processes that scan over or evaluate the image pattern.

To investigate the relative skills of deaf and hearing subjects in generating visual images, we utilized a task similar to that devised by Kosslyn et al. (1988); we modified this task so that only one X mark appeared, and again varied the complexity of the letters and the location of the probe marks. This task allows us to assess the ease with which one activates stored visual information and adds segments to an image, and hence to compare the ability to generate images *per se* by examining the effects of complexity and probe location in the three groups. By comparing the relative effects of complexity and probe location on response times and errors, we eliminate the contribution of processes that encode the cue, encode of the probe mark, make an on/off decision, and generate a response; all of these processes are held constant across the different levels of complexity and probe location (for further discussion of the logic, see Kosslyn et al., 1990).

We hypothesized that ASL signers would be better at generating images than non-signers because the production of certain constructions in ASL may require one to form detailed mental images. Specifically, the topographic classifier system of ASL must be used to describe spatial locations of objects and people in real-world or imagined space. Unlike English, ASL requires spatial relations to be encoded linguistically and specified explicitly when describing the layout of a scene. For example, within the classifier system of ASL, it is impossible to sign "The bed is on the right and the chair on the left" without also specifying the orientation and location of the bed and chair as well as their relationship to each other. Spatial information is layered within a sign and produced simultaneously (see Supalla, 1986 and in press, for a more detailed description). When a signer describes a scene, the language appears to require him or her to create a more detailed mental image compared to an English speaker. English does not demand the same kind of explicit spatial information to describe a similar scene; indeed, to be as explicit, several adjunct phrases must be added within each sentence.

Note that spoken languages differ in which aspects of space must be encoded obligatorily (see Choi & Bowerman, 1991; Jackendoff & Landau, 1991). For example, some languages require certain aspects of the geometry of paths to be encoded in the verb, and some languages have obligatory morphemes which encode size or shape properties of objects. What is unique about ASL is that space itself is used to mark spatial relationships. Thus, not only does ASL have a very rich linguistic system for marking spatial relations, but these relations are directly encoded in space. We argue that what is crucial is the interaction between what has to be encoded from the referent (when it is in fact spatial) and how it is encoded in ASL. The richness of the linguistic system and the spatial encoding may engender more explicit and possibly more frequent mental image generation.

In addition, Liddell (1990) argues that under certain conditions signers may imagine referents as physically present, and these visualized referents can be relevant to the expression of verb agreement morphology. Liddell gives the following example involving the verb ASK (in this case, articulated toward the head):

> To direct the verb ASK toward an imagined referent, the signer must conceive of the location of the imaginary referent's head. For example, if the signer and addressee were to imagine that Wilt Chamberlain was standing beside them ready to give them advice on playing basketball, the sign ASK would be directed upward toward the imaged height of Wilt Chamberlain's head . . . This is exactly the way agreement works when a referent is present. Naturally, if the referent is imagined as laying down, standing on a chair, etc., the height and direction of the agreement verb reflects this. Since the signer must conceptualize the location of body parts of the referent imagined to be present, there is a sense in which an invisible body is present. The signer must conceptualize such a body in order to properly direct agreement verbs. (Liddell, 1990, p. 184)

If deaf subjects are in fact generating visual images prior to or during sign production, then the speed of forming these images would be important, and we expect signers to develop enhanced abilities to generate images. Of course, all ASL discourse does not involve descriptions of spatial scenes or imagined referents; thus, the influence of this aspect of ASL syntax may not be strong enough to enhance deaf signers' ability to generate visual images outside a linguistic context. The present experiment allows us to investigate this issue.

Finally, we also administered a perceptual task in order to ensure that differences in the imagery task reflect imagery *per se*. The perceptual baseline task was analogous to the imagery task. In this case, a gray shape remained in the grid when the X mark appeared, and the subjects merely indicated whether the X was on or off the shape.

Method

Subjects

Twenty-four deaf signers (12 native, 12 non-native) and 28 hearing subjects participated in this experiment. Ten HD signers (matched with 10 deaf signers and 10 hearing subjects) also participated.

Imagery condition materials

A set of 4×5 grids was drawn, and upper-case letters were formed within them by blackening specific cells. Ten letters were used, five of which (L, C, U, F, H) contained three or fewer segments in the grid (the simple letters), and five of which (P, J, O, S, G) contained four or more segments (the complex letters). The letters L and O were used only for the practice trials in the testing session. All stimuli were memorized by the subjects prior to the testing session proper.

A second set of stimuli was created. Each stimulus consisted of a 4×5 grid that was empty except for a single X mark. The X mark was created by connecting the corners of a cell with diagonal lines. Two "yes" and two "no" trials were created for each letter. For "yes" trials, the probe X mark was placed in a cell that would have been occupied by the first or second segment of the upper-case letter (an "early" trial), or the X mark appeared in a cell that would be occupied by the last or penultimate segment (a "late" trial); for "no" trials, the probe mark was placed in a cell that was adjacent to one that would be occupied by a letter segment. The procedure used to determine which letter segments are imaged early and which are imaged late is described in Kosslyn et al. (1988).[2] The corresponding lower-case letter appeared immediately prior to these grids.

Each stimulus was then modified so that the grid lines were removed and only the four corners of the grid remained visible, as is illustrated in Figure 3. Thus, we created a new set of 10 upper-case letters for the initial training session, and a new set of test stimuli. We created this second set of "brackets" materials because previous research (Kosslyn et al., 1988) has shown that the left cerebral hemisphere of right-handed normal subjects is better able to form images when the grid lines are intact, whereas the right hemisphere is better able to form images when the grid lines are removed. Although we did not lateralize stimuli in the present experiments, if we find differences between deaf and hearing subjects for the two types of stimuli this might provide an important hint about underlying differences in processing.

[2]In previous articles, probe locations were referred to as "near" or "far". We have changed these labels to "early" and "late" to describe the sequence of events during image generation more accurately.

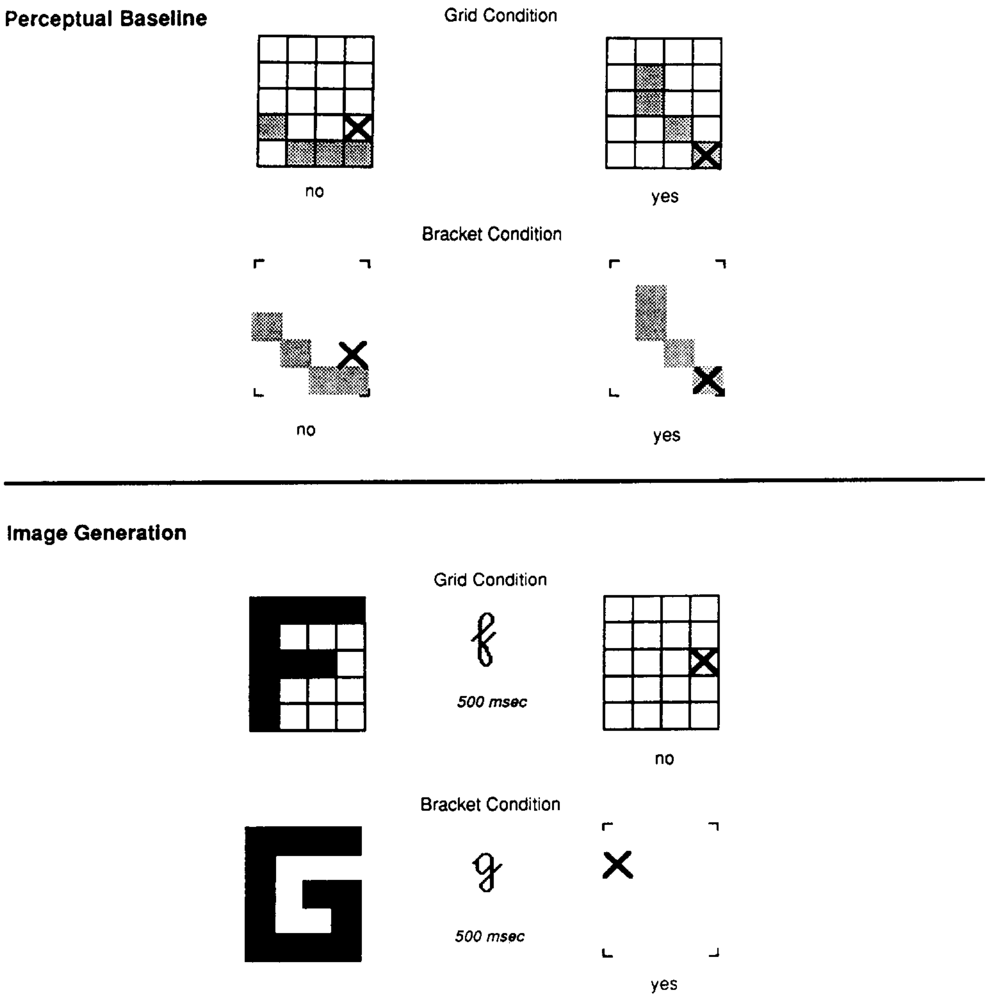

Figure 3. *Examples of stimuli from the perceptual baseline and image generation tasks. The top panel illustrates grids and brackets stimuli as they appeared in the baseline task and the bottom panel illustrates image generation stimuli; subjects became familiar with the block letters prior to the task. The lower-case letters served as cues to image generation.*

A total of 64 stimuli were prepared (half within a 4×5 grid and half within brackets).

Image generation procedure

Subjects began by memorizing the appearance of the upper-case letters and the correspondence between them and their script lower-case letters. Subjects were asked to study the upper-case letters, and then were given a blank page with a grid or set of corner brackets (depending on the block of trials.) A lower-case script letter was presented in the center of the computer screen, and subjects were asked to draw the corresponding upper-case letter in the empty grids or brackets. If the subject made an error, he or she was given the upper-case letter and asked to study it again. This procedure was repeated until the subjects could draw each letter correctly from memory.

Following this initial training session, the subjects were given 8 practice trials and then the test trials. Subjects were first presented with a lower-case script cue letter (center screen) for 500 ms, followed by a blank screen for 500 ms. A grid (or set of corner brackets) containing a probe X then appeared. The subjects were to decide whether the corresponding upper-case letter would cover the X if it were present in the grid or brackets. After each response, the subject pressed the space bar to initiate the next trial.

Perceptual baseline condition materials

The materials used in the perceptual task were identical to those used in the maintenance task (see below), except that the empty grids were now modified so that the pattern appeared in light gray. The probe X appeared either superimposed on the gray shape or off to one side (see Figure 3). A total of 96 stimuli were presented (half within a 4×5 grid and half within brackets).

Perceptual baseline condition procedure

The subject's task was simply to decide whether the X appeared on or off the pattern. This task also was used as a baseline for the image maintenance task described below. All other aspects of the procedure were the same as in the imagery condition.

Results

Separate analyses of variance (ANOVAs) were conducted for response times and error rates. Subject group, gender, stimulus type (grid/brackets), complexity, and probe location were treated as independent variables. Within the deaf group we also compared native signers and non-native signers (and divided this last group into early and late signers). For all analyses reported in this article, outliers were removed prior to the ANOVA. An outlier was defined as a response time that was two standard deviations from the mean in a given cell for a given subject. This procedure eliminated less than 5% of the data. All effects and interactions not mentioned here or in subsequent Results sections were not significant ($p > .05$ in all cases). In some cases, however, we will report non-significant results if they are of particular theoretical interest.

There was no effect of, or interaction with, gender and age of sign acquisition (native vs. non-native (or early and late) signers), and therefore these variables were not included in the analyses reported below.

Image generation response times

As is illustrated in Figure 4, deaf signers were able to generate images of complex letters faster than hearing (but non-signing) subjects, but the deaf and hearing groups required roughly equal time to generate images of simple letters, $F(1, 50) = 4.14$, $p < .05$, for the interaction of group and complexity. This finding suggests that the deaf signers were able to form images more quickly than the hearing subjects. For both groups, response times increased for "late-imaged" probes relative to "early-imaged" ones, $F(1, 50) = 66.58$, $p < .001$, which indi-

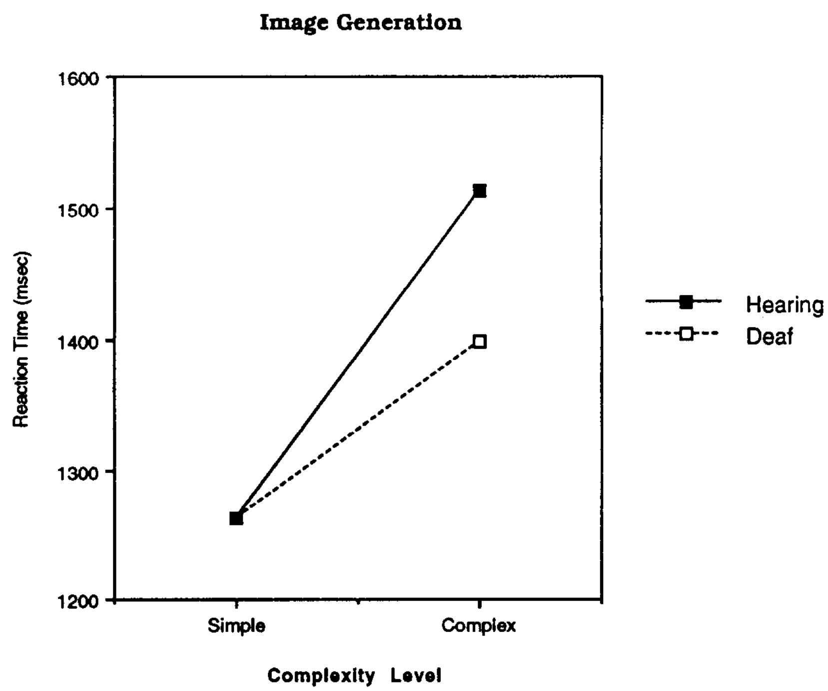

Figure 4. *Mean response times for deaf and hearing subjects for simple and complex stimuli. Deaf signers show an enhanced ability to generate complex images.*

cates that subjects were constructing images of letters a segment at a time (see Kosslyn et al., 1988). If deaf signers add segments to the image more quickly than hearing subjects, then there should be a smaller effect of probe location for the deaf signers. As is evident in Figure 5, there may be a trend for deaf subjects to show a smaller difference between early and late-imaged probes compared to hearing subjects, but the interaction between subject group and probe location did not approach significance, $F(1, 50) = 2.37$, $p > .1$.

As expected, "late " probes required relatively more time to evaluate for the complex letters than for the simple letters, $F(1, 50) = 8.43$, $p < .001$; this makes sense because more segments had to be imaged before reaching the "late" probes on the complex letters than had to be imaged before reaching the "late" probes on the simple letters. We did not find an overall difference between the groups, and found no differences for the two types of stimuli (grids/brackets), $p > .2$ in all cases.

Image generation error rates

The error rates were analyzed using an ANOVA with the same independent variables. Error rates were greater for complex compared to simple letters,

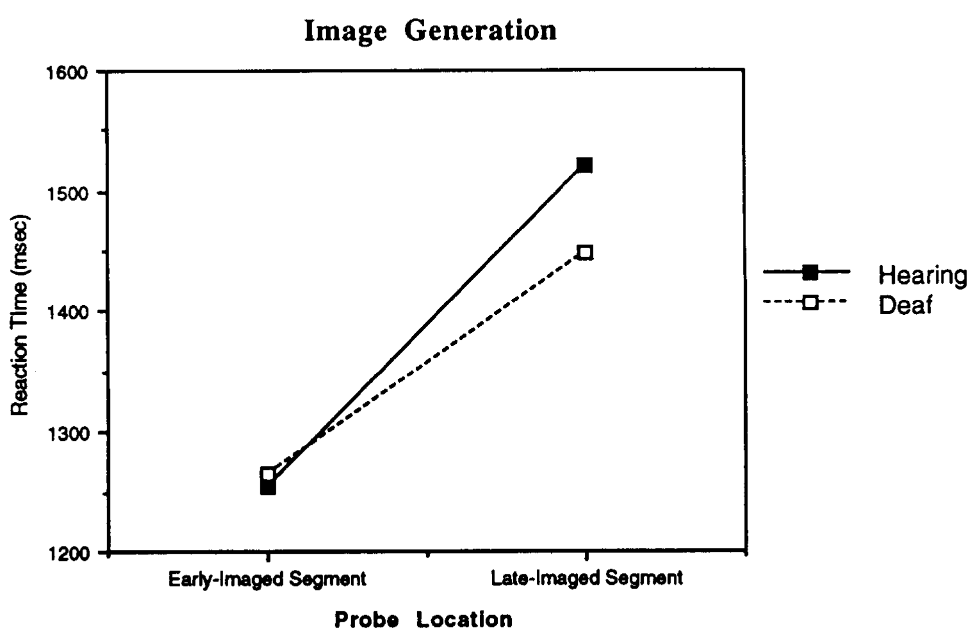

Figure 5. *Mean response times for deaf and hearing subjects for probes located on early-versus late-imaged segments.*

$F(1, 50) = 34.17$, $p < .001$, and this was true for both groups, $F < 1$ for the interaction of subject group and complexity. Thus, our response time results cannot be ascribed to a speed–accuracy trade-off. Subjects also made more errors for the late-imaged probes (mean = 9.8%) than for the early-imaged ones (mean = 3.5%), $F(1, 50) = 52.12$, $p < .001$, and subjects made relatively more errors on late probes for the more complex letters, $F(1, 50) = 14.75$, $p < .001$, for the interaction of location and complexity. Unlike the response time data, the effect of probe location was amplified for the brackets stimuli (with a difference of 8.2% between early and late-imaged probes) compared to the grid stimuli (with a difference of 4.5%), $F(1, 50) = 6.80$, $p < .01$ for the interaction of probe type and probe location. This difference was the same for both groups, $F < 1$, for the interaction of group, stimulus type, and probe location.

Hearing-of-deaf comparison for image generation

As is evident in Figure 6, the HD signers performed like the deaf signers. HD signers and hearing non-signers required about the same amount of time to image the simple stimuli, but the HD signers (like the deaf signers) required less time to image the complex stimuli, $F(1, 18) = 6.58$, $p < .05$, for the interaction between

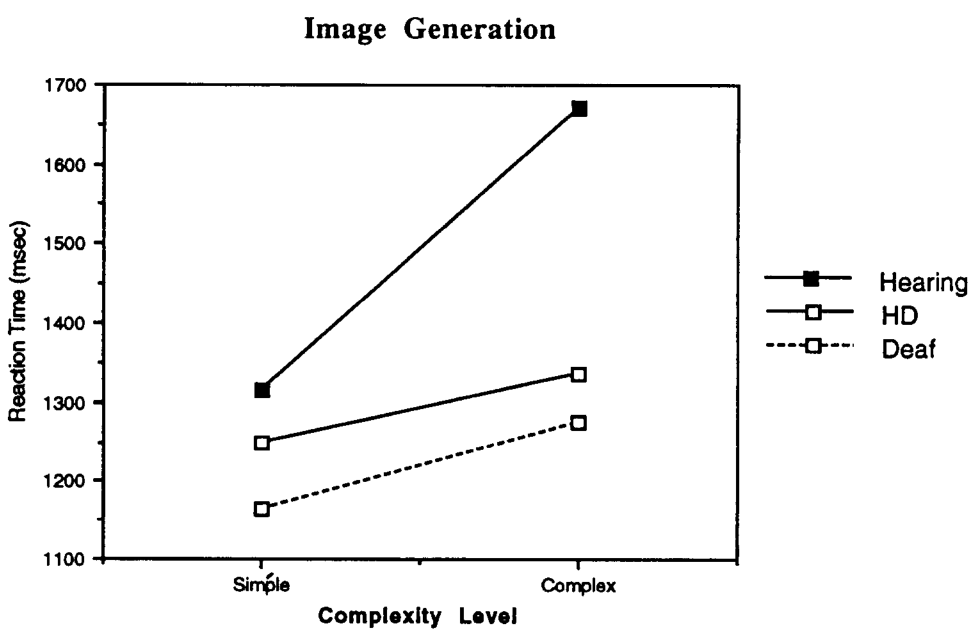

Figure 6. *Mean response times for deaf, hearing, and HD signers for simple and complex stimuli. Deaf and HD signers show an enhanced ability to generate complex images.*

complexity and group. HD signers and hearing subjects did not differ in error rate, $F < 1$, and thus the difference in response time cannot be due to a speed–accuracy trade-off. The HD signers did not differ significantly from deaf signers in any comparison.

Perceptual baseline condition response times and error rates

As illustrated in Figure 7, deaf signers and hearing non-signers did not differ significantly in their performance in the perceptual task. No group differences were observed for either response times or error rates. However, subjects in both groups evaluated the brackets stimuli more quickly than the grids stimuli, $F(1, 50) = 11.38$, $p < .002$; this difference may be due to a speed–accuracy trade-off, given that both groups were more accurate in the grid condition, $F(1, 50) = 5.44$, $p < .05$. In addition, there were no effects of, or interactions with, complexity or probe location for either response times or error rates. These results mirror those of Kosslyn et al. (1988), and provide additional evidence that the imagery task in fact taps image generation, and not processes that underlie our ability to inspect or scan patterns. The performance of the HD signers did not differ from either the deaf signers or hearing subjects in any comparison.

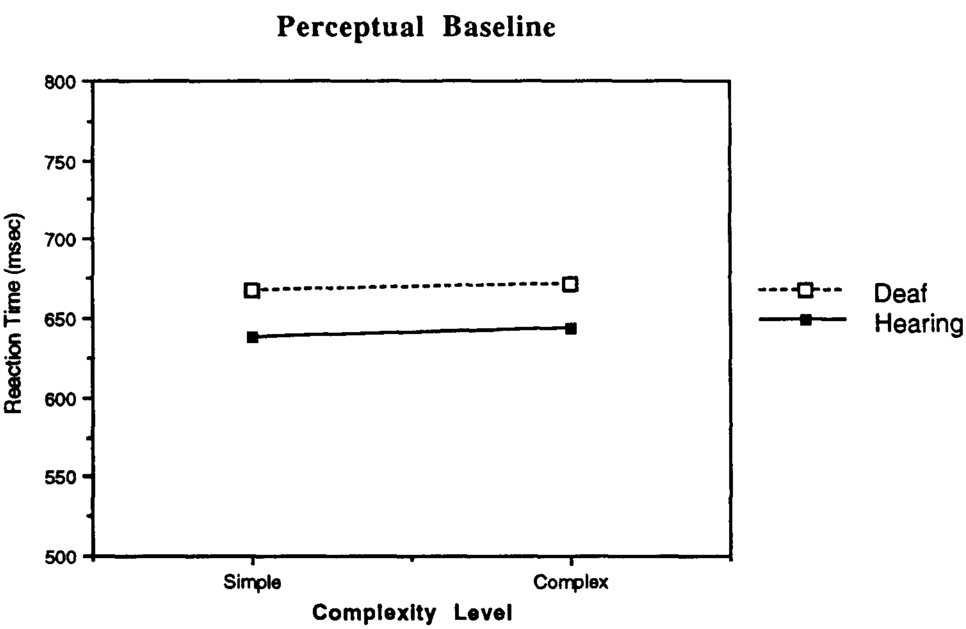

Figure 7. *Mean response times for deaf and hearing subjects on the perceptual baseline tasks.*

Discussion

The finding that both deaf and HD signers form relatively complex images faster than non-signers suggests that experience with ASL may affect image generation ability. The results from the perceptual task indicate that this difference in performance was due to a difference in image generation ability, rather than to differences in scanning or inspection; signers and non-signers did not differ in their ability to evaluate probe marks when the shape was physically present. The signing and non-signing subjects were equally accurate, which suggests that although signers create complex images faster than non-signers, they generate equally good images. The fact that the HD signers performed like the deaf signers shows that the enhancement of image generation is not a consequence of auditory deprivation. Rather, it appears to be due to experience with a visual language.

Deaf and hearing subjects appear to image letters in the same way; both groups of subjects required more time and made more errors for probes located on late-imaged segments, and these effects were of comparable magnitude in the two groups. This finding indicates that neither group of subjects generated images of letters as complete wholes, and both groups imaged segments in the same order. The error rates indicated that the effect of probe position was less pronounced with the grid stimuli than with the bracket stimuli. It is possible that the grid lines helped the subjects to locate the probe X in relation to the imaged letter, particularly for late-imaged segments.

One might want to argue that our findings are an artifact of hearing subjects having more experience with letters. However, there is little reason to expect that deaf, hearing, and HD subjects have different amounts of practice with written letters. In particular, there is no reason to expect that hearing people who have deaf parents (HD signers) have more experience with written letters than hearing people who do not sign. And yet one would have to make this assumption in order to explain our results in terms of experience with written letters. In any event, we wanted to make sure that our results could not be explained by differences in familiarity with letters, and so we compared the number of errors that each subject group made when copying the letter stimuli from memory during training. For example, errors occurred when subjects omitted the "hook" segment on the lower part of the "J" or extended the lower horizontal segment of the "F" such that it was the same length as the top segment. There were no group differences in the number of copying errors: 37% of the deaf subjects made one or more copying errors, 36% of hearing subjects made one or more errors, and 20% of the HD signers made a copying error.

In short, we found that deaf signers are relatively good at creating complex mental images. We expected such a result if certain aspects of ASL structure require mental imagery, and the fact that HD and deaf signers produced similar results supports this conjecture. It appears that using a visual language facilitates one's ability to form visual mental images. We hypothesize that the initiation or "loading" phase of image generation is enhanced for ASL signers, but cannot rule out the possibility that the process which adds components to create an image is also enhanced for ASL signers.

IMAGE MAINTENANCE

In this experiment, we investigated the ability of deaf and hearing subjects to maintain an image in short-term memory. We have reason to hypothesize that deaf signers may show improved visual short-term memory compared to hearing subjects. As mentioned in the Introduction, nominals in ASL are associated with specific spatial loci in signing space. Signers refer to these loci throughout the discourse, and therefore the association between nominals and their spatial loci must be maintained in memory over stretches of discourse. These linguistic memory requirements may enhance non-linguistic visual short-term memory.

However, deaf signers also encode much more information visually compared to hearing subjects, who can utilize both auditory and visual memory stores. If we find a difference in performance between these groups, it could be because of the general reliance on visual memory by deaf signers, in contrast to hearing subjects. By examining the performance of the HD signers, we can tease apart whether any observed differences are due to linguistic influences or to an enhanced visual memory caused by auditory deprivation.

In this task, the subjects first studied a pattern within a grid or within four corner brackets. After they memorized the pattern, it was removed and an X probe appeared within the empty grid or brackets. The subjects indicated whether the X would have fallen on the pattern, were it still present. Thus, the subjects did not need to retrieve information from long-term memory or generate the image; they simply needed to retain an image of the pattern in visual short-term memory. Similarly, ASL signers may retain visual information about linguistic spatial loci in short-term memory. This ability is not completely analogous to the non-linguistic image maintenance task presented here between the linguistic "image" may be somewhat more abstract and may also be transferred to long-term memory at some point during discourse. However, the task we used provides a measure of the initial stage in which a visual image must be maintained, and it also provides a strong test concerning the degree of overlap between linguistic and non-linguistic visual processing that is necessary to affect non-linguistic visual abilities.

In this experiment, we not only varied the complexity of the to-be-retained pattern, but also varied the time that the subject had to retain the image; the probe appeared a short (500 ms) or long (2500 ms) time after the pattern was removed. Hence, we were able to examine two aspects of image maintenance capacity: the effects of decay over time and the effects of the amount of material to be retained.

Finally, we also presented subjects with a memory task that required them to evaluate the shape of a pattern. Subjects studied one pattern, it was removed, and shortly thereafter another pattern appeared. The subjects decided whether the second pattern was the same as the first. This task will allow us to determine whether the subjects differed in their ability to store the patterns *per se*.

Method

Subjects

Thirty deaf signers (14 native and 16 non-native signers) and 30 hearing subjects participated in the maintenance and shape memory tasks. Again, the same 10 HD signers participated.

Maintenance task materials

As illustrated in Figure 9, nonsense patterns were created by blackening contiguous cells in 4 × 5 grids. The patterns had 1, 2, or 3 perceptual units; a perceptual unit was defined using the Gestalt laws of good continuation and symmetry. A 1-unit pattern was a vertical or horizontal bar, which varied in length and position; 2- and 3-unit patterns were composed of distinct clumps of filled cells, with two clumps touching at a single corner point. The patterns were created so that each cell of the grid was filled approximately equally often at each level of complexity. Each pattern was paired with an empty grid, and a single X mark was placed in the empty grid. For half the grids at each level of complexity, the X mark would have fallen on the pattern were it present ("yes" trials); for the other half, it would have fallen in a cell adjacent to a filled cell ("no" trials). A total of 48 grid stimuli were prepared. A second set of 48 stimuli was created by eliminating the grid lines, leaving only the four corner brackets (as was done in the image generation task).

Maintenance task procedure

The subjects were asked to study each stimulus, and the computer recorded the time they spent memorizing the stimuli. When the pattern had been memorized, subjects pressed the space bar, and the pattern plus the grid (or set of brackets) disappeared. In one set of trials, a probe mark appeared in an empty grid (or brackets) after 500 ms; in the other set, the probe appeared after 2500 ms. The subjects decided as quickly as possible whether the X probe would have been covered by the previous pattern, were it still visible. After each response, the subjects pressed the space bar to initiate another trial. A total of 192 trials were presented in four blocks: two with the short delay and two with the long delay; and one of each of these within grids and one within brackets.

Shape memory task materials

The shapes used in the maintenance task were also used here. However, instead of being paired with an X probe mark, each pattern was paired with a second pattern. For half of the stimuli at each level of complexity, the same pattern was used twice; these were "same" trials. For the other half, the value of one cell was altered; for half of these, a filled cell was unfilled, and vice versa for the other half. These were the "different" trials.

Shape memory task procedure

The subjects were first presented with a pattern, which they were to memorize. When ready, they pressed the space bar and another pattern was presented after a 1 s delay. The subjects decided as quickly as possible whether the second pattern was the same as the first. A total of 96 stimuli were presented, half in the grid condition and half in the bracket condition.

Results

Separate ANOVAs were conducted for response times and error rates. Subject group, gender, stimulus type (grid/bracket), delay (500/2500 ms), and memory load (1, 2, or 3 units) were treated as independent variables. Native and non-native signers (either as a group or divided into early and late signers) were also compared for the deaf group. In all other respects, the data were analyzed as in the image generation task. We found no main effect of, or interaction with, gender or age of sign acquisition; therefore, the data were collapsed across these variables.

Image maintenance memorization times

Deaf signers took less time to memorize the patterns than hearing subjects, $F(1, 58) = 6.48$, $p < .05$ (with means of 997 ms vs. 1388 ms). Both groups took longer to memorize more complex patterns, $F(2, 116) = 29.34$, $p < .001$, and longer to memorize stimuli in the long delay condition, $F(1, 58) = 11.10$, $p < .01$. Memorization times were not recorded for the shape memory task.

Image maintenance response times

In contrast to the results from the generation task, there were no effects or interactions that involved subject group in the maintenance task. As is illustrated in Figure 8, deaf and hearing subjects had very similar response times. We inferred that results from the generation task reflect the time to activate information in long-term memory prior to producing a response; in this task, information presumably was not stored in long-term memory. The failure to find such effects was not due to a lack of power. Subjects required more time when they had to hold the image longer, $F(1, 58) = 63.02$, $p < .001$, and more time for more complex patterns, $F(2, 116) = 68.22$, $p < .001$. As is illustrated in Figure 9, the effect of complexity was greater for the long delay, $F(2, 116) = 6.24$, $p < .01$, for the interaction between delay and complexity.

In addition, increasing the retention interval affected the different stimuli in different ways, $F(1, 58) = 12.77$, $p < .001$, for the interaction between delay and

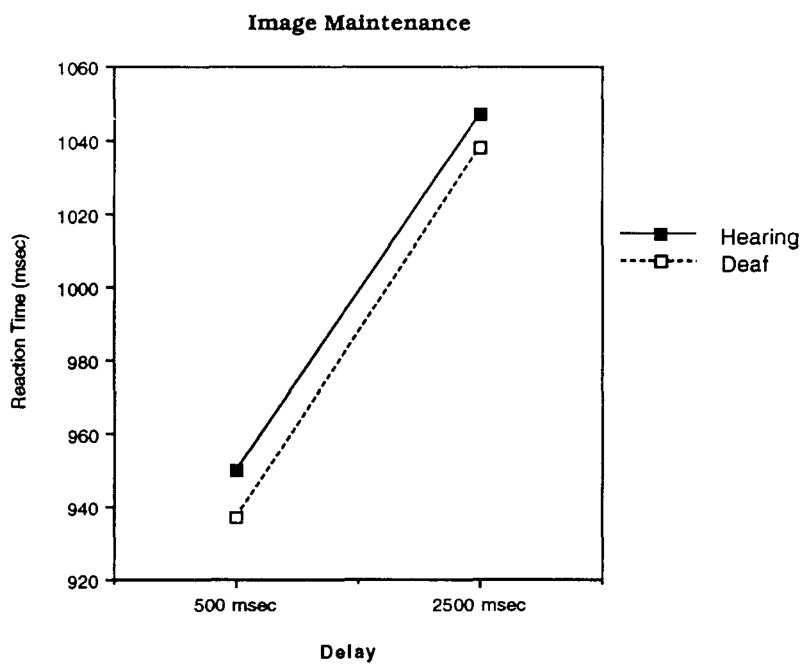

Figure 8. *Mean response times for deaf and hearing subjects in the image maintenance task.*

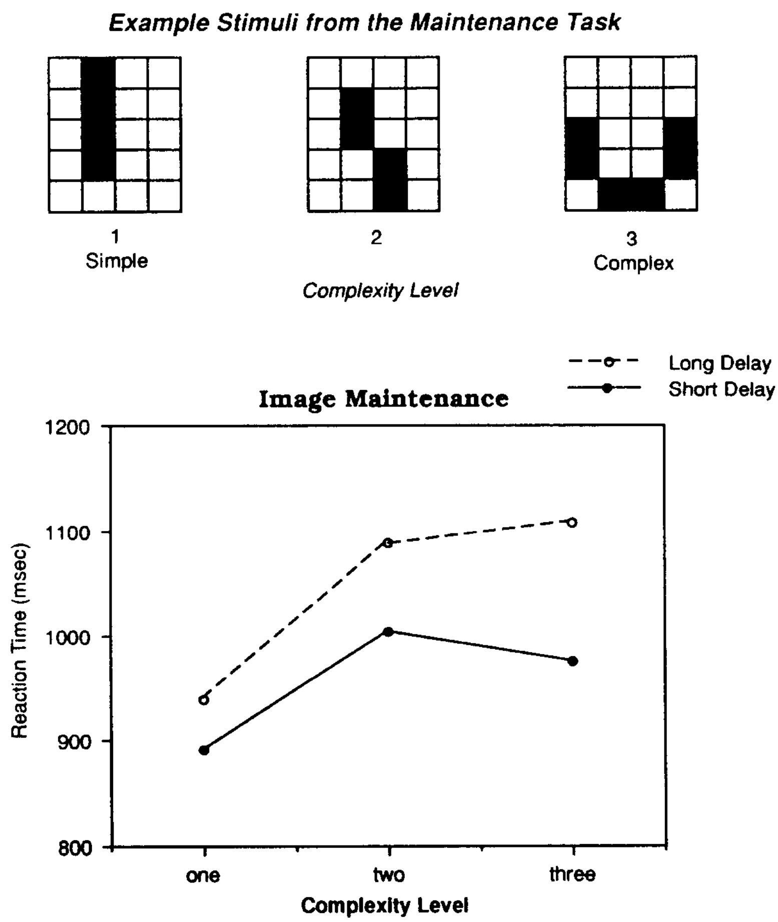

Figure 9. *Illustration of the interaction between presentation delay and stimulus complexity.*

stimulus type. Specifically, for the short delay, the subjects were faster for grid stimuli than brackets stimuli, $F(1, 58) = 4.72$, $p < .05$, for the appropriate contrast; this difference was not present for the long delay, $F < 1$. For the short delay, the internal grid lines appeared to aid both groups of subjects in retaining the image in memory.

Image maintenance error rates

The deaf made more errors than the hearing subjects, $F(1, 58) = 6.18$, $p < .02$ (10.0% and 6.2%, respectively); however, this finding may reflect nothing more than the fact that deaf signers took less time to memorize the patterns. There were no other differences between the subject groups. In addition, there was no difference between the two delays ($F < 1$), and subjects made more errors with the complex patterns, $F(2, 116) = 27.10$, $p < .001$. Finally, subjects made more errors with the bracket stimuli (8.9%) than with the grid stimuli (7.2%), $F(1, 58) = 7.28$, $p < .01$.

Shape memory response times and error rates

There were no differences between the groups in either response times or error rates in this task. Both response times, $F(2, 116) = 9.96$, $p < .001$, and error rates, $F(2, 116) = 7.09$, $p < .01$, increased for the more complex patterns. However, response times increased with complexity only for the grid stimuli, $F(2, 116) = 5.18$, $p < .01$, for the interaction of complexity and stimulus type. The mean response times for the grid stimuli were 821, 880, and 872 ms for 1-, 2-, and 3-unit patterns; for the bracket stimuli the means were 856, 879, and 858 ms for the same respective levels of complexity.

Hearing-of-deaf comparison for maintenance and shape memory tasks

In contrast to the results from the image generation task, in the maintenance and shape memory tasks the HD signers responded more like the hearing subjects than the deaf signers. In the maintenance task, the matched deaf signers required less time to memorize the stimuli than did the HD signers, $F(1, 18) = 4.81$, $p < .05$, and HD and matched hearing subjects did not differ significantly in their memorization times, $F(1, 18) = 1.91$, n.s. In addition, HD and hearing subjects had similar error rates in the maintenance task (4.6% and 5.8%, respectively), and deaf signers tended to have higher error rates (10.0%); however, the differences in error rate did not approach significance, $F(2, 27) = 2.03$, $p = .15$.

On the maintenance task, all subjects required more time to respond, $F(1, 27) = 25.11$, $p < .001$, and made more errors, $F(1, 27) = 7.05$, $p < .05$, in the long delay condition. Subjects also required more time, $F(2, 54) = 37.05$, $p < .001$, and made more errors, $F(2, 54) = 7.34$, $p < .01$, for the more complex patterns. On the shape memory task, subjects also required more time to respond, $F(2, 54) = 5.07$, $p < .01$, and made more errors, $F(2, 54) = 3.56$, $p < .05$, for complex patterns.

Discussion

Experience with a visual language does not enhance one's ability to *maintain* a pattern in a visual image in the task we examined. In fact, the deaf signers actually made more errors than the hearing subjects and HD signers; however, these greater error rates may have occurred because the deaf signers took less time to memorize the patterns. Deaf signers may have had undue confidence in their ability to perform the task, and therefore spent less time memorizing the patterns. Our findings suggest that although ASL requires information about spatial location to be retained in memory during discourse, this linguistic process does not transfer to a non-linguistic visual image. The overlap between short-term linguistic and non-linguistic visual image retention does not appear to be enough to influence non-linguistic visual short-term memory.

We must note, however, that we measured image retention over a relatively short time (0.5 s and 2.5 s). In ASL discourse, spatial loci must be maintained over much longer intervals. It is possible that we would have found a difference in image retention between deaf signers and hearing subjects if we examined spatial memory over longer periods of time. It is also possible that signers did not show enhancement for image maintenance because images of referential spatial loci may not be maintained as visual images but rather are transferred to a more abstract representation which is not located in visual short-term memory. Further research into ASL processing and non-linguistic visual memory in deaf and hearing signers should help to determine the relationship between memory for non-linguistic visual images and memory for linguistic structure that is visually and spatially coded.

Our results also indicate that auditory deprivation does not necessarily lead to enhanced visual memory. This result is consistent with other findings in the literature. For example, Mills (1985) asked deaf and hearing subjects to view a visual temporal pattern (a string of Xs, each appearing with a different duration), and after a 1 s delay to determine whether the timing of a second pattern was the same or different. There was no difference in the performance of the deaf and hearing subjects in this task. In addition, Tomlinson-Keasey and Smith-Winberry (1990) found that although deaf signers were significantly worse than hearing subjects on the WAIS-R digit span task, the two groups did equally well on a visual sequential memory task that required them to remember a sequence of colored lights (the Simon game). Therefore, it appears that deaf signers do not have enhanced short-term visual memory for information about spatial patterns, temporal patterns, or sequential order (at least for these types of tasks).

MENTAL ROTATION

Finally, we examined the ability of deaf and hearing subjects to mentally rotate imaged objects. We used a mental rotation task similar to the one devised by Shepard and Metzler (1971). They showed subjects pairs of forms created by juxtaposing cubes to form angular, multi-segment arms, and asked the subjects to decide whether the two forms were the same regardless of orientation. Response times in this task increased linearly with the angular disparity of the stimuli suggesting that subjects had "mentally rotated" one form to match the orientation of the other before making a comparison (Shepard & Metzler, 1971). Our task used two-dimensional analogs of the forms used by Shepard and Metzler.

Mental rotation is required when subjects must compare forms that may differ in subtle ways (Shepard & Cooper, 1982). The most common discrimination is between a form and its mirror reversal. It was of interest to use this discrimination in our study for another reason: ASL makes use of "mirror" or reversal transformations, and hence we hypothesized that deaf signers might be faster at making these judgments. For example, during sign comprehension, the perceiver (i.e., the addressee) must mentally reverse the spatial arrays created by the signer such that a spatial locus established on the right of the signer (and thus on the left of the addressee) is understood as on the right in the scene being described by the signer. The scene is normally understood from the signer's perspective, not the addressee's. This problem is not unlike that facing understanders of spoken languages who have to keep in mind the referent directions "left" and "right" with regard to the speaker. The crucial difference for ASL is that these and other spatial relations are encoded spatially by the signer. The spatial loci used by the signer to depict a scene (e.g., describing the position of objects and people) must therefore be understood as the reverse of what the addressee actually *observes* during discourse (assuming a face-to-face interaction).

For example, the top of Figure 10 (adapted from Corina, Bellugi, Kritchevsky, O'Grady-Batch, & Norman, 1990) shows a bird's-eye view of a typical signer/addressee relationship in a signed conversation. The signer is describing the layout of three objects in a room – a lamp is on the signer's left, a table and stool are to his or her right, and the table is behind the stool. This description reflects the signer's perspective. To understand the relationship between these objects with respect to the signer, the addressee must mentally transform the signer's perspective into his or her own (i.e., how the addressee would view the scene if he or she were the signer). If the addressee were to repeat the signer's statement (e.g., for clarification), the addressee would not copy the signer exactly (e.g., using the same spatial loci), but rather would reverse all of the spatial loci so that, for example, the lamp would be on the addressee's left (but the signer's right). Although the same "absolute" space is often used during discourse (i.e., the addressee uses the same space as the signer, pointing to the same loci that the signer established), in the narrative mode the scene is most often understood from the signer's viewpoint. Spatial relationships are then mentally represented as the reverse of what the addressee actually sees.

In fact, in order to understand and process sign, the subject must perceive the reverse of what they themselves would produce (assuming that both signers are

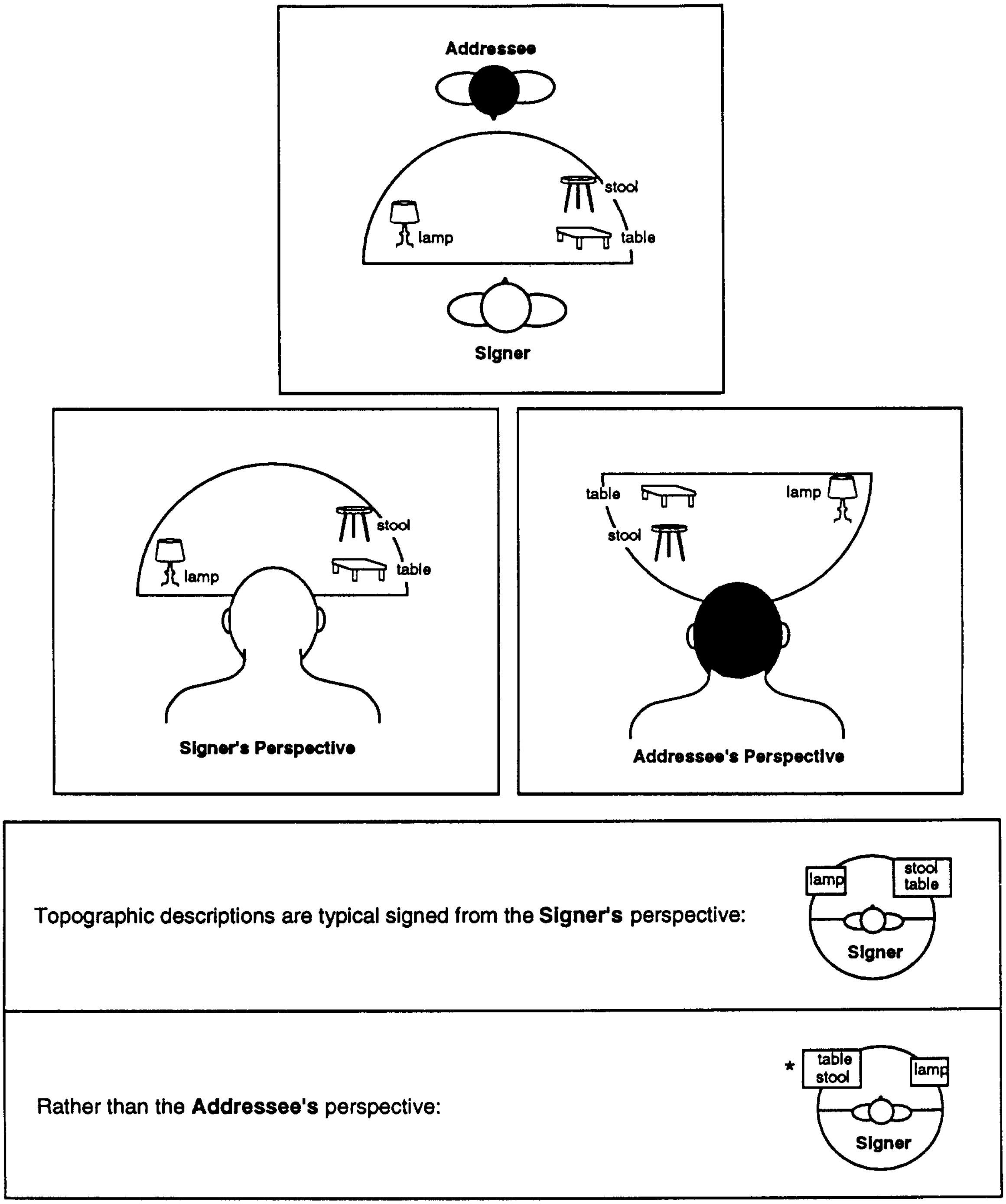

Figure 10. *Illustration of perspective in ASL.*

right handed). Anecdotally, hearing subjects have great difficulty with this aspect of learning ASL; they do not easily transform a signer's articulations into the reversal that must be used to produce the signs. Given these linguistic requirements, we hypothesized that signers might be better than hearing subjects at making the required reversal judgment at all degrees of rotation, including when no rotation is necessary.

Method

Subjects

Thirty-four deaf signers (16 native and 18 non-native) and 32 hearing subjects participated in the experiment. The same 10 HD signers also participated.

Materials

The stimuli were produced by first selecting four or five cells in a 4 × 5 grid (as are illustrated in Figure 3); these cells formed a single asymmetrical connected shape, but otherwise were selected at random. All lines that were not part of the outline of the form were then eliminated, producing stimuli like those illustrated in Figure 11. Pairs of stimuli were constructed, and one was placed to the left of a fixation point and the other to the right of this fixation point. The stimulus on the left was upright (i.e., the longest axis through the stimulus was aligned vertically), whereas the stimulus on the right was presented at 0°, 90°, 135°, or 180° of rotation. On half of the trials of each type, the right-hand pattern was mirror reversed and on half it was normal. The top cell of each stimulus was black, which helped the subjects to discover the relative orientations of the figures; the subjects must locate the tops in order to know which direction to rotate most efficiently (people typically rotate patterns "the short way around"; see Shepard & Cooper, 1982). The two stimuli together subtended about 20° of visual angle. Eight shapes were created: half with four cells (simple stimuli) and half with five (complex stimuli). Each shape appeared at each angle and in each lateral orientation, which resulted in a total of 64 stimuli. Two additional stimuli were created for practice trials, and a total of 16 practice trials were administered prior to the experiment proper.

Procedure

An exclamation point appeared at the beginning of each trial, which remained until the subjects pressed the space bar. The exclamation point then disappeared

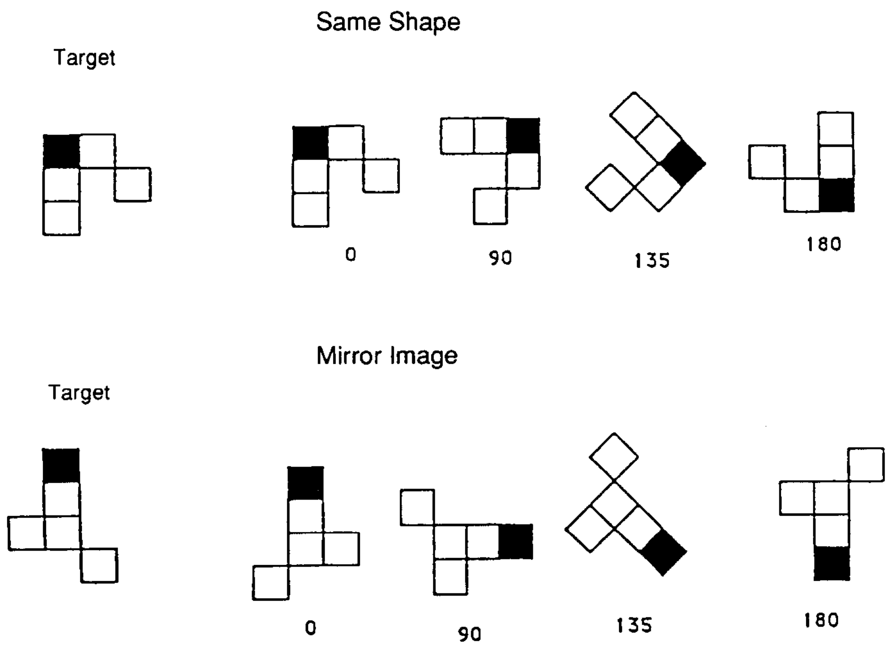

Figure 11. *Example stimuli from the mental rotation task.*

and the screen went blank; 500 ms later a fixation point appeared at the center of the screen, which remained for another 500 ms. The stimulus pair then appeared, and the subjects were to decide whether the two shapes were the same, regardless of their relative orientations. If the shapes were the same, they were to respond "yes"; if they were mirror reversals, they were to respond "no". The exclamation point returned after the subjects responded, and a new trial began.

Results

The data were analyzed as in the previous two experiments. Subject group, gender, degree of rotation (0°, 90°, 135°, 180°), and complexity were treated as independent variables. There was no effect of or interaction with gender, and therefore this variable was not included in the analyses reported below.

Response times

As is evident in Figure 12, deaf signers performed this task more quickly than hearing subjects, $F(1, 64) = 4.16$, $p < .05$. In addition, the angular disparity of the

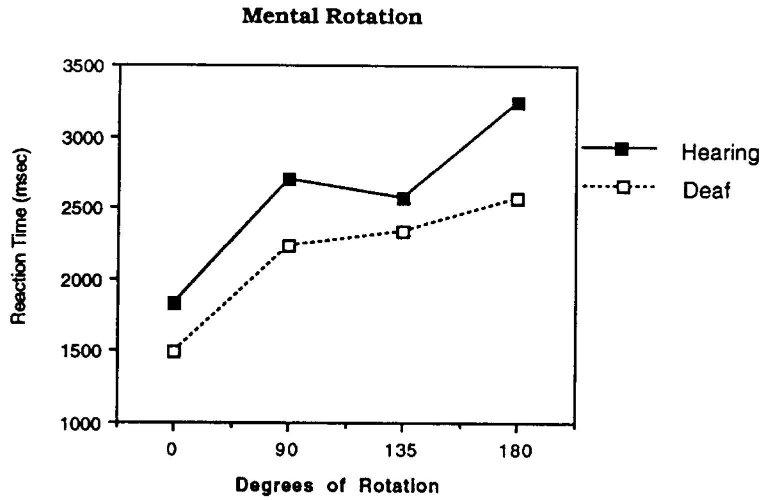

Figure 12. *Mean response times for hearing and deaf subjects on the mental rotation task.*

stimuli affected the two groups differently, $F(3, 192) = 4.77$, $p < .01$, for the interaction of angle and group. However, as is evident in Figure 12, the slopes of the two functions did not differ ($t < 1$); thus, the deaf did not rotate objects in images more quickly than hearing subjects. Rather, the overall fast response times suggest that deaf signers were faster than hearing subjects at making mirror image judgments. As Figure 12 illustrates, deaf subjects were faster than hearing subjects even when no rotation was required (i.e., at 0°).

Subjects generally required different amounts of time with the different angular disparities, $F(3, 192) = 143.56$, $p < .001$; as is evident in Figure 12, the response times generally increased with increased angle of rotation. Subjects required more time for the more complex figures, $F(1, 64) = 54.57$, $p < .001$. Furthermore, the effect of angular disparity depended on the complexity of the stimulus, $F(3, 192) = 6.53$, $p < .001$, for the appropriate interaction. Contrasts revealed that complexity interacted with angular disparity only between 0° and 90°, $F(1, 64) = 14.43$, $p < .001$; subjects evaluated complex figures oriented at 90° more slowly than the corresponding simple figures.

Finally, as is illustrated in Figure 13, the influence of complexity on the effects of angular disparity varied for the two subject groups, as witnessed by a three-way interaction of angular disparity, complexity, and subject group, $F(3, 192) = 3.17$, $p < .05$. For simple stimuli, hearing and deaf subjects showed a similar increase in response time with increasing angular disparity, $F(3, 192) = 2.06$, $p > .11$, for the interaction between subject group and angle of rotation. In contrast, for complex stimuli, the effect of angular disparity was different for the two subject groups, $F(3, 192) = 5.93$, $p < .001$, for the interaction. As can be seen in Figure 13, this

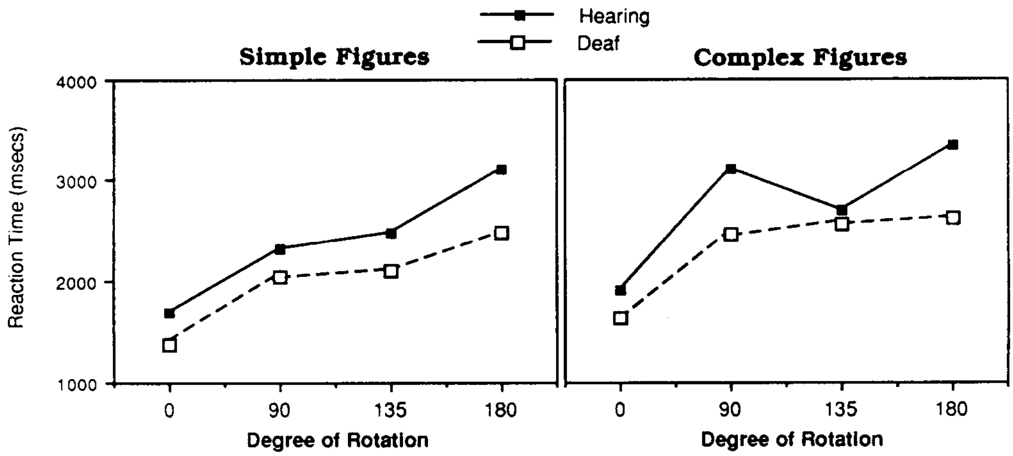

Figure 13. *Illustration of the three-way interaction between subject group, degree of rotation, and stimulus complexity.*

interaction seems to be largely due to an odd decrease in response time for hearing subjects at 135° rotation; the explanation for this decrease in response time is unclear.

Error rates

Deaf signers were as accurate as hearing subjects, $F(1, 64) = 1.13$, $p > .25$, and so the difference in response times cannot be ascribed to a speed–accuracy trade-off. In addition, errors varied in the same way for the different angular disparities in the two groups, $F(3, 192) = 1.03$, $p > .35$, for the interaction. Errors varied for the different angular disparities, $F(3, 192) = 7.91$, $p < .001$, and more errors were made with the more complex stimuli, $F(1, 64) = 8.60$, $p < .005$.

As in the response times, angular disparity had different effects for the simple and complex stimuli, $F(3, 192) = 5.69$, $p < .001$, for the interaction. As illustrated in Figure 14, for simple stimuli, error rates were similar for 0°, 90°, and 135° of rotation, but sharply increased at 180°; for complex figures, error rates sharply increased at 90° and then stabilized.

Finally, we found that deaf subjects who were exposed to sign language from birth (native signers) made fewer errors than the non-native signers who were exposed to ASL later in childhood; this was evident both when we compared native signers with non-native signers as a group, $F(1, 32) = 6.54$, $p < .02$, and when we broke down the non-native group into early signers (mean age of exposure to ASL = 4.9 years, $N = 11$) and late signers (mean age of exposure to ASL = 14.5 years, $N = 6$), $F(2, 31) = 3.62$, $p < .05$. As shown in Figure 15, native

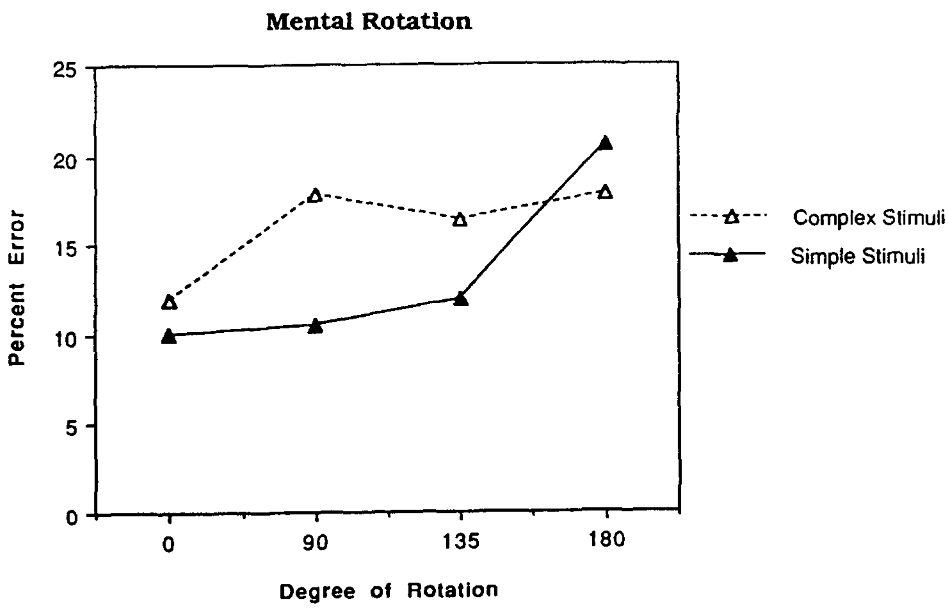

Figure 14. *Illustration of the interaction between complexity and degree of rotation for error rates.*

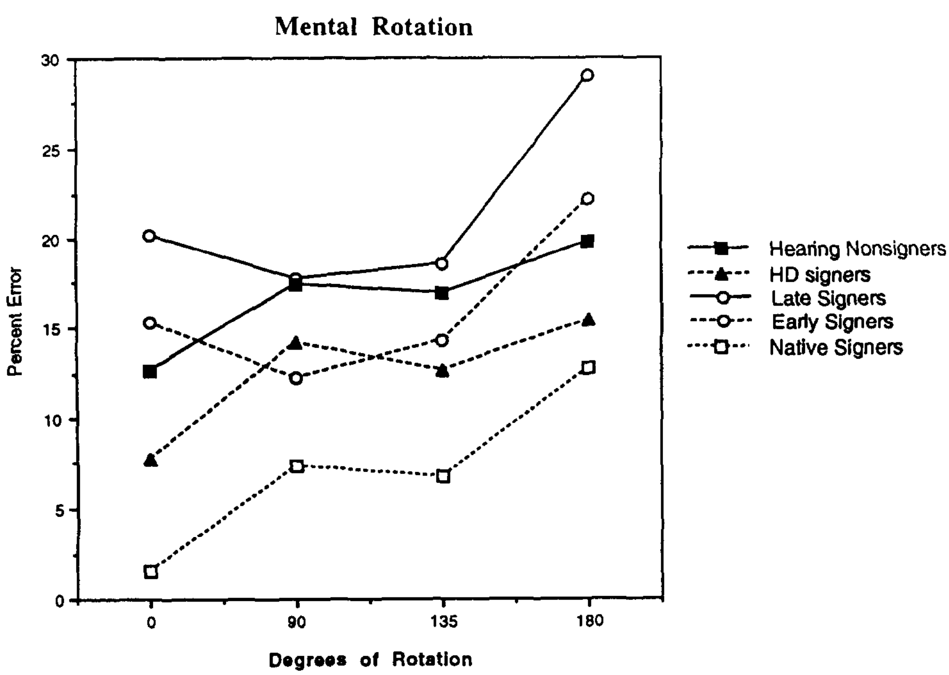

Figure 15. *Mean response times for native, early, and late signers. Hearing non-signers and "hearing-of-deaf" (HD) signers are plotted for comparison.*

signers made fewer errors compared to both early signers, $F(1, 26) = 4.85$, $p < .05$, and late signers, $F(1, 21) = 8.06$, $p < .01$; the difference between early and late signers was not significant ($F < 1$). The results from hearing non-signers and HD signers are shown in Figure 15 as a comparison. There were no interactions with age of sign acquisition, and the lower error rates for the native signers were not due to a speed–accuracy trade-off because native and non-native signers did not differ in reaction time, $F(1, 32) = 1.29$, $p > .25$.

Hearing-of-deaf comparison for mental rotation

As illustrated in Figure 16, HD signers responded like the deaf signers. In an ANOVA including all three groups, there was clear evidence that the groups differed, $F(2, 27) = 3.48$, $p < .05$. Planned comparisons revealed that the deaf and HD signers did not differ in their time to mentally rotate figures, $F < 1$, whereas HD signers were faster than the hearing non-signers, $F(1, 18) = 4.60$, $p < .05$. Again, this difference is not due to a speed–accuracy trade-off; we found no differences in error rates between subject groups, $F < 1$ (note that the matched group of deaf subjects included both native and non-native signers).

All subjects required different amounts of time with the increasing angular disparity, $F(3, 81) = 67.70$, $p < .001$. In addition, angular disparity interacted with subject group, $F(6, 81) = 3.04$, $p < .01$. Again, this interaction may be due to the odd decrease in response time for hearing subjects at 135° rotation.

Subjects also had different error rates depending upon the angular disparity,

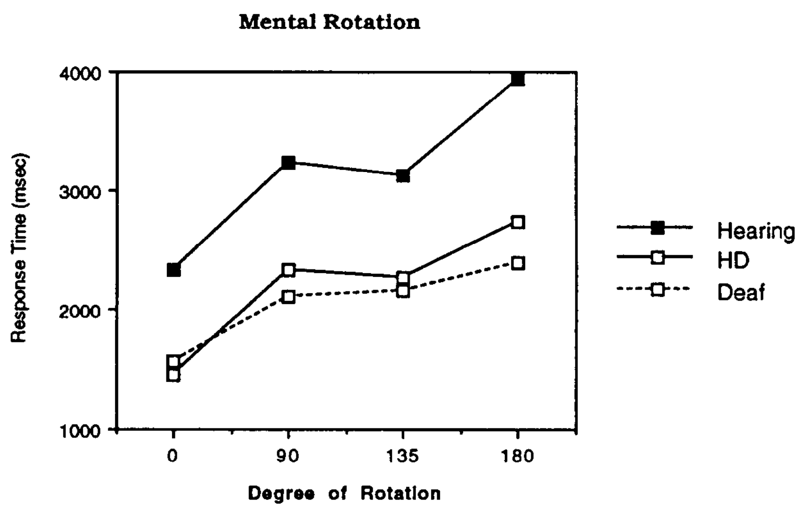

Figure 16. *Mean response times for hearing signers, "hearing-of-deaf" (HD) signers, and hearing non-signers.*

$F(3, 81) = 7.99$, $p < .001$, but the interaction between angular disparity and subject group was not significant in the analysis of error rates, $F(6, 18) = 1.48$, $p > .15$.

Finally, all subjects required more time, $F(1, 27) = 35.83$, $p < .01$, and made more errors, $F(1, 27) = 8.77$, $p < .01$, with more complex patterns. Complexity did not interact with subject group in the analysis of response times, $F(2, 27) = 2.05$, $p > .14$, or error rates, $F(2, 27) = 1.35$, $p > .25$.

Discussion

Deaf signers did not mentally rotate imaged patterns better than non-signers; rather than finding differences in the speed of rotation *per se*, our results suggest that signing subjects were better able to evaluate mirror reversals. HD signers performed similarly to deaf signers, which suggests that the enhanced ability on this task may be due to experience with ASL rather than to auditory deprivation. We hypothesize that an enhanced ability to evaluate mirror reversals may be tied to certain visual–spatial linguistic requirements (in particular, perspective transformations). However, it will be important to test directly whether the overall faster reaction times and lower error rates of the signing groups were due only to better reversal judgments and not to some other aspect of the task that is rotation independent. We are currently designing a study which investigates various reversal judgments in which no rotation is required.

The fact that deaf signers did not rotate images faster than non-signers suggests that the deaf do not have a generally enhanced ability to transform images. This inference is buttressed by the findings of Tomlinson-Keasey and Smith-Winberry (1990), who report no difference between deaf and hearing subjects on the WAIS-R task that requires subjects to mentally fold boxes. Indeed, there was some suggestion that deaf signers were actually worse than hearing subjects at this task. Although this task requires mental transformations, it does not involve mental rotation or mirror reversals, and there are no strong analogs in ASL to mentally creating a 3-D form from its 2-D "flattened" representation. In contrast, McKee (1987) found that deaf signers performed significantly better than hearing subjects on the 3-D orientation subtest of Gordon's (1986) cognitive laterality battery. This task is similar to our mental rotation task. Using a slide projector, subjects were shown three angular "S" shapes constructed out of cubes. All three shapes were identical, but were rotated around a vertical axis; one of the three was a mirror image of the other two. Subjects had 15 s to indicate which two forms were exactly alike, and deaf signers were more accurate than hearing subjects.

Recent evidence from signers with focal lesions also bears directly on this issue. Corina et al. (1990) show that the ability to mentally rotate an image and to understand perspective shift in ASL are linked. The patient they studied, D.N., was a young hearing signer (age 35) who was exposed to ASL early in life. Her father was a native signer, and D.N. grew up with her deaf grandmother; she is currently a certified interpreter for the deaf. D.N. suffered damage to the mesial superior occipital–parietal area of the right hemisphere. The lesion was caused by surgical evacuation of a parietal–occipital hematoma and an arteriovenous malformation. D.N. was not aphasic for English or ASL. Tests of both English and ASL phonology, morphology, and syntax revealed no linguistic deficits. Linguistic analysis of her spontaneous signing revealed flawless use of the spatially organized syntax of ASL at the sentential level. However, there was one specific area in which she exhibited some problems: topological descriptions and perspective shift.

As described earlier, topographic relationships are signed in relation to the signer's perspective. Corina et al. (1990) present evidence that this process is disrupted in D.N. In contrast to normal signers, D.N. preferred topographic descriptions signed in relation to her own frame of reference. That is, in the example in Figure 10, if D.N. were the addressee she would prefer that the signer describe the scene from her (D.N.'s) perspective rather than from the signer's perspective. In this way, D.N. avoids the mental transformation required to alter the signer's perspective into her own. However, this type of description (from the addressee's perspective) is completely unnatural and marked in ASL.

The nature of D.N.'s deficit was illuminated by the results of a paper-and-pencil version of the mental rotation and image generation tasks described here. On the image generation test, her score was nearly identical to the mean for normal deaf signers. However, on the mental rotation task, she showed marked impairment. Her score fell nearly two standard deviations below the mean for normal deaf signers. The fact that she showed impairment on mental rotation within the linguistic domain (perspective shift) and on a non-linguistic mental rotation task suggests that these two abilities are associated.

Finally, native signers detected mirror reversals more accurately than subjects who acquired ASL later in childhood. Is this increased accuracy due to practice effects or to the fact that native signers began acquiring ASL from birth? Although the late signers had been using ASL as their primary language for a shorter period of time than native signers (a mean number of 13 years of signing experience compared to 25 years for native signers), native and early signers had roughly the same amount of practice with ASL (a mean number of 23 compared to 25 years of experience for early and native signers, respectively). The fact that native and early signers did not differ in the number of years of signing practice suggests that the increased accuracy of native signers was due to exposure to a visual–spatial language from birth. However, as Figure 15 shows, HD signers, who were also exposed to ASL from birth, had error rates similar to the early signers rather than to the native signers. This result suggests that it is the combination of auditory deprivation and exposure to a signed language from birth that results in an enhanced ability to make accurate judgments of mirror reversal.

In summary, our results suggest that deaf and HD signers judge mirror reversal faster than hearing subjects. These results, in conjunction with those in the literature, suggest that signers do not show an overall enhancement of the ability to transform mental images; rather, enhancement may be restricted to mental rotation or mental reversals. We hypothesize that experience with shifting spatial arrays and transforming perspectives in a visual–spatial language leads to this superior performance.

GENERAL DISCUSSION

ASL signers are better than non-signers in specific aspects of visual mental imagery. Indeed, we found that both deaf and hearing signers have an enhanced ability to generate visual mental images; we also found that they were better able to detect mirror reversal. In contrast, there were no group differences in the ability to retain information in images for brief periods of time or to imagine objects rotating. Signers' enhanced visual imagery abilities may be tied to specific linguistic requirements (e.g., referent visualization, perspective transformations).

As noted in the Introduction, although deaf signers use ASL as their primary language in adulthood, they were first exposed to the language at varying points in their lives. In each of our experiments, we addressed the question of whether differences in visual imagery depended upon early exposure to sign language. The age at which sign language was acquired did not influence signers' ability to generate mental images or to maintain an image in memory. However, native signers were more accurate than non-native signers in the mental rotation task, but both groups were faster than hearing non-signers in this task. Table 1 presents summary data for response times and error rates for each of the three experiments for native, early, and late signers and for hearing non-signers. The age of exposure to sign language had only a small effect on non-linguistic visual imagery abilities (affecting only accuracy on one task); in contrast, late exposure to language has a very large effect on adult *linguistic* competence and processing. For example, Newport and her colleagues have found that the later in life one acquires sign language, the poorer is one's grasp of its grammar (Newport, 1988, 1990, 1991; Newport & Supalla, 1990). Emmorey and her colleagues have found similar results for on-line ASL processing (Emmorey, 1991; Emmorey, Bellugi, Friederici, and Horn, 1992; Emmorey & Corina, 1990). These differences in grammatical knowledge and processing were not due to practice effects; the subjects had been signing for an equal number of years (generally, over 20 years).

Similarly, the increased accuracy of native signers on the mental rotation task cannot be attributed to greater practice in signing. Rather, the maturational state

Table 1. *Mean reaction times (ms) and error rates (%) for the deaf subject groups and hearing non-signers for Experiments 1–3*

Image generation		
Subject group	Simple stimuli	Complex stimuli
Native signers	1345 (4%)	1492 (7%)
Early signers	1350 (5%)	1433 (13%)
Late signers	1197 (2%)	1006 (8%)
Hearing non-signers	1262 (10%)	1536 (4%)
Image maintenance		
Subject group	Short delay	Long delay
Native signers	981 (8%)	1089 (8%)
Early signers	996 (14%)	1048 (12%)
Late signers	834 (8%)	917 (9%)
Hearing non-signers	950 (6%)	1047 (6%)

Mental rotation				
	Degrees rotation			
Subject group	0	90	135	180
Native signers	1436 (2%)	2023 (7%)	2209 (7%)	2454 (13%)
Early signers	1587 (15%)	2614 (12%)	2558 (14%)	2805 (22%)
Late signers	1500 (20%)	2230 (18%)	2245 (19%)	2323 (29%)
Hearing non-signers	1795 (13%)	2702 (17%)	2575 (17%)	3210 (20%)

of the brain at the time of exposure to signing may play a critical role in the way signing affects adult visual processing. Furthermore, early auditory deprivation appears to play a supplementary role in altering adult performance for this non-linguistic visual task. HD signers (who are also native signers, exposed to ASL from birth) were no more accurate on this task than hearing non-signers, which suggests that native signers' proficiency in detecting mirror reversals was due to the combination of early deafness and exposure to ASL from birth. Many researchers have argued that both the visual system (e.g., Hubel & Wiesel, 1963; Sperry, 1951) and language (e.g., Curtiss, 1977; Lenneberg, 1967) have critical periods for normal development. The populations of deaf and hearing individuals studied here can provide unique insights into how these systems might interact during maturation and how early experience can differentially affect adult cognition.

In conclusion, these experiments reported here are a first exploration of how a visual–spatial ability within one functional domain (language) may exert an influence on a visual–spatial ability within a different functional domain (imagery). Overall, our results indicate that deaf and hearing signers show *selective* enhancement of certain visual abilities that may be recruited for ASL processing. Our results are particularly interesting with respect to Fodor's "modularity of mind" hypothesis (Fodor, 1983). Fodor argues that linguistic processes are "encapsulated" – insulated from other types of processes. Our findings suggest that the processing that underlies one sort of human language is not entirely modular. Image generation and reversal transformation appear to be deeply embedded in using ASL, and these are not peripheral processes that must obviously be involved in both visual imagery and ASL. Note that our results indicate that visual imagery is involved in the *processing* of ASL; imagery may or may not be related to the principles that underlie ASL grammar. The grammar of ASL has been shown to conform to principles of universal grammar (see, for example, Lillo-Martin, 1987/1990), and we may find that the principles that underlie natural human language may be autonomous and not shared by other cognitive modules. Nonetheless, our results indicate that central aspects of ASL processing are not domain specific and are not insulated from other types of visual processing. As Fodor himself has pointed out, the notion of modularity ought to admit of degrees (Fodor, 1983, p. 37). In this article, we have presented evidence for limits on the degree of modularity for human language processing and thus constrained the theory of cognitive modularity.

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