A34

In D.S. Martin (Ed.), Advances in Cognition, Education and Deafness.
Washington, DC: Gallaudet University Press, 1991, 11-35.

The Link Between Hand and Brain: Implications from a Visual Language

Ursula Bellugi

The occasion of the Second International Symposium on Cognition, Education, and Deafness evoked memories of Edward Corbett's keynote address (1985) at Gallaudet's First International Symposium. Dr. Corbett's concerns at that time offer a perspective on how our field has advanced over the last five years.

At that first symposium, Dr. Corbett expressed the need for new directions in research in areas in which the special capacities of deaf people should be revealed. One such area, he asserted, was the visual competence of deaf individuals. He recommended that researchers begin studies of vision and visual language, and that they focus on "the fact that deaf people's cognitive efforts are enhanced by their use of vision, rather than identifying the weaknesses of their auditory mechanisms." He raised several important questions with respect to the contrast between visual and auditory information processing, suggesting that researchers in the field should turn their attention to visually mediated thinking

This research was supported in part by National Institutes of Health grants #DC00146, #DC00201, #HD13249, and #HD266022, as well as National Science Foundation grants #BNS86-09085 and BNS88-20673; the Axe Houghton Foundation grant to The Salk Institute for Biological Studies; and the John D. and Catherine MacArthur Foundation Research Network on 'The Transition to Early Childhood.' We thank David Corina, Karen Emmorey, Angela Fok, Karen van Hoek, Edward S. Klima, Lucinda O'Grady-Batch, and Judy Reilly for their help in these studies. Illustrations copyright Ursula Bellugi, The Salk Institute for Biological Studies.

and to investigations of the cerebral cortex with respect to vision in deaf people. Dr. Corbett also pointed out that, unfortunately, many researchers up to that time equated speech with language and vice versa. His directive to the field was to conduct research on visual language and visual processing in order to provide new information to complement our understanding of speech and hearing.

This last decade of the twentieth century is an exciting one for those of us who are involved in sign language research, the study of deafness, and education of deaf children. We stand at a new vantage point now, looking toward future developments that were almost unimaginable only a decade ago. Fundamental and important changes have taken place in our field and in the public's perception of deafness. There is the emerging awareness that American Sign Language is a full-fledged language, as complex and expressive as any spoken language. There is a growing appreciation of Deaf culture in its many manifestations. Additionally, there is a new consciousness of the capabilities of deaf people.

The papers presented in this volume attest to the depth and breadth of the research now being done on the language, cognition, and culture of deaf people. At research centers across the country and around the world, important and far-reaching questions are being addressed. We now see researchers in linguistics, cognitive psychology, and cognitive neurosciences looking to studies of deaf people for important findings about cognition and language and about how language is represented in the brain. Interestingly, that research has taken place in precisely those areas that Dr. Corbett challenged us to address.

The research my colleagues and I have conducted in the Laboratory of Language and Cognitive Studies at The Salk Institute over the past decade, reflect the above-mentioned developments in the field. Initially, we asked questions about the nature of signing: Whether it was a form of pantomime executed face-to-face, whether it was a simple, gestural form of communication, and whether it had any kind of linguistic structure. Over the years, we have worked with more than five hundred deaf people in many different roles, and we have benefited greatly from having several deaf researchers on our laboratory staff, including Lucinda O'Grady-Batch and Freda Norman.

In the past decade we have learned a great deal from the comparison of signed and spoken languages and have made significant discoveries about universal properties that appear in both visual and auditory languages (see, for example, Bellugi, Poizner & Klima 1989; Bellugi & Studdert-Kennedy 1980; Klima & Bellugi 1988). We have found that the basic properties of signed and spoken languages are very much the same. Signed and spoken languages have the same kinds of organizational principles, the same kinds of rule systems, and the same grammatical complexity and expressive power.

We can now define the characteristics of language as it manifests itself in each of the modalities, and can begin to specify precisely which surface aspects of the form language arise from the visual modality compared to the auditory modality. Having established that signed and spoken languages are remarkably similar at the deepest level, we are also interested in determining how differences in transmission modality, between vocal-auditory and manual-visual channels, might affect the surface form of language and also might influence cognitive processing.

Three main points arise from research on signed languages everywhere.

1. The concept of language must now be broadened to include signed as well as spoken languages.
2. Signed languages present an important new alternative to spoken languages and are particularly revealing because they depend so heavily on visual rather than auditory processing.
3. Signed language, like spoken language, is preferentially processed by the left hemisphere, suggesting that the left hemisphere in humans has an innate predisposition for language.

In a number of ways, signed languages provide a new perspective on language and reveal unexpected links between hand and brain.

PROPERTIES OF SPOKEN AND SIGNED LANGUAGES

One of the central issues that we can now address arises from some new discoveries about the nature of language. Until recently, nearly everything we had learned about language had come from the study of spoken languages. But now research into signed languages has revealed that there are primary linguistic systems, passed down from one generation of deaf people to the next, which have become forged into separate languages not derived from spoken languages. Thus for the first time we can examine properties of communication systems that have developed in an alternative transmission system, the *visual-gestural channel.* The existence of such fully expressive systems arising outside the mainstream of spoken languages affords a new vantage point for investigating the biological underpinnings of language and cognition.

The past decade has seen many investigations of language and its formal architecture, as well as its representation in the brain, through the study of languages that have arisen outside the mainstream of spoken languages; that is, the visual-gestural systems developed among deaf people. American Sign Language (ASL) has been forged into an autonomous language with its own internal mechanism for relating visual form to meaning. ASL has evolved linguistic mechanisms that are not derived from those of English (or any spoken language), offering a new perspective on the determinants of language form.

A lively field of research in the structural properties of ASL (e.g., *Sign Language Studies*; Liddell & Johnson 1986; Wilbur 1987; and many others) now exists. In our laboratory at The Salk Institute, we have been specifying the extent to which the modalities involved in the perception and production of languages shape their formal properties. We have found that the modality in which a language develops makes a crucial difference in the form of its grammatical devices.

The complex organizational properties of language have been assumed to be intimately connected with the production and processing of vocally articulated sounds. There is good evidence that human beings have evolved for speech. Spoken languages have been found to manifest certain basic structural principles assumed to result from the fact that language is normally spoken and heard. The existence of signed languages allows us to ask fundamental questions about the determinants of language organization. What would language be like if its transmission were not based on the vocal tract and the ear? How is language processed when its basic lexical units are produced by the hands moving in space and when the signal is organized spatially as well as temporally? What implications does acquiring a visual-spatial language have for the neural substrate for language in the brain? We can now address these issues together and consider their implications for the study of cognition and for the education of deaf children.

What are the differences between spoken and signed languages? That was really our central research question for a long time. What we wanted to do was sift out the properties that are common across all languages and then look at the special properties with respect to sign language on the surface. We are looking at the effect of having a language for the eyes rather than for the ears—a language that is designed and suited specifically for vision.

Signed languages clearly present test cases of communication systems that have developed in alternative transmission systems: in visual-gestural channels. Because American Sign Language is a visual language, it engages different aspects of brain function for its production and perception than does the use of spoken languages. Thus, the study of ASL opens new windows to reveal previously unseen aspects of how the brain is organized to generate and comprehend language. The most striking surface difference between signed and spoken languages is in the reliance on spatial contrasts at all linguistic levels—most evident at the level of syntax. Figure 1 shows ASL grammatical morphology as spatially nested forms and aspects of verb agreement and spatially organized syntax.

SIGN LANGUAGE UNIVERSALS: THE EFFECTS OF MODALITY ON LINGUISTIC FORM

Our research investigates the effects of the change in modality (from ear to eye, from vocal tract to hands) on the form that signed languages take. Our objectives are to determine the underlying properties that all languages have in common and to examine the distinctive properties of signed languages that show the effects of modality on language organization. We are examining the formal devices utilized by Chinese Sign Language (CSL), in contrast to American Sign Language (see Fok, Bellugi & van Hoek, this volume), in order to test our hypotheses regarding the effects of language modality on the form that languages take. We chose to study CSL because it has developed in the context of a completely different spoken language (spoken Chinese) that has essentially no inflectional morphology and a nonalphabetic writing system.

We find that at each level of organization, including phonology, morphology, and syntax, CSL and ASL are remarkably similar in overall surface organization. Signs in both languages are composed of simultaneously articulated layered elements consisting of a small set of handshapes, locations, and movements. Morphological patterning is layered simultaneously with the root. The two languages are similar also in the ways they utilize space and spatial contrasts in the service

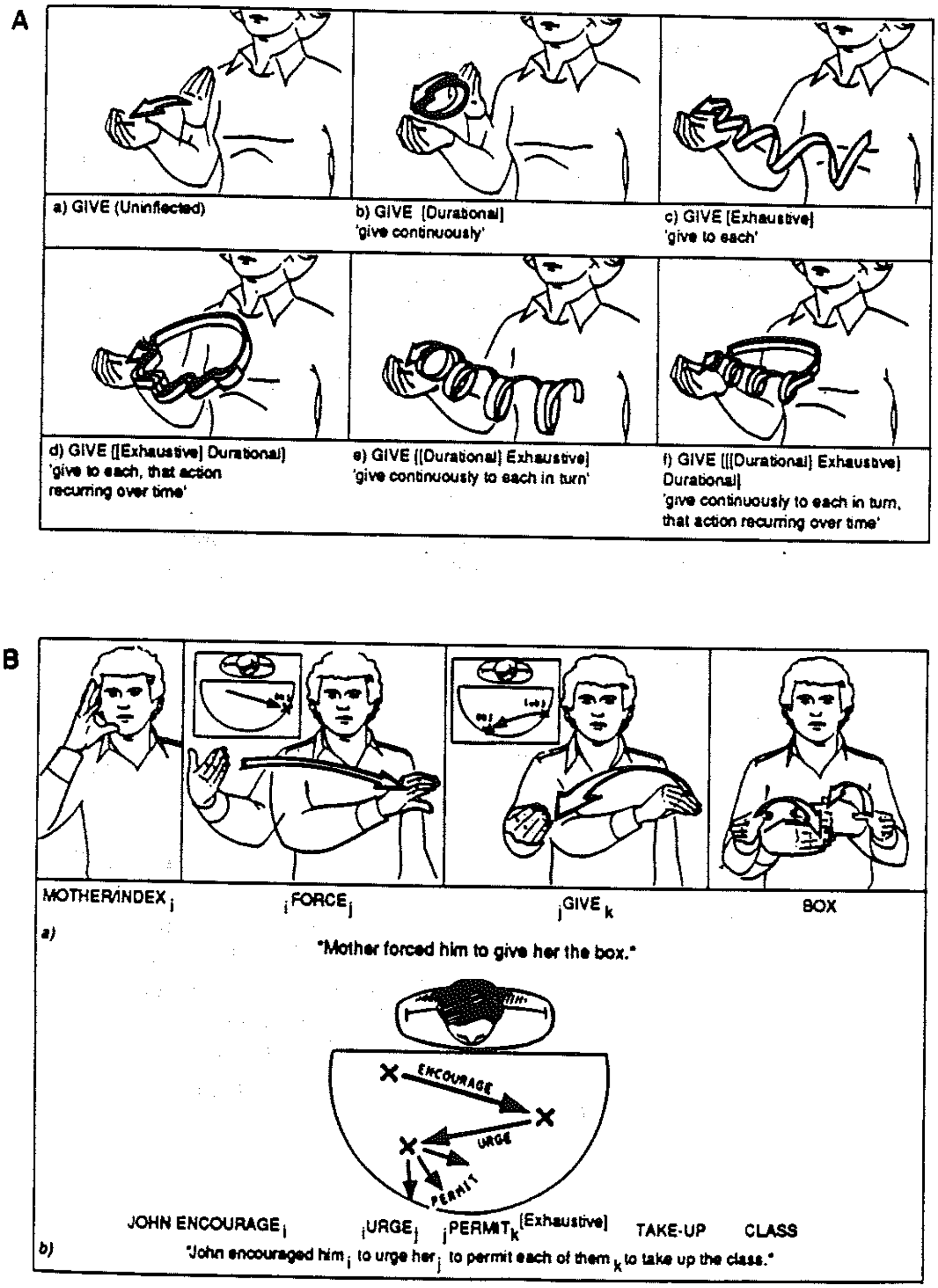

FIGURE 1 ASL-layered morphology and spatially organized syntax.

of syntax. In terms of surface organization, then, CSL and ASL are quite similar, clearly showing the imprint of the modality on language form. But at the same time, as completely autonomous signed languages developing without any points of contact, each has its own lexicon and its own distinctive phonology, grammatical morphology, and rules of syntax. Moreover, as one might expect, the two signed languages are mutually incomprehensible. We have now identified consistent "phonological" and even "phonetic-level" contrasts between the two signed languages, leading to phenomena similar to "accent" in spoken languages that occur when a user of one signed language learns another.

Since spoken Chinese (Mandarin or Cantonese) has little or no grammatical inflection, it is important to examine whether CSL similarly exhibits a paucity of grammatical inflections. Our studies show clearly that CSL is profoundly different from spoken Chinese. Like ASL, but in contrast to Chinese, CSL turns out to be a richly inflecting language. CSL exhibits a large number of inflections for grammatical arguments, number, derivational distinctions, and grammatical aspect, expressed in the form of movement contours that are layered with the sign root, articulated simultaneously rather than sequentially. Moreover, the syntax of CSL, as in ASL, is expressed spatially (Fok, Bellugi, van Hoek & Klima 1988; Fok & Bellugi 1986; Fok et al., this volume; Poizner, Fok & Bellugi, in press).

This course of development in ASL grammar represents one possibility afforded by the visual-spatial modality; whether it is the favored or only possibility for a visual-spatial language is unknown. We are investigating whether principles of linguistic organization (e.g., the spatially organized syntax) will turn out to be more general characteristics of natural signed language systems. We have been examining for the first time the grammatical properties of CSL, focusing on both similarities and differences between ASL and CSL. These studies allow us to determine the detailed ways in which signed languages differ from one another with respect to the most modality-conditioned aspects of signed languages.

COMPUTER GRAPHIC ANALYSIS OF SIGNED LANGUAGE

ASL has developed as a fully autonomous language with complex organizational properties not derived from spoken languages. This fact illuminates the biological determinants of language. ASL exhibits formal structuring at the same levels as spoken language and principles similar to those of spoken language (e.g., constrained systems of features, rules based on underlying forms, and recursive grammatical processes). Yet the surface form of grammatical processes in a visual-spatial language is rooted in the modality in which the language developed. This difference in surface form between signed and spoken languages makes possible new investigations into the perception and production of language.

Dynamic Point-Light Displays

Linguistic analyses and experimental studies of sign language have been linked together, allowing researchers to study the interplay between the perception of language and the perception of motion. Specifically, one can now investigate the nature of perception of movement organized into a linguistic system. To investigate linguistic movement in ASL experimentally, a method was developed to isolate movement of the hands and arms, adapting a technique introduced by Johansson to study the perception of biological motion (Johansson 1975). Small incandescent bulbs were placed at the major joints of the arms and hands, and signing was recorded in a darkened room so that only the patterns of moving lights appeared against a black background (see Figure 2a).

Even with the information reduced to minimal point-light displays, deaf signers identified morphological processes of ASL with a high degree of accuracy, demonstrating that these patterns of dynamic contours of movement form a distinct, isolable layer of structure in ASL.

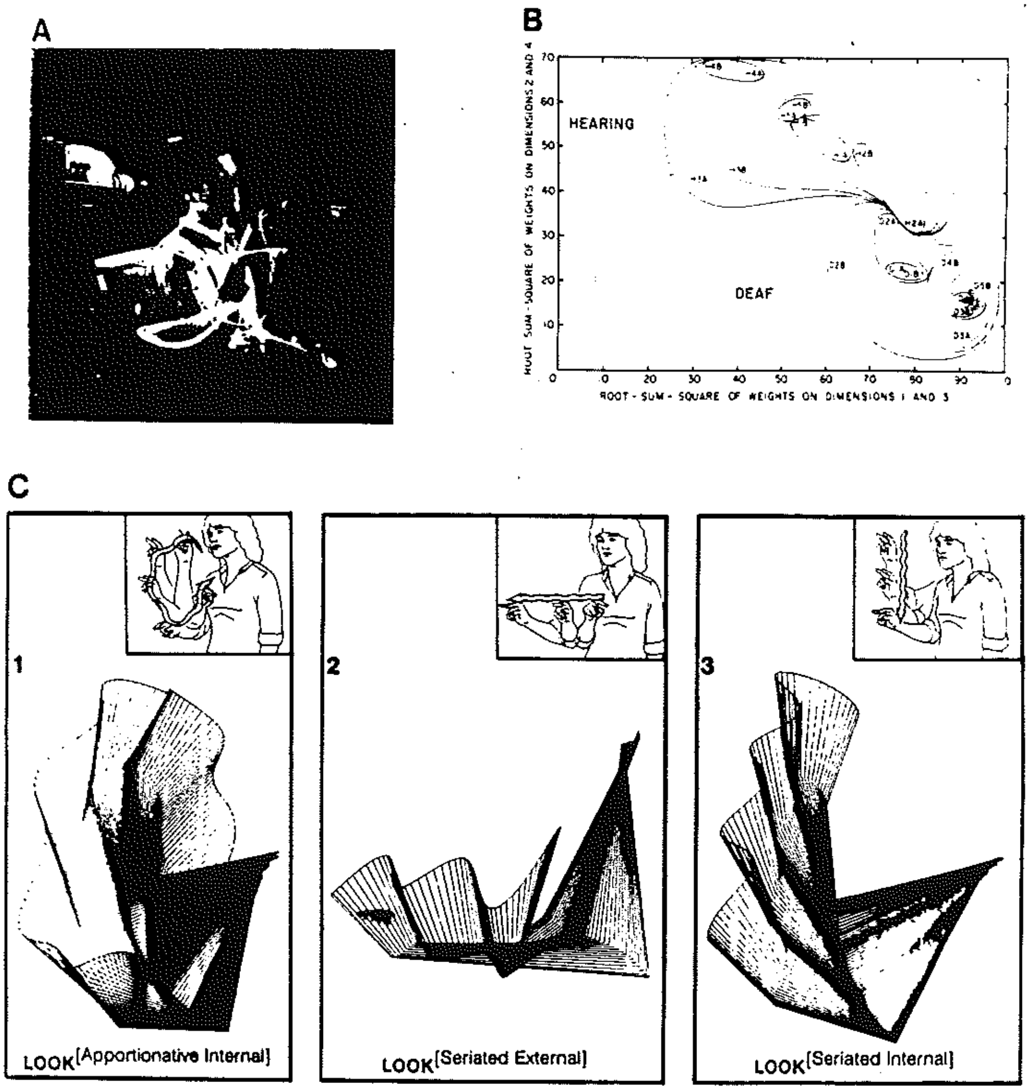

FIGURE 2 Computergraphic analysis of ASL.

The Interplay Between Perceptual and Linguistic Processes

To investigate the relation between basic perceptual and higher-order linguistic processes, the psychological representation of ASL movement by native deaf signers was contrasted with that of hearing nonsigners. Triads of ASL signs were presented as point-light displays, and subjects were asked to judge similarities between movements. Multidimensional scaling and hierarchical clustering of judgments for both groups of subjects revealed that the inflectional movements were perceived in terms of a limited number of underlying dimensions. Furthermore, the psychological representation of movement differs for deaf and hearing subjects, with perception of movement form tied to linguistically relevant dimensions for deaf subjects but not for hearing subjects (see Figure 2b). Thus, the data suggest that acquisition of a visual-gestural language can modify the natural perceptual categories into which linguistically relevant forms fall (Poizner 1983).

The study of sign languages provides a powerful vehicle for analyzing language production. In sign language, but not in spoken language, movements of the hands are directly observable. In order to analyze the structure of movements that have been forged into a linguistic system, methods have been developed to track movements in three-dimensional space and reconstruct them using computer graphics (Poizner, Klima, Bellugi & Livingston 1986). Figure 2c shows three-dimensional reconstructions of the sequential positions of the arm and hand throughout the course of three grammatical inflections expressed in ASL through modulations of movement. These illustrate the essential nature of grammatical contrasts that have developed in ASL, conveyed through dimensions unique to visual-spatial language, such as planar locus and geometric array. Thus, processing grammatical relations in sign language also requires processing of spatial relations, since the two are intimately intertwined. These powerful techniques for the three-dimensional computer graphic analysis of movement are now being coupled with linguistic analysis to explore how the brain controls movement at different levels—*linguistic*, *symbolic*, and *motoric* (see Figure 2).

THE CHILD'S CAPACITY FOR LANGUAGE

Another major avenue of study examines the deaf child's capacity for language in the broader sense, and not (as generally prevailed in the past) cataloguing deficiencies with respect to learning English. Twenty years of research on the development of sign language in deaf children of deaf parents shows that language acquisition in this population occurs just as does the acquisition of spoken language—with the same maturational timetable, the same milestones, and the same capacities for creating complex linguistic systems.

Studies of children's acquisition of spoken language have illuminated the nature of linguistic systems, the biological foundations for language, and the human capacity for language. American Sign Language is markedly different in surface form from English and from spoken languages in general. ASL is, for example, unique in its use of space at all linguistic levels. Given this difference in form, the task that the deaf child faces in learning a sign language may be radically different from that faced by the hearing child learning a spoken language. The change in the transmission system (from the ear to the eye, from the vocal apparatus to the hands) might have a profound influence on the acquisition process. In a language where the articulators are directly observable and manipulable, the language learning situation can take on a different character.

What effects might these special characteristics of a visual language have on the acquisition process? We are investigating the acquisition of spatially organized syntax and the acquisition of its spatial cognitive underpinnings. We have completed studies with more than sixty deaf children of deaf parents, from two to ten years of age, involving tests that tap knowledge of phonological, morphological, and syntactic processes in ASL (Bellugi 1988; Bellugi, van Hoek, Lillo-Martin & O'Grady 1988).

Inflections and Spatial Verb Agreement

The ASL system of verb agreement functions is like that of spoken languages, but the form of verb agreement in ASL requires that the signer mark connections between spatial points. Around the age of two, deaf children begin using uninflected signs, even in imitating their mothers' inflected signs and even where the adult grammar requires marking for person and number. Although they are perceiving complex inflected forms, deaf children begin, as hearing children do, by analyzing the uninflected stems. By the age of three, deaf children have learned the basic aspects of verb morphology in ASL (inflections for person, for temporal aspect, and for number). At this age, they make overgeneralizations to noninflecting verbs, analogous to overgeneralizations like *eated* in the speech of hearing children. Such "errors" reveal the child's analysis of forms across the system. So, despite the difference in the form of spatial marking, the development and the age of mastery of the spatial inflection for verb agreement are the same in ASL as for comparable processes in spoken languages.

Spatially Organized Syntax and Discourse

The integration of the pronominal reference and spatial verb agreement systems in the sentences and discourse of ASL is highly complex. When deaf children first attempt to index verbs to arbitrary locus points in space, they may index all verbs for different referents to a single locus point. In telling stories, for example, three-year-old children characteristically "stack up" referents in space, rather than using arbitrary spatial points to keep referents distinct. By the age of five, however, children give the appropriate spatial index to nearly every nominal and pronoun that requires one, and almost all verbs show the appropriate agreement.

The deaf child, like the hearing child, extracts discrete components of the system. Furthermore, the evidence suggests that even when the modality and the language offer possibilities that seem intuitively obvious or transparent (pointing for pronominal reference, for example), deaf children ignore this directness and analyze the language input as part of a formal linguistic system.

The young deaf child is faced with the dual task in sign language of spatial perception, memory, and spatial transformations on the one hand, and processing grammatical structure on the other, all in one and the same visual event. Our studies of the acquisition process have found that deaf and hearing children show a strikingly similar course of development if exposed to a natural language at the critical time. These data suggest that language, independent of its transmission mechanisms, emerges in the child in a rapid, patterned, and—above all—*linguistically driven* manner.

A Sensitive Period for Learning Language

Current studies of language learning have important implications for education of deaf children and for our understanding of language development. One example is Supalla's research with deaf children of hearing parents whose only language exposure was to Signed English in the classroom and at home (S. Supalla, in press). He elicited the children's use of sign language with specially designed tests that focused on the expression of verbs and verb relations. These studies investigated the children's use of space in sentences, finding that individual children changed the input from Signed English when they signed among themselves by making it more spatial. This finding indicates that language modality, that is, language for the eyes rather than the ears, has a profound effect on language form.

Other research is relevant to a fundamental language issue: "Is there a critical period for language learning?" That is, does language learning have to take place during certain specified periods of early development in order to occur optimally? This point of view has been espoused by researchers such as Lenneberg (1967), who emphasized the maturational and biological aspects of language acquisition. In nonhuman species, there is evidence for critical periods in the acquisition of complex skills. Some species of birds, for example, exhibit a critical period for learning birdsong (Marler 1970).

It has been difficult to obtain clear evidence regarding human spoken language because children usually receive speech input at all stages of their development. However, Newport has conducted a "natural" experiment by studying a group of deaf people who came from the same community, went to the same school for the deaf, and had signed for a minimum of thirty years (Newport 1988). But they had been exposed to sign language at different ages, some early, some later in life. One group of deaf children of deaf parents had been exposed to sign language since birth; another group of deaf children with hearing parents were first exposed to sign language between four and six years of age when they began attending a school for deaf children; a third group were first exposed after the age of twelve.

All subjects were profoundly deaf and used ASL as their primary language. The grammatical processing of these different groups—different only in the age of exposure to sign language—has been studied, and the results suggest that there is indeed a sensitive period for learning language. In other words, language learning in humans is optimized at specific early ages. This is important information, educationally and theoretically.

The Interplay Between Spatial Cognition and Spatial Language

In a series of studies, we are examining the early writing skills of deaf children in Hong Kong who are exposed both to a visual-spatial primary language (Chinese Sign Language) and a visual-spatial script (Chinese kanji or logographs). We have found that deaf children just beginning to learn to write Chinese characters actively seek to discover the internal regularities underlying the architectural forms of the characters, and they make use of such regularities in creating new character forms (Bellugi, Tzeng, Klima & Fok 1989; Fok & Bellugi 1986; Fok et al., this volume). The forms invented by both hearing and deaf children alike are almost always perfectly acceptable character forms following all the implicit rules of character formation. Furthermore, the deaf children bring their own knowledge of sign language to the process of constructing characters. The evidence so far suggests that they actively seek to impose principles of sign construction borrowed from sign language and apply them to the written form of Chinese that they are learning.

In a recent experiment, we investigated the ability of deaf and hearing children who are just beginning to learn to read and write Chinese to analyze Chinese script through movement patterns in space. We used a technique that enabled us to highlight movement patterns as dynamic patterns of light, using a small light-emitting diode attached to the fingertip. We recorded patterns of movement on videotape in a darkened room, resulting in a continuous trace of light as the finger traces a Chinese pseudocharacter. In this way, only the dynamic pattern of movement representing the pseudocharacter is shown on the video screen.

Our subjects were deaf and hearing first-graders living in Hong Kong, who were just beginning to read and write in school. We asked them to watch sixty such continuous movement patterns, and each time, to write down the pseudo-character (involving discrete strokes) that was represented by the continuous flow of motion. The deaf children were significantly better than the hearing children in remembering, analyzing, and decoding spatial displays that involve movement patterns (see Fok et al., this volume). Deaf children exposed to a visual-spatial language appear to bring markedly enhanced spatial abilities to this task.

The Development of Hand Dominance in Signing

Studies of handedness in the past have linked right-hand dominance with left-hemisphere specialization for language. Since ASL uses the hands linguistically, and children begin to sign by their first birthday, testing hand dominance in deaf children who are learning ASL as their native language from their deaf parents represents a unique opportunity to determine degree of hand dominance for language and the implied underlying lateralization at a very early age. We have completed studies of right- and left-handed adult deaf signers (Vaid, Bellugi & Poizner 1989).

A set of cross-sectional linguistic and nonlinguistic studies was given to twenty-six deaf children of deaf parents. The subjects ranged from three to ten years of age. For the linguistic study, we selected a particular set of stimuli—pictures of common objects that were easily labeled with one-handed signs used by young deaf children (e.g., APPLE, BIRD, GIRL). We asked children to produce the signs for these pictured objects, recording which hand was used, and we asked them to produce the signs as rapidly as possible, first with one hand, then with the other, counterbalanced for hand used.

For the nonlinguistic study, we examined reaching for objects presented at midline, as well as performance on the Grooved Pegboard and the Harris Test of Lateral Dominance. Overall, the deaf children showed a hand preference for the nonlinguistic task that is above 50%, equivalent to published norms for age-matched hearing subjects (see Figure 3). However, in the linguistic task (hand dominance for one-handed signing), the children were at 100% dominant hand use, and in tests of speeded signing with the nondominant hand, there were more than 20% intrusions from the dominant hand. The results demonstrated that the subjects in this sample showed strong hand dominance for signs. In the speeded signing tests, the right hand was strongly dominant, even for the youngest children, averaging twice as fast as the left hand.

These findings suggest that hand dominance for linguistic tasks is stronger than hand preference for nonlinguistic tasks in these deaf signing children, and moreover, that hand dominance for linguistic activities is early, reliable, and robust (Bellugi, Klima, Lillo-Martin, O'Grady & Vaid 1986). We obtained convergent evidence by drawing upon our longitudinal study of many deaf children of ages one to three learning ASL as a native language. We scored the one-handed linguistic signs and the nonlinguistic manual behaviors for hand use. The deaf children showed hand preference for nonlinguistic actions generally above 50%, as has been found in hearing children. In contrast, the deaf children showed a stronger hand dominance for signing at levels ranging from 70% to 100%, even from the first signs made at the age of one year. Thus, hand dominance for linguistic activities manifests at an early age and is qualitatively and quantitatively different from that for nonlinguistic activities in young deaf signing children.

Studies of the development of handedness in sign language provide a new

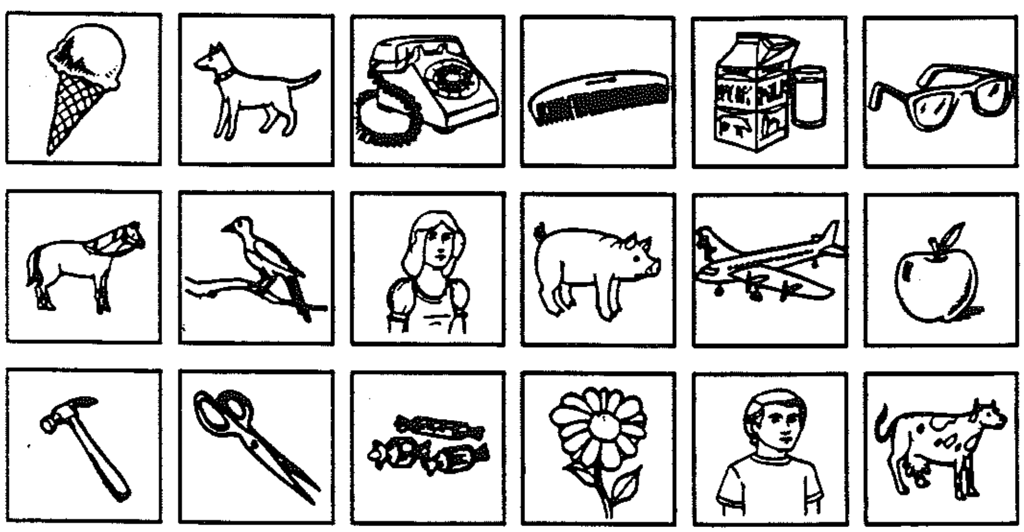

FIGURE 3a Picture cards used in one-handed signing task.

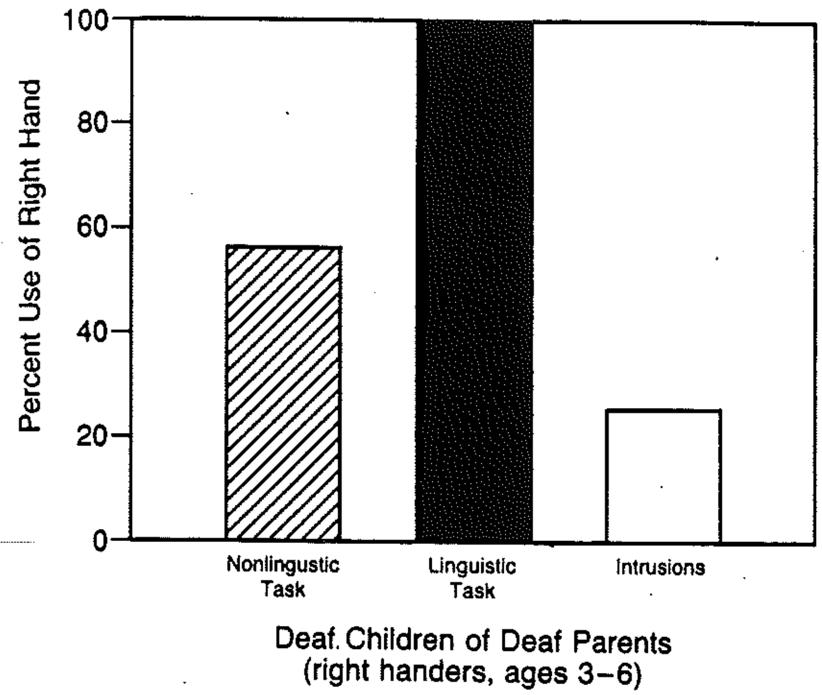

FIGURE 3b Hand dominance in linguistic tasks and hand preference in nonlinguistic tasks.

perspective on the relationship between hand preference and cerebral specialization, through a language in which the hands are the primary articulators.

BRAIN ORGANIZATION: CLUES FROM A VISUAL-SPATIAL LANGUAGE

Patterns of breakdown of a visual-spatial language in deaf signers may bring a new perspective on the nature of cerebral specialization for language, since in sign language there is interplay between visual-spatial and linguistic relations within the same system. ASL displays the complex linguistic structure found in spoken languages but conveys much of its structure by manipulating spatial relations, thus exhibiting properties for which each of the hemispheres of hearing people shows a different predominant functioning. The study of brain-damaged deaf signers offers a particularly revealing vantage point for understanding the organization of higher cognitive functions in the brain, and how modifiable that organization may be. We address questions such as the following: Is the development of hemispheric specialization dependent upon auditory experience? How is language represented in the brain when it is expressed spatially? Does acquisition of a language with spatially expressed grammatical functions modify cerebral specialization for nonlanguage spatial functions?

We have investigated brain organization for sign language along several parallel tracks and have developed a systematic program of studies that examines the effects of brain lesions on sign language processing and on spatial cognition in deaf signers with either left or right hemisphere lesions. We have studied functional asymmetries for sign language in the normal brain in a series of experimental investigations. Most recently we have had a unique opportunity to extend these studies under conditions of chemical anesthesia to the brain. These lines of investigation provide converging evidence bearing on the basis for specialization of the two cerebral hemispheres in humans. Our broad aim is to investigate the relative contributions of the cerebral hemispheres with special reference to the interplay between linguistic functions and the spatial mechanisms that convey them. Subjects are given a battery of tests especially designed to assess their capacities vis-à-vis each of the levels of ASL linguistic structure. We focus on the levels of the structure of ASL where there may be special processing requirements for a language whose form is perceived visually (Bellugi, Poizner & Klima 1989; Klima, Bellugi & Poizner 1988a, 1988b; Poizner, Klima & Bellugi 1987).

Language Capacities of Left- and Right-Brain-Lesioned Signers

We have worked with many deaf signers who have suffered unilateral brain damage due to lesions. This report concerns three subjects with damage to the left hemisphere and three with damage to the right hemisphere. Our general program includes the following array of probes:

1. Our ASL adaptation of the Boston Diagnostic Aphasia Examination.
2. Linguistic tests we designed to assess the processing of the structural levels of ASL (sublexical, semantic, morphological, and syntactic).
3. An analysis of production of ASL at all linguistic levels.
4. Tests of nonlanguage spatial processing.

The battery of language and nonlanguage tasks was administered to deaf brain-lesioned subjects and to matched deaf controls. The signers with left hemisphere damage showed frank sign language aphasias (as indicated by their results on our aphasia examination) on tests for processing the structural levels of ASL, and on a linguistic analysis of their signing. One left-hemisphere-damaged signer was agrammatical for ASL. Her signing was severely impaired, halting, and effortful, reduced often to single sign utterances, and completely without the syntactic and morphological markings of ASL. Her lesion was typical of those that produce agrammatical aphasia for spoken language.

The other two left-hemisphere-damaged signers had fluent sign aphasias. They differed, however, in the nature of their impairments. One made selection errors in the formational elements of signs, producing the equivalent of phonemic paraphasias in sign language. Her signing, however, was perfectly grammatical, though vague. She often failed to specify to whom or to what she was referring. The third left-hemisphere-damaged signer made many grammatical errors. He made selection errors and additions within ASL morphology and erred in the spatialized syntax and discourse processes of ASL. Thus, differential damage within the left hemisphere produced sign language impairments that were not uniform but cleaved along lines of linguistically relevant components. Figure 4 represents characteristic errors of the three left-lesioned patients.

The signers with right hemisphere damage presented special issues in testing for language impairments because sign language makes linguistic use of space, and these signers showed nonlanguage spatial deficits. Left hemispatial neglect, for example, may introduce particular difficulties in signing, since the addressee must either view signs in the neglected visual field or shift his or her gaze away

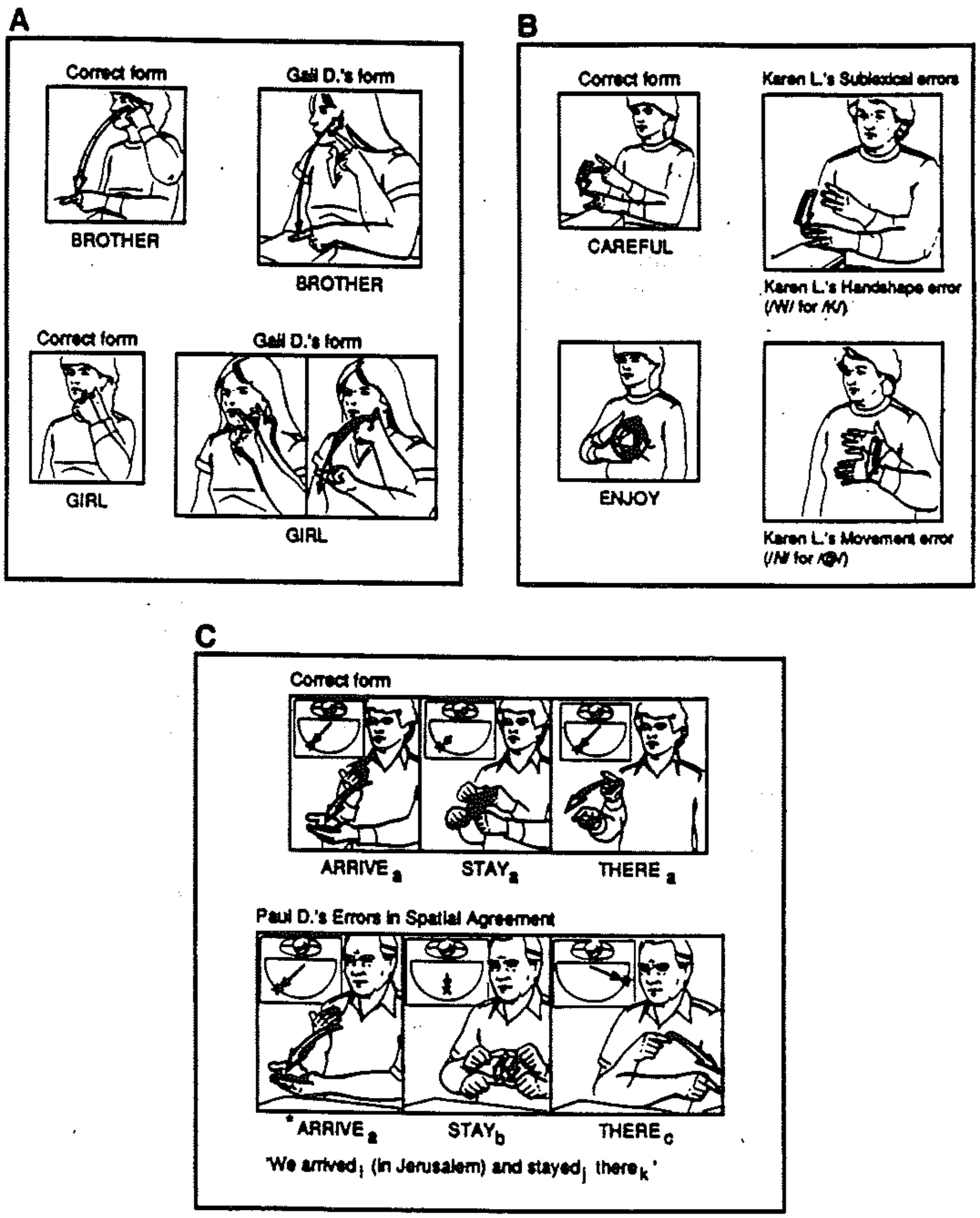

FIGURE 4 Characteristic errors across patients.

from the signer. Quite remarkably, the first three signers with right-hemisphere damage whom we examined in depth were not aphasic for sign language. They exhibited fluent, grammatical, virtually error-free signing, with a good range of grammatical forms, no agrammatism, and no signing deficits. Furthermore, only the right-hemisphere-damaged patients were unimpaired in our tests of ASL structures at different linguistic levels.

In one of the tests of ASL linguistic structure, subjects were asked to indicate the two pictures that represented the sign equivalent of *rhyme* in ASL (see Figure 5a). The correct answer in this case would be *apple* and *key* since their associated signs are the same in two of the three major parameters (e.g., they have the same handshape and movement, but differ only in spatial location). On the ASL Rhyming Test and, indeed, across the range of language tests given, the right-hemisphere-damaged signers were not impaired, whereas the left-hemisphere-damaged signers were generally impaired.

This preserved signing existed in the face of marked deficits among the right-hemisphere-damaged signers in processing nonlanguage spatial relations (these deficits are described below). Across a range of tests, these signers showed the classic visual-spatial impairments found in hearing patients with right hemisphere damage. The right-hemisphere-damaged patients, then, had no impairment in the grammatical aspects of their signing, including their spatially organized syntax; they even used the left side of signing space to represent syntactic relations, despite their neglect of the left hemispace in nonlanguage tasks.

Spatial Cognition in Right- and Left-Hemisphere-Damaged Signers

We administered selected tests that are sensitive distinguishers of visual-spatial performance in left- versus right-hemisphere-damaged hearing subjects. These tests included drawing, block design, selective attention, line orientation, facial recognition, and visual closure. As an example, results of a block design test given to deaf signers in which the subjects must assemble either four or nine three-dimensional blocks to match a two-dimensional model of the top surface are shown in Figure 5b.

Clear-cut differences in performance were found between the left-hemisphere-damaged patients (upper row) and the right-hemisphere-damaged patients (lower row). The left-hemisphere-damaged patients produced correct constructions on the simple block designs and made only internal-feature errors on the more complex designs. In contrast, the right-hemisphere-damaged patients produced erratic and incorrect constructions and tended to break the overall configurations of the designs. The general difficulty of the right-hemisphere-damaged patients with this task reflects the classic visual-spatial impairments found in hearing patients with right-hemisphere damage. The two groups of deaf signing patients differed across the range of visual-spatial tasks administered, with right-hemisphere-damaged patients reflecting gross spatial disorganization. These nonlanguage data show that the right hemisphere in deaf signers can develop cerebral specialization for nonlanguage visual-spatial functions. The drawings of the right-hemisphere-damaged patients also tended to show severe spatial disorganization, whereas those of the left-hemisphere-damaged patients did not. The right-hem-

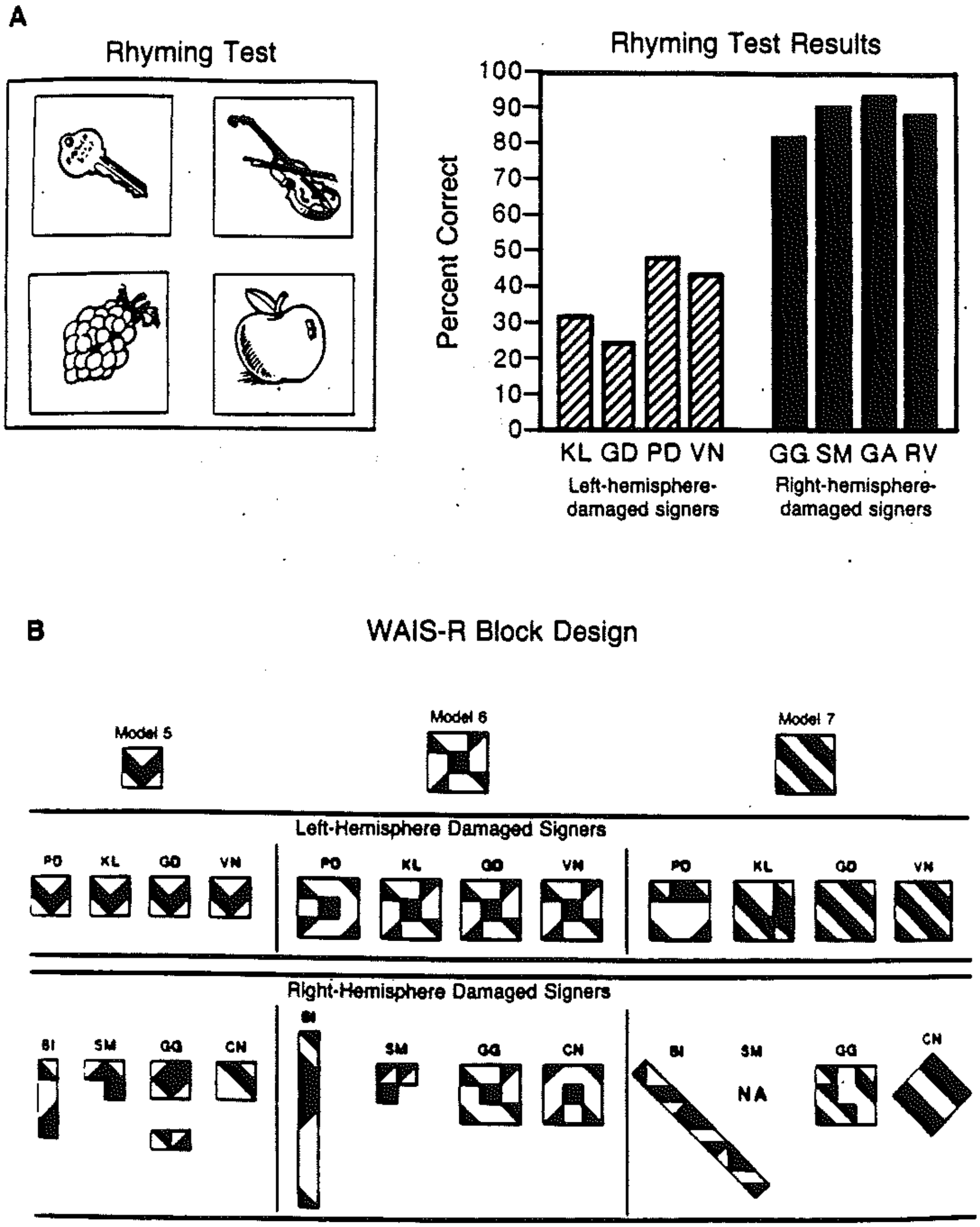

FIGURE 5 **The contrast between language and spatial abilities in left- and right-hemisphere-damaged signers.**

Note the double dissociation between language abilities (impaired in LHD but spared in RHD) and nonlanguage visuospatial abilities (spared in LHD but impaired in RHD) in these deaf signers.

isphere-damaged patients were not able to indicate perspective; several neglected the left side of space, and one right-hemisphere-damaged patient even added unprompted verbal labels to the drawings. The drawings of the left-hemisphere-damaged patients in general showed superiority, with overlap spatial configurations preserved.

One right-hemisphere-damaged signer, who was an artist before her stroke, showed severe spatial disorganization after the stroke, including neglect of left hemispace and inability to indicate perspective, but her sign language (including spatially expressed syntax) was completely unimpaired. In light of her severe visual-spatial deficit for nonlanguage tasks, correct use of the spatial mechanisms for signed syntax in these right-hemisphere-damaged patients may point to the abstract nature of these mechanisms in ASL. This point shows how little effect right-hemisphere damage can have on language function, even when expressed as a visual-spatial language. In contrast, the left-hemisphere-damaged signer, who was most severely aphasic for sign language (completely agrammatical, without any morphology or syntax), showed normal nonlanguage visual-spatial skills.

In summary, the right-hemisphere-damaged patients generally showed severe left-side neglect and were seriously impaired in nonlanguage visual-spatial capacities, but their signing was still fluent and remarkably unimpaired. They showed virtually no impairments in any of the grammatical aspects of their signing; their impairments, however, were vividly apparent in spatial mapping, which we will consider next.

The Contrast Between Spatial Syntax and Spatial Mapping

Spatial contrasts and spatial manipulations figure structurally at all linguistic levels in ASL. For syntactic functions, spatial loci and relations among these loci are actively manipulated to represent grammatical relations. 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. We investigated the breakdown of two uses of space within sign language, one for syntax and the other for mapping. Subjects were asked to describe the spatial layout of their living quarters from memory. In this task, signing space is used to describe actual space, and spatial relations are thus significant. The descriptions given by the right-hemisphere-damaged signers were grossly distorted spatially. In contrast, room descriptions of the left-hemisphere-damaged signers were linguistically impaired (matching their linguistic breakdown in other domains) but without spatial distortions.

When space was used in ASL to represent syntactic relations, however, the pattern was reversed. The left-hemisphere-damaged signer who showed consistent failure in his spatially organized syntax was able to describe the layout of his room with some omissions but no spatial distortions. A dissociation was also dramatically displayed in a right-hemisphere-damaged signer. The description she gave of her room showed severe spatial disorganization—furniture was piled in helter-skelter fashion on the right, and the entire left side of the signing space was left bare. However, in her use of the spatial framework for syntax in ASL, she established loci freely throughout the signing space (including on the left) and maintained consistent reference to spatial loci. Thus, even within signing, the use of space to represent syntactic relations and the use of space to represent spatial relations may be differentially affected by brain damage, with the syntactic relations disrupted by left-hemisphere damage and the spatial relations disrupted by right-hemisphere damage (Bellugi, Poizner & Klima 1989).

Lateralization of Facial Signals with Linguistic Function

Investigations of lateralization for sign language have so far focused on manual signs. However, sign language has another structural layer that also can afford a clue to hemispheric specialization, namely nonmanual (facial) signals. For signers of ASL, facial signals can function in two distinct ways, one linguistically, the other to convey affect (Corina 1989; Liddell 1980; Reilly, McIntire & Bellugi 1990, in press). In users of spoken languages, there is by now considerable evidence for right hemisphere involvement in the processing of faces, especially facial affect. Facial signals in ASL thus pose an interesting challenge to strict right-hemisphere processing of facial expression, since certain facial signals in ASL function as part of a tightly constrained linguistic system.

We have new evidence that affective facial signals and linguistic facial signals are differentially lateralized for deaf signers. Parallel lines of investigation in brain-damaged and brain-intact signers are being carried out. In one line of experimentation, linguistic and affective facial signals are presented tachistoscopically to deaf signers without known neurological disorders so that we may infer which cerebral hemisphere is primary in mediating the processing of each type of signal. Figure 6 shows examples of affective and linguistic facial expressions that were used in the delayed matching task. Deaf signers showed greater left-hemisphere mediation of those facial signals that served a linguistic function compared to those with an affective function, while hearing subjects unfamiliar with sign language did not show this difference (Corina 1989).

Two deaf signers, one with a lesion to the right hemisphere and one with a lesion to the left hemisphere, show important dissociations between affective and linguistic facial expression signals. We examined all instances in two stretches of signing (narrative and biographical sketch) of clear sentence contexts in which either affective facial expression would be expected or specifically linguistic facial expression (e.g., adverbial, relative clause, conditional) would be required. Interestingly, the right-lesioned patient was far more likely to produce linguistic facial expression where it was required and showed a clear tendency to omit affective facial expression where it was expected. Thus, linguistic facial expression was relatively spared while affective facial expression was quite impaired in the right-lesioned signer (see Figure 6). In contrast, the left-lesioned signer showed precisely the opposite effect, with full use of affective facial expression present, but linguistic facial expression absent where it would be expected.

These are important findings, since presumably one and the same muscular system is involved. Thus, one cannot account for the findings in terms of weakness of facial musculature, but rather in terms of a dissociation between linguistic and affective facial expression (Bellugi, Corina, Norman, Klima & Reilly 1989). By examining, in deaf signers, hemispheric specialization for the processing of both affective facial signals and linguistic ones, we can investigate an area in which physical form vs. linguistic function may be finely differentiated as a basis for cerebral dominance.

CONVERGING EVIDENCE REGARDING BRAIN ORGANIZATION FOR SIGN

A recent study analyzed the sign language of a hearing signer proficient in ASL during a left intracarotid injection of sodium amytal (Wada Test), and before and after a right temporal lobectomy for her epilepsy (Damasio, Bellugi, Damasio, Poizner & van Gilder 1986). Neuropsychological and anatomical asymmetries suggested left cerebral dominance for an auditory-based language. Single Photon Emission Tomography revealed lateralized activity of left Broca's and Wernicke's areas for spoken language. The Wada Test, during which all left language areas were rendered inoperative, caused a marked aphasia in both English and ASL. The patient's signing was markedly impaired, with many incorrect sign responses and sign neologisms. Interestingly, since she was hearing and could sign and speak at the same time, it was possible to compare her responses in two languages simultaneously—a unique possibility for languages in different modalities. This comparison revealed frequent mismatches between word and sign, the sign often incorrect both in meaning and in form.

Subsequently, the patient had the anterior portion of her right temporal lobe surgically removed. Analysis of her language after the surgery revealed no impairment of either English or sign language. These findings add further support to the notion that the left cerebral hemisphere subserves language in visual-spatial as well as auditory mode.

Very important converging evidence also comes from a combination of behavioral and neurophysiological studies in deaf signers without lesions (Neville 1988, in press; Neville & Lawson 1987). In Neville's studies, digitized sequences of ASL signs were presented to the left and right visual fields of deaf native signers and hearing nonsigners. The deaf native signers, but not the hearing nonsigners, showed specific left-hemisphere specialization for processing signs of ASL, providing strong evidence for left-hemisphere specialization for sign language in deaf signers without brain lesions. From these converging perspectives, it is becoming clear that the primary specialization of the left hemisphere rests not on the form of the signal, but rather on the linguistic function it subserves.

SUMMARY

We have reviewed some studies that investigate language, its formal architecture, and its representation in the brain, by analyzing visual-spatial languages passed down from one generation of deaf people to the next. Analysis of patterns of breakdown in deaf signers provides new perspectives on the determinants of hemispheric specialization for language. First, the data show that hearing and speech are not necessary for the development of hemispheric specialization: Sound is *not* crucial. Second, it is the left hemisphere that is dominant for sign language. Deaf signers with damage to the left hemisphere show marked sign language deficits but relatively intact capacity for processing nonlanguage visual-spatial relations. Signers with damage to the right hemisphere show the reverse pattern. Thus, not only is there left-hemisphere specialization for language functioning, but there is also a complementary specialization for nonlanguage spatial functioning.

The fact that grammatical information in sign language is conveyed via spatial manipulation does not alter this complementary specialization. Furthermore, components of sign language (lexicon and grammar) can be selectively impaired, reflecting differential breakdown of sign language along linguistically relevant lines. These data suggest that the left hemisphere in humans may have an innate predisposition for language, regardless of the modality. Since sign language involves an interplay between visual-spatial and linguistic relations, the study of sign language breakdown in deaf signers provides a new key to the link between hand and brain.

COGNITION, EDUCATION, AND DEAFNESS: THE FUTURE CHALLENGE

For educators who are committed to the improvement of cognitive functioning of all deaf learners, the data reported here suggest the importance of

1. Continuing experimentation with alternative communication modalities in the classroom;
2. Preparing teachers who are knowledgeable about the application of research results from the general fields of both cognition and language; and
3. Keeping high expectations for deaf learners.

Our data and that of other authors in this volume continue to indicate that deaf learners as a group have the full normal range of intellectual potential, and some aspects of cognition may even show an enhancement. We hope that educators who are familiar with cognition research can devise applications now to help learners reach their full potential.

This is a very exciting time to be thinking about the future of the education of deaf children. As we all know, there has been a rapid increase in awareness of Deaf culture and of its cultural products. Many wonderful expressions of Deaf culture—art, poetry, literature, theater—are occurring now that were not thought of ten or twenty years ago. "The Deaf Way," a celebration of Deaf culture from around the world, took place at Gallaudet University during the summer of 1989. One can now develop an extensive library from excellent videotapes available for teaching sign language and for watching storytelling, poetry, history, and narrative in sign language.

Linda Bove, a deaf actress, is an important figure on *Sesame Street* who provides a role model for deaf children. The television program *Deaf Mosaic*, among many others, is a news magazine that provides news features and interviews with deaf leaders. There are also classics, fairy tales, and stories from different countries on videotape. There are many adult books, children's books, and television programs for teaching different forms of signed language, including Signed English. There are a variety of techniques, including computerized ones, for captioning films and television broadcasts, and even for captioning on-line meetings and classes. There are many books about Deaf culture and history (e.g., Padden & Humphries 1988; Sacks 1989; Lane 1984).

Technologies are becoming available that provide opportunities for education that were undreamed-of ten years ago. For example, Hanson and Padden have developed a laser-disc video interface that allows deaf children to communicate by means of a touch screen and a computer keyboard. In this way, children can go back and forth between English and ASL, touching the screen to see ASL and English at the same time. This is a powerful and highly motivating way to approach English through signs (Hanson & Padden, in press). ASL, now offered for course credit in many colleges and universities across the country, is accepted as a way of fulfilling the foreign language requirement. Deaf children now have access to sign language in a variety of forms, ranging from ASL to Signed English, and some bilingual programs are teaching English through ASL. These teaching methods will have important ramifications in the children's development of language, whether ASL or English.

This is an exciting time for the fields of cognition, deafness, and education. The papers in this volume communicate the current state of these developments and are intended to stimulate the reader to envision the future of deaf education in light of this new work.

REFERENCES

Bellugi, U. 1988. The acquisition of a spatial language. In *The development of language and language researchers, essays in honor of Roger Brown*, ed. F. Kessell, 153–185. Hillsdale, NJ: Lawrence Erlbaum Associates.

Bellugi, U., Corina, D., Norman, F., Klima, E., & Reilly, J. 1989. Differential specialization for linguistic facial expression in left and right lesioned deaf signers. *Academy of Aphasia*, Santa Fe, NM.

Bellugi, U., Klima, E., Lillo-Martin, D., O'Grady, L., & Vaid, J. 1986. *Examining language dominance through hand dominance*. Eleventh Annual Boston University Conference on Child Language Development.

Bellugi, U., Poizner, H., & Klima, E. 1989. Language, modality and the brain. *Trends in Neurosciences* 10:380–388.

Bellugi, U., & Studdert-Kennedy, M., eds. 1980. *Signed and spoken language: Biological constraints on linguistic form*. Deerfield Beach, FL: Verlag Chemie.

Bellugi, U., Tzeng, O.J.L., Klima, E.S., & Fok, A. 1989. Dyslexia: Perspectives from sign and script. In *From reading to neurons*, ed. A.M. Galaburda, 137–172. Cambridge: MIT Press/Bradford Books.

Bellugi, U., van Hoek, K., Lillo-Martin, D., & O'Grady, L. 1988. The acquisition of syntax and space in young deaf signers. In *Language development in exceptional circumstances*, ed. D. Bishop & K. Mogford, 132–149. Edinburgh: Churchill Livingstone.

Corina, D. 1989. Recognition of affective and noncanonical linguistic facial expressions in hearing and deaf subjects. *Brain and Cognition* 9:227–237.

Corbett, E.E. 1985. Cognition, education, and deafness: The challenge. In *Cognition, education, and deafness: Directions for research and instruction*, ed. D.S. Martin, 16–20. Washington, DC: Gallaudet University Press.

Damasio, A., Bellugi, U., Damasio, H., Poizner, H., & van Gilder, J. 1986. Sign language aphasia during left hemisphere amytal injection. *Nature* 322:363–365.

Fok, Y.Y.A., & Bellugi, U. 1986. The acquisition of visual-spatial script. In *Graphonomics: Contemporary research in handwriting*, ed. H. Kao, G. van Galen, & R. Hoosain, 329–355. Amsterdam: North Holland.

Fok, Y.Y.A., Bellugi, U., van Hoek, K., & Klima, E.S. 1988. The formal properties of Chinese languages in space. In *Cognitive aspects of the Chinese language*, ed. M. Kiu, H.C. Chen, & M.J. Chen, 187–205. Hong Kong: Asian Research Service.

Hanson, V.L., & Padden, C. In press. Computers and videodisc technology for bilingual ASL/English instruction of deaf children. In *Cognition, education, and multi-media: Exploring ideas in high technology*, ed. D. Nix & R. Spiro. Hillsdale, NJ: Lawrence Erlbaum Associates.

Johansson, G. 1975. Visual motion perception. *Scientific American*, 232, 76–89.

Klima, E.S., & Bellugi, U. 1979. *The signs of language*. Cambridge: Harvard University Press.

Klima, E.S., Bellugi, U., & Poizner, H. 1988a. Grammar and space in sign aphasiology. *Aphasiology* 2:319–328.

———. 1988b. The neurolinguistic substrate for sign language. In *Language, speech, and mind*, ed. L.M. Hyman & C.N. Li, 138–152. London: Routledge.

Lane, H. 1984. *When the mind hears: A history of the deaf*. New York: Random House.

Lenneberg, E. 1967. *Biological foundations of language*. New York: John Wiley & Sons.

Liddell, S. 1980. *American Sign Language syntax*. The Hague: Mouton.

Liddell, S., & Johnson, R. 1986. American Sign Language compound formation processes, lexicalization, and phonological remnants. *Natural Language and Linguistic Theory* 4:445–513.

Marler, P. 1970. Bird song and speech: Could there be parallels? *American Scientist* 59:669–673.

Neville, H. J. 1988. Cerebral organization for spatial attention. In *Spatial cognition: Brain bases and development*, ed. J. Stiles-Davis, M. Kritchevsky, & U. Bellugi, 327–342. Hillsdale, NJ: Lawrence Erlbaum Associates.

———. In press. Neurobiology of cognitive and language processing: Effects of early experience. In *Brain maturation and behavioral development: Biosocial dimensions*, ed. K. Gibson & A.C. Peterson. New York: Aldine de Gruyter.

Neville, H.J., & Lawson, D. 1987. Attention to central and peripheral visual space in a movement detection task (Parts I-III). *Brain Research* 405:253–294.

Newport, E.S. 1988. Constraints on learning and their role in language acquisition: Studies of the acquisition of American Sign Language. *Language Sciences* 10(1): 147–172.

Padden, C., & Humphries, T. 1988. *Deaf in America: Voices from a culture*. Cambridge: Harvard University Press.

Poizner, H. 1983. Perception of movement in American Sign Language: Effects of linguistic structure and linguistic experience. *Perception and Psychophysics* 33(3):215–231.

Poizner, H., Fok, Y.Y.A., & Bellugi, U. (In press). The interplay between perception of language and perception of motion. *Language Sciences*.

Poizner, H., Klima, E.S., & Bellugi, U. 1987. *What the hands reveal about the brain.* Cambridge: MIT Press/Bradford Books.

Poizner, H., Klima, E.S., Bellugi, U., & Livingston, R. 1986. Motion analysis in a visual gestural language. In *Event cognition*, ed. V. McCabe & G. Balzano, 155–174. Hillsdale, NJ: Lawrence Erlbaum Associates.

Reilly, J., McIntire, M., & Bellugi, U. 1990. Faces: The relationship between language and affect. In *From gesture to language in hearing and deaf children*, ed V. Volterra & C. Erting. New York: Springer-Verlag.

Reilly, J., McIntire, M., & Bellugi, U. In press. Baby face: A new perspective on universals in language acquisition. In *Theoretical issues in sign language research: Psychology*, ed P. Siple & S. Fischer. Chicago: University of Chicago Press.

Sacks, O. 1989. *Seeing voices: A journey into the world of the deaf.* Berkeley: University of California Press.

Sign Language Studies. Linstok Press.

Supalla, S. In press. Manually coded English: The modality question in signed development. In *Theoretical issues in sign language research*, ed. P. Siple & S. Fischer. Chicago: University of Chicago Press.

Vaid, J., Bellugi, U., & Poizner, H. 1989. Hand dominance for signing: Clues to brain lateralization of language. *Neuropsychologia* 27:949–960.

Wilbur, R. 1987. *American Sign Language*. Boston: Little, Brown & Co.