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Language, Spatial Cognition, and Brain Organization

Ursula Bellugi

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Bellugi has been a visiting professor at Rockefeller University, the University of Hong Kong, and at Consiglio Nationale delle Richerche in Rome. She has contributed to many papers and texts, including *The Signs of Language* (which won an award from the Association of American Publishers), and *What the Hands Reveal about the Brain*. Since 1970, Bellugi and Klima have received grants from the National Institutes of Health, National Science Foundation, March of Dimes, MacArthur Foundation, and others. Their research explores some of the central issues of cognitive neuroscience that link cognitive functions to brain organization. These issues include studies of language, modality and the brain; brain organization; clues from sign aphasia; spatial language and spatial cognition; and fractionations between language and cognition.

Language, Spatial Cognition, and Brain Organization

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Until recently, almost everything known about human language was derived from the study of spoken language. However, in the same manner that humans around the world have developed various spoken languages—which differ only superficially from the linguistic point of view—deaf individuals have developed and passed down through the generations "languages in the hands and for the eyes." Over the last 20 years or so, studies of the sign languages used by deaf people have provided insight into many aspects of language in general. One major difference between sign and spoken languages is that sign languages—unlike spoken languages—make use of space at all linguistic levels in crucial ways. Thus, the study of sign languages has also shed light on aspects of spatial cognition. Finally, comparison of the brain areas specialized for processing sign versus spoken languages has revealed the extent to which the sensory modality of language—visual-manual versus auditory-vocal, respectively—influences brain organization.

The complex structure and spatial dependence of sign languages can be illustrated with several examples from American Sign Language (ASL). Thus, signs—such as "candy," "apple," and "jealous"—can share the same place of articulation and movement, but differ in hand shape (Figure 1A). Alternatively, the words "summer," "ugly," and "dry" are indicated with identical hand shapes and movements, but are differentiated from one another by the spatial location in which the sign is made—across the

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forehead, nose, and chin, respectively (Figure 1B). Finally, movement alone may distinguish words—for example, "tape," "chair," and "train"—that share identical space and hand shape (Figure 1C).

ASL and other sign languages possess rich grammatical structures, which are totally unrelated to those of the languages of the corresponding hearing populations—English, in the case of ASL—and which are conveyed by spatial and movement patterns imposed on individual signs. Crucial differences in syntax are also apparent between sign and spoken languages. Thus, in English, the order of words in a sentence sometimes is important;

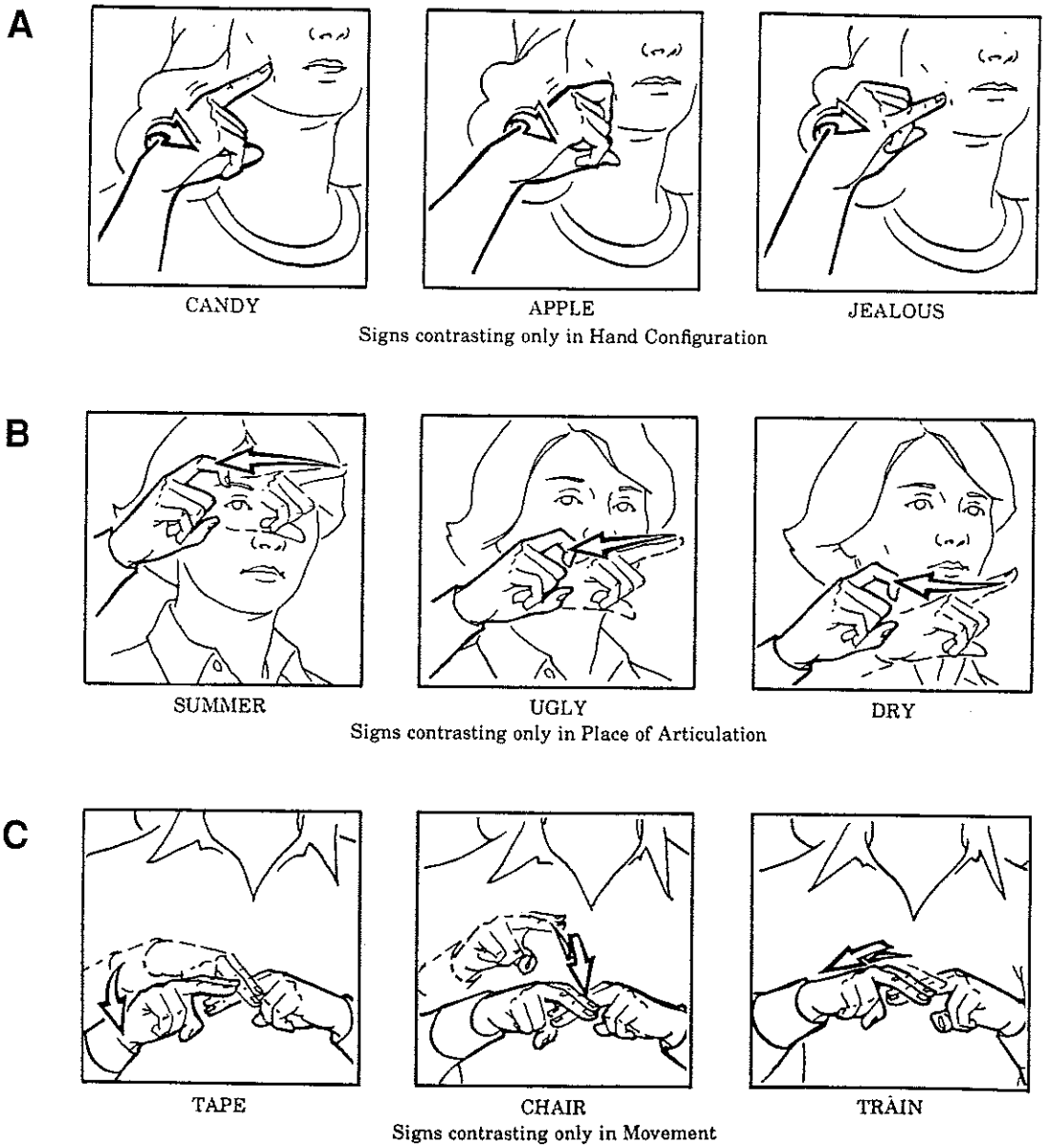


Figure 1. Use of hand shape (**A**), space (**B**), and movement (**C**) to distinguish signs in ASL. [Reproduced with permission from Klima, Bellugi (1979).]

for example, although the words in the sentences "the dog bites the cat" and "the cat bites the dog" are identical, the orders of the words and the meanings of the sentences are different. However, in ASL, the signer sets up a defined plane in space, in which nominals can be placed at arbitrary positions; thus, the sign for "cat" could be made at any position in the defined plane, and the sign for "dog" at any other position in the plane, and the direction of movement of the sign for "bites" would reveal the subject and object of the verb. The introduction of nouns at specific locations in the plane of signing space also allows prenominal referencing: pointing back to the space allocated to a previously introduced noun sign as a means of referring back to that noun later in the discourse. Moreover, in addition to the signing plane for definite reference, additional planes are set up for generic and hypothetical reference, for example.

Studies on the structure of sign languages have provided insight into human languages in general, particularly into how languages are formed and their basic organizing principles. One of the major superficial differences between sign and spoken languages is that whereas spoken languages rely on rapid temporal patterning, sign languages rely on simultaneous, multi-dimensional patterning.

In addition to ASL, other sign languages have developed among generations of deaf individuals in communities for which the spoken language is not English. However, although ASL and Chinese Sign Language (CSL), for example, use different signs and show differences in morphology and syntax, the basic principles of the two sign languages are similar, providing evidence that the mode in which a language is rooted influences the underlying structure of language. Also of interest is the fact that ASL and the sign language used in Great Britain—in each case the language of the corresponding hearing population being English—show many superficial differences and are mutually incomprehensible. Thus, sign languages in different deaf communities have evolved independently and autonomously. Furthermore, a native signer in one sign language often shows an "accent" when learning a different sign language; the accent is manifest by subtle differences in hand shapes and movements.

A series of studies have examined the interplay between perceptual and linguistic processes in sign languages. One approach that has been applied in these studies is based on a technique originally used by Johansson to look at biological motion. This technique involves attaching point-light sources to the fingertips and arm joints so that grammatical signing can be analyzed by recording the movements of the lights (Figure 2). Differences in the perception of such light displays are apparent between hearing and deaf

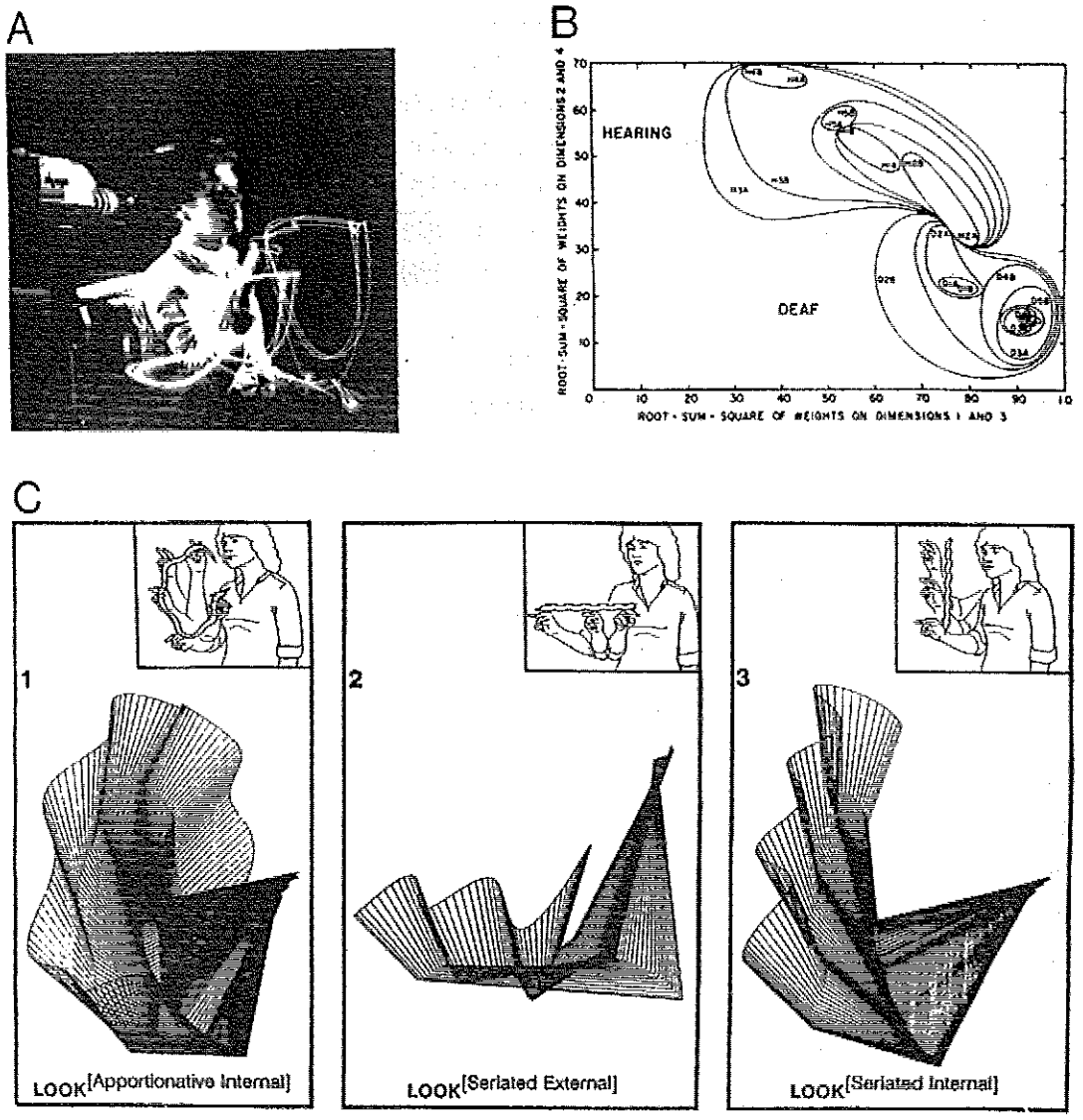


Figure 2. Multidimensional analysis of movement organized into a linguistic system. (**A**) A grammatical inflection conveyed through dynamic point-light displays. (**B**) Hierarchical clustering of correlations among subjects (closed contours) superimposed on the multidimensional scaling of judgments of movement similarity by deaf and hearing subjects. The position of each replication (A or B) of each deaf subject (D1 through D5) and each hearing subject (H1 through H5) was determined from each subject's combined weights on dimensions 2 (plane) and 4 (direction) versus his combined weights on dimensions 1 (repetition) and 3 (direction) of the scaling solution. Note the virtually complete separation between deaf and hearing subjects, reflecting the different perceptual salience of dimensions of movement for the two groups. (**C**) Three-dimensional reconstructions of the positions of the arm and hand for grammatical inflections in ASL contrasting in both planar locus and geometric array. The first and third reconstructions contrast minimally in geometric array (circular versus linear path movement), whereas the second and third reconstructions contrast minimally in planar locus (horizontal versus vertical). [Reproduced with permission from Bellugi, Poizner, Klima (1989).]

subjects and between American and Chinese deaf subjects. One specific question that has been addressed with this technique concerns whether individuals who have been deprived of auditory experience from birth and who communicate by sign language show the same spatial cognitive capacity as hearing subjects. In one approach to this question, pseudo–Chinese characters were presented as point-light displays written in the air—the images therefore include both the strokes and the transitions between them—to Chinese deaf and hearing children. The children were then required to write down what they thought were the underlying characters of the displays. The characters drawn by the deaf, signing children were significantly better representations of the characters underlying the light displays than those drawn by the hearing children. These results and those of many other studies suggest that deaf children, as well as deaf adults, show a distinct advantage in certain aspects of spatial cognition. It should be emphasized that these studies were performed with individuals who were deaf from birth and who had deaf parents.

The study of brain-damaged deaf signers has made an important contribution to our knowledge of the organization of higher cognitive functions in the brain. Deaf signers with lesions either to the left or right hemisphere have been subjected first to a sign diagnostic aphasia examination, in order to obtain a profile of sign language deficits, and then to more specific tests of individual linguistic components, such as spatially organized syntax, morphology, and "phonology." Subjects were also required to undergo tests of nonlanguage spatial cognition. For each subject, the nature of the lesion was determined by computerized tomography or magnetic resonance imaging. Given that sign languages involve spatial processing at all linguistic levels, the most fundamental question addressed by these studies concerned how such languages are represented in the brain.

Deaf signers with left-hemisphere damage showed clear sign language aphasias, but the nature of the specific deficits varied among individuals. The ASL of one left hemisphere–damaged signer (G.D.) was found to be highly agrammatical (Figure 3A). Although this patient had a large lesion, she had no difficulty with motor acts such as smoking and drinking. However, she had great difficulty with signing across all levels; her signing was hesitant, with many articulatory problems, and was devoid of grammar and morphology. Her lesion was similar to those that produce agrammatical aphasia for spoken language. Another left hemisphere–damaged signer (K.L.) made sublexical, or "phonological," errors after her stroke (Figure 3B). Also, although she used space freely and consistently in signing, she neglected to set up nominal references, so it was not clear to whom or to what

she was referring in conversation. A third signer with a left-hemisphere lesion (P.D.) showed marked deficits in his ability to write English. Before his stroke, this subject was capable of elaborate writing in English, but after

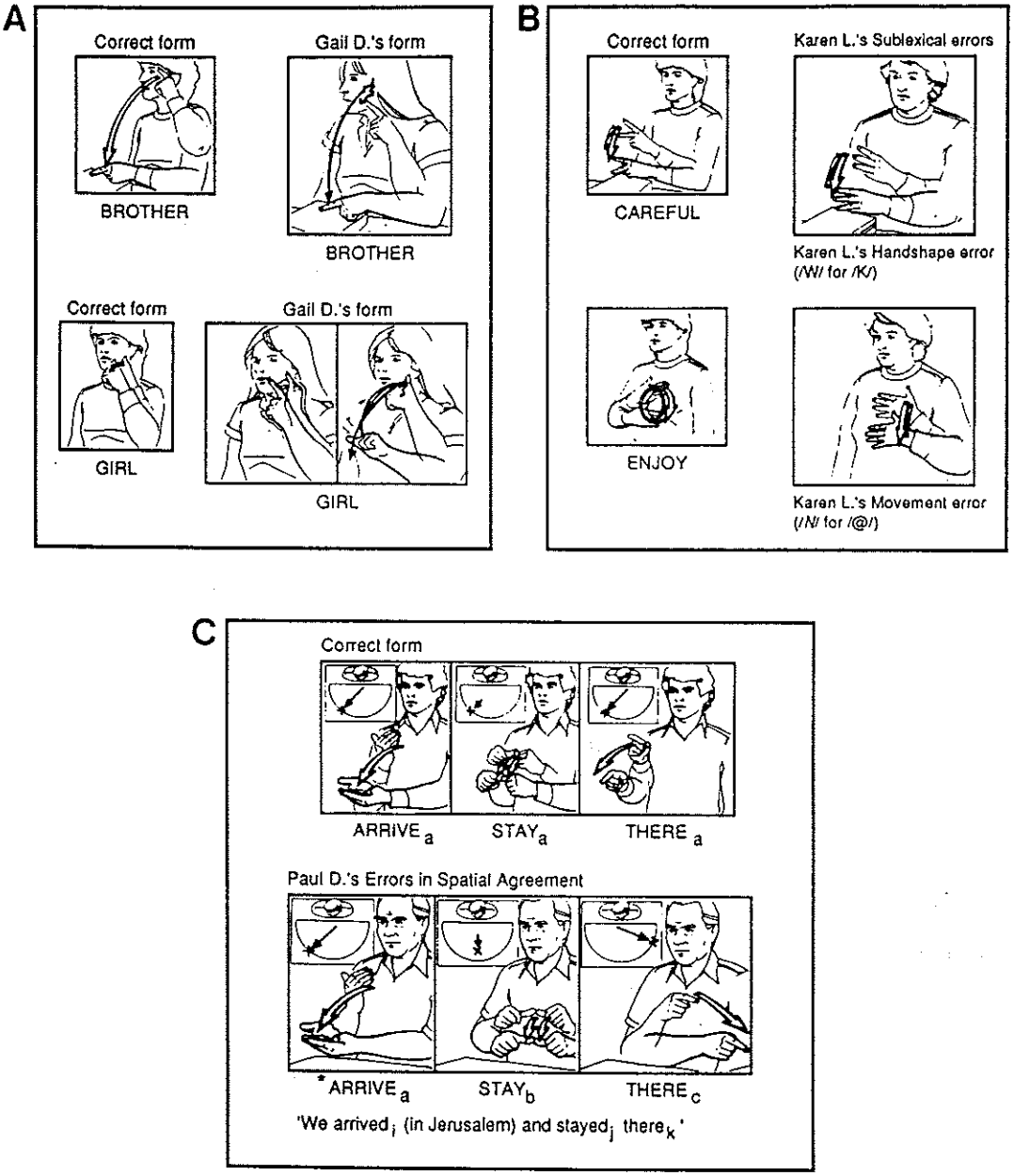


Figure 3. Characteristic errors of left-lesioned signers showing breakdown of ASL at different structural levels. (A) Articulatory difficulty characteristic of G.D.'s signing. In the example, she searches for the Handshape, Movement, and Location of two signs, although on other occasions she can produce the signs smoothly. (B) Sublexical (or "phonological") errors typical of K.L.'s signing. Note selection errors within major formational parameters of ASL of Handshape and Movement. These are the equivalent of phonemic paraphasias in spoken language. (C) Failure of spatially organized syntax in P.D.'s signing. Note the lack of spatial agreement in P.D.'s sentence, rendering it ungrammatical in ASL. [Reproduced with permission from Bellugi, Poizner, Klima (1989).]

the stroke his writing showed many features that are characteristic of Wernicke's aphasia, including neologisms and semantic errors (Figure 4). The signing of P.D. before and after his stroke showed a similar pattern to his writing. Whereas before the stroke, his signing was eloquent, after the stroke he made errors in morphology and invented grammatical neologisms. In addition, he displayed errors of spatially organized syntax (Figure 3C).

Surprisingly, given the spatial nature of sign language, deaf signers with right-hemisphere damage were found not to be aphasic for sign language. These individuals performed normally on tests for grammatical structure at various linguistic levels and on all language-processing tests applied.

Despite the preserved signing ability of right hemisphere–damaged signers, these individuals showed marked deficits on tests of nonlanguage

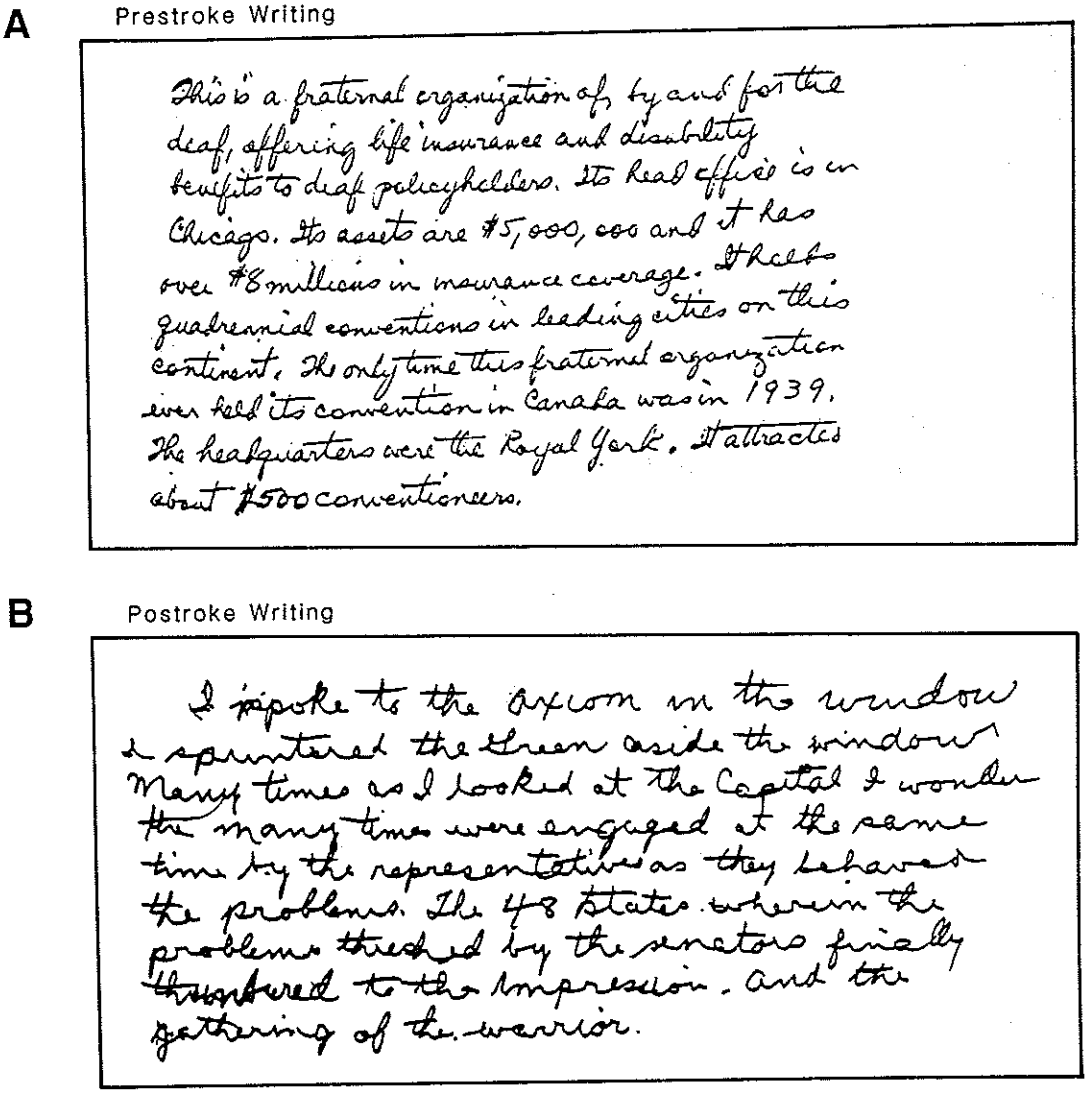


Figure 4. Example of writing of a deaf signer before (**A**) and after (**B**) a stroke in the left hemisphere. [Reproduced with permission from Poizner, Klima, Bellugi (1987).]

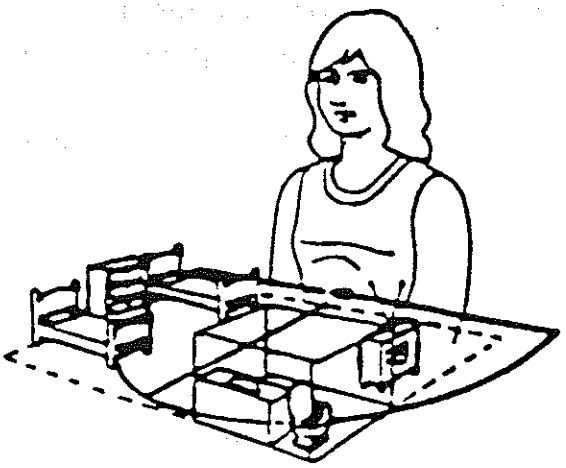
spatial cognition. On several tasks—including block design and drawing, for example—right-lesioned signers showed the classic visuospatial impairments that are typical of right-hemisphere damage in hearing subjects. One particularly interesting patient was an artist before a stroke in her right hemisphere; after the stroke, her drawings were disorganized, and showed a lack of perspective and neglect of left hemispace. Her signing, on the other hand, was impeccable, and she had no difficulty with processing sign language at any linguistic level. In contrast to the impaired performance of right-lesioned signers on nonlanguage visuospatial tasks, the performance of left-lesioned signers on such tasks was virtually normal.

Thus, the basic conclusion from these initial studies with brain-damaged deaf signers was that, despite its visual-manual mode, sign language, like spoken language, is processed by the left hemisphere.

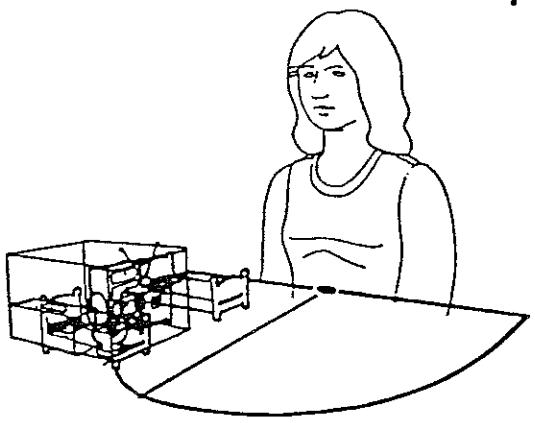
Although in ASL the hands constitute the primary means of communication, facial expressions are also used to convey information. In addition to conveying affect, as they do in spoken languages, facial expressions in ASL also subserve specific linguistic functions, including the marking of nonmanual adverbs, the functional equivalent of relative clauses, and conditionals. The linguistic facial expressions differ from the expressions used for affect, they use individual facial muscles, and they have rapid onsets and offsets that are tightly synchronized with the manual linguistic signals. Given that the same facial muscles contribute to linguistic and affective facial expressions, it was of interest to determine the hemispheric representation of both types of expression.

A right-lesioned deaf signer showed a dissociation in her ability to produce linguistic versus affective facial expressions. After her stroke, the subject usually produced linguistic facial expressions when required, but displayed little, if any, affective expression. In contrast, a left-lesioned signer showed normal affective facial expressions, but linguistically required facial expressions were largely absent. Similar results have been obtained with additional brain-damaged subjects.

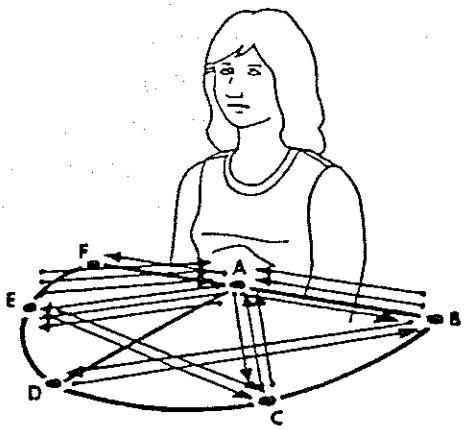
In addition to its use in syntax, space in ASL can also subserve a topographic function; thus, the positions in space in which signs are made can represent the actual topographic relations between the objects described. Whereas the spatial relations between nominals in syntax are arbitrary, spatial relations are significant when used in topographic representations. The brain mechanisms underlying the use of space in syntax and mapping have been studied by asking brain-damaged deaf signers to describe the layout of their homes. A right-lesioned signer was found to be able to use space correctly for syntax, but her description of her room showed severe



Correct Spatial Layout



Incorrect Signed Spatial Layout



Correct Signed Syntax

Figure 5. The use of space for syntactic and spatial relations by a right-lesioned deaf signer. [Reproduced with permission from Poizner, Klima, Bellugi (1987).]

spatial disorganization, with the contents of the room all piled up on the right side of signing space (Figure 5). In contrast, the description of his room given by a left hemisphere–damaged signer was impaired with respect to spatially organized syntax, but showed no spatial distortions with regard to the layout of objects in the room. Again, similar results have been observed with additional subjects. Thus, even within sign language, different hemispheres appear to subserve different uses of space: The left hemisphere

mediates the use of space for syntactic relations, and the right hemisphere is responsible for the use of space for the description of topographic relations.

One left hemisphere–damaged signer was found to show a principled separation between sign and gesture. When asked to give a sign, this subject would often provide a pantomime gesture instead—even when the sign and gesture were similar. Furthermore, in a signed version of the Pantomime Recognition Test, the patient was able to recognize the pantomimes as well as control subjects, but was impaired in the recognition of signs.

The cortical sites that are essential for spoken language and ASL have been mapped electrophysiologically in a hearing patient—who used ASL to communicate with her deaf sister—during brain surgery. An anatomical dissociation between sites essential for oral and signed language was apparent.

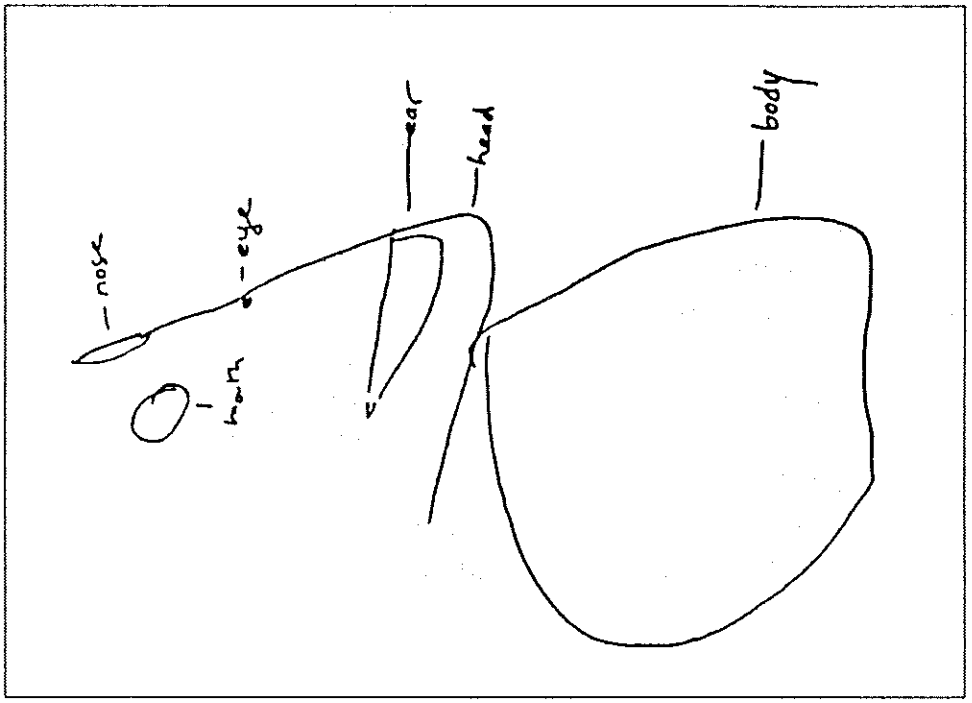
Clues to the way in which language and spatial cognition are represented in the brain have also been provided by studies of children with specific genetic neurodevelopmental disorders. Williams syndrome is a rare metabolic disorder that is characterized by pixie-like facial features, a heart defect, infantile hypercalcemia, and an unusual pattern of neuropsychological function. Adolescents with Williams syndrome show significant impairments in cognition and, like individuals with Down syndrome, are classified as mentally retarded. However, older children with Williams syndrome show a remarkable sparing of linguistic function. These children provide a vivid illustration of fractionation both within and across higher domains of cognition.

Children aged 10 years and above with Williams syndrome have been matched one-on-one with Down syndrome children with regard to age, sex, IQ, and background, in order to compare and contrast the neuropsychological characteristics of the two disorders. Williams syndrome children show a marked contrast between visuospatial and language abilities. For example, a drawing of an elephant by an 18-year-old adolescent with Williams syndrome and an IQ of 49 would be unrecognizable if it were not for the elaborate verbal description of an elephant she provided while making the drawing (Figure 6).

Tests of general cognitive ability have also shown a marked dissociation between cognition and language in Williams syndrome. For example, the concept of conservation of volume—illustrated by appreciation of the fact that, when water is poured from one container into another of a different shape, the volume remains the same—is normally acquired at an age of 6 to 8 years, which is also approximately the age at which children normally

18-Year-Old Williams Syndrome Subject

Drawing of an Elephant



Verbal Description of Elephants

And what an elephant is, it is one of the animals. And what the elephant does, it lives in the jungle. It can also live in the zoo. And what it has, it has long gray ears, fan ears, ears that can blow in the wind. It has a long trunk that can pick up grass, or pick up hay. . . . If they're in a bad mood it can be terrible. . . If the elephant gets mad it could stomp; it could charge. Sometimes elephants can charge, like a bull can charge. They have big long tusks. . . They can damage a car. . . It could be dangerous. When they're in a pinch, when they're in a bad mood it can be terrible. You don't want an elephant for a pet. You want a cat or a bird.

Figure 6. Contrast between visuospatial and language abilities in Williams syndrome. [Adapted with permission from Bellugi, Bihrle, Neville, et al. (1992).]

acquire the ability to appreciate passive sentence construction. However, despite their ability to perform perfectly on difficult tests of passive sentence construction, adolescents—and even adults as old as 44 years—with Williams syndrome cannot appreciate the principle of conservation of volume.

Williams and Down syndrome children contrast in the nature of their verbal responses to conditional questions, such as "What if you were a bird?" When scored for content, morphology, and syntax, the language of Down syndrome children is limited and ungrammatical, as one would expect from the degree of mental retardation. On the other hand, Williams syndrome children have rich, fanciful, and complex language (Figure 7). When they are compared on grammar tests, Williams syndrome children achieve high scores and Down syndrome children obtain low scores. The syntax of Williams syndrome children is remarkably spared, with rich, if perhaps somewhat deviant, semantics. Thus, when Down syndrome children are asked, for example, to "Name all the animals you can," a typical response might be something like "elephant, lion, snake, elephant, lion, bird, horsey, ice cream." From Williams syndrome children, a typical response might be "ibex, Chihuahua, saber-toothed tiger, vulture, albatross."

Language Processing in Williams and Down Syndrome Adolescents

What if you were a bird?

WS 1: You could fly, you could have babies, fly north or south, east or west.	**DS 1:** Bird seeds.
WS 2: Good question. I'd fly through the air being free.	**DS 2:** You'd be strong.
WS 3: I would fly through the air and soar like an airplane and dive through trees like a bird and land like a bird.	**DS 3:** I don't fly.
WS 4: I would fly where my parents could never find me. Birds want to be independent.	**DS 4:** I not a bird, you have wing.
WS 5: I would fly and if I liked a boy, I would land on his head and start chirping.	**DS 5:** Fly in the air.

Figure 7. Verbal responses of Williams (WS) and Down (DS) syndrome children to the conditional question "What if you were a bird?" [Courtesy Ursula Bellugi, Salk Institute for Biological Studies.]

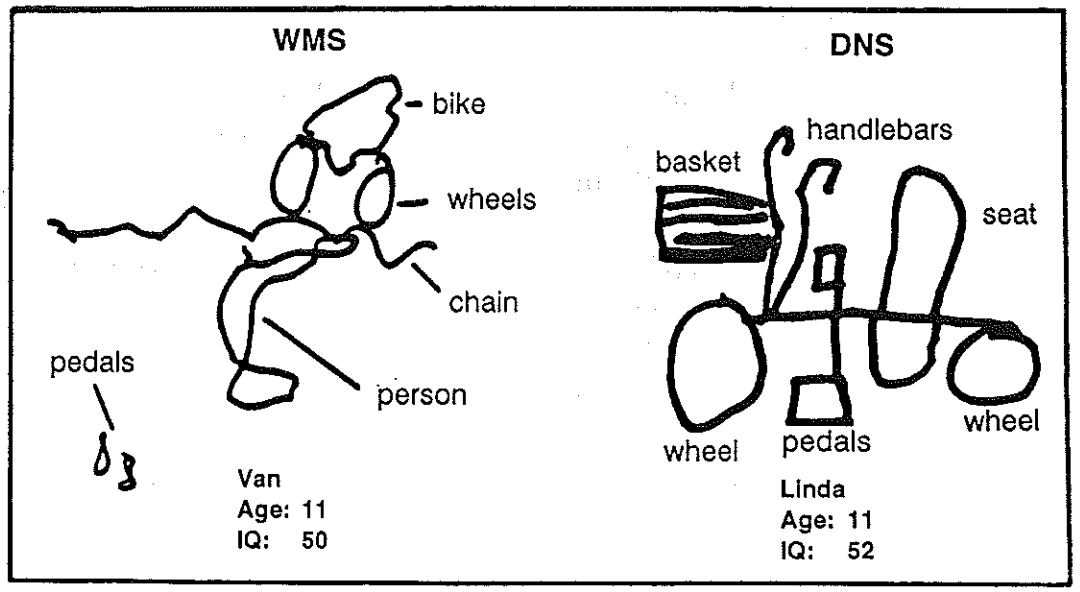


Figure 8. Drawings of a bicycle by Williams syndrome (WMS) and Down syndrome (DNS) subjects matched for age and IQ. [Reproduced with permission from Bellugi, Bihrle, Neville, et al. (1992).]

The visuospatial abilities of Williams and Down syndrome children have been compared in drawing tasks. In one such task, children were asked to draw a bicycle (Figure 8). As was the case with the drawing of the elephant described in the text above, the drawings made by Williams syndrome children were unrecognizable if it were not for the added labels. However, this impaired visuospatial capacity of Williams syndrome children is not a function of mental retardation per se; Down syndrome children of matched age and IQ typically produced complete, though simple, drawings in which the bicycle parts were all present, recognizable, and in the right place. The spatial disorientation shown in the drawings of Williams syndrome children is reminiscent of that associated with right-hemisphere damage.

Williams syndrome subjects also show impaired performance on tests of line orientation. However, on the Benton Facial Recognition Test, Williams syndrome children perform almost as well as normal adults. The performance of Williams syndrome children on these related tasks—neither of which involves any construction—thus reveals fractionation within the domain of nonlanguage spatial cognition.

In block design, both Down and Williams syndrome subjects fail completely, but analysis of the designs created reveals that the two groups fail in distinct and characteristic ways. Down syndrome children maintain the overall configuration of the blocks but make errors of internal detail,

whereas Williams syndrome children cannot maintain the overall configuration of the block design.

In summary, studies of brain-damaged deaf signers have revealed that the left hemisphere of the brain appears to have an innate predisposition for language in humans, regardless of the modality of language. The importance of the interplay between the visuospatial and linguistic aspects of sign languages suggests that studies of sign language breakdown in deaf signers may, in the long term, bring us closer to understanding the fundamental principles underlying hemispheric specialization. Furthermore, children with Williams syndrome show fractionations within the language and spatial domains of higher cognitive function. These fractionations differ from previously described neuropsychological profiles and should provide insight into the relations between brain structure and function.

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