Evidence for a right hemispheric involvement in language processing, in particular at the level of word meaning, has emerged within the last half century. Hemispheric functional specializations are dynamic; right hemispheric language participation significantly increases under certain conditions, such as during an epileptic seizure and during recovery from stroke. Interhemispheric connections via the corpus callosum critically mediate these and other higher cortical functions.

What is LH∇G1AD? It includes the ability to recognize orthographic (written) and phonologic (spoken) symbols and to extract meaning from these singly and in a series. The symbols may deviate considerably from their prototypes (e.g., D vs. G), just as the symbol’s meaning may deviate widely from its usual sense (e.g., baking vs. being a “tough cookie”), yet language includes the ability to realize the intended meaning by taking into consideration contextual (situational, emotional) factors. Both receptive and productive functions are fundamental to language: language also encompasses the ability to translate thought into an ordered and contextually meaningful series of phonologic or orthographic symbols.

Perhaps the most striking gross morphological characteristic of the human brain is that there are two seemingly symmetrical cerebral hemispheres. However, the functions attributed to each half of the brain are very distinct. One major question in neuroscience is how each hemisphere contributes to language processing. A variety of methods have been employed to answer this question: experimentation with “callosotomy” patients whose corpus callosum had been resected to prevent the spread of epileptic seizures from one hemisphere to the other allowed researchers to test each hemisphere in isolation; investigators have studied patients with brain damage restricted to one hemisphere to determine which language functions are impaired and which spared by the lesion; and finally, experimenters have conducted behavioral and functional imaging experiments with healthy individuals. The findings from these approaches provide converging evidence that each hemisphere plays a critical and, importantly, complementary role in language processing.

An association between the left cerebral hemisphere and language has been recognized since antiquity. Still, until the end of the 19th century, aphasics patients who had lost the ability to speak were considered mentally ill and confined to psychiatric institutions. Such a patient was sent to the French surgeon Paul Broca in 1861 for treatment of gangrene. For thirty years this patient’s utterances had been restricted to various expletives and the syllable “tan,” which Broca adopted the patient’s name. Tan died from unrelated causes shortly afterward, providing Broca with the opportunity to autopsy his brain. He discovered a lesion in the left inferior frontal lobe and associated this region with the capacity for articulation and speech. Supported by Wernicke’s association of the sound of words (Klangbilder) with the left superior posterior temporal lobe and Déjérine’s recognition of the acquired inability to read and write (alexia with agryphasia) subsequent to left angular gyral damage, a preeminent role of the left hemisphere in language processing was inexorably established. In 1865, the neurologist Norman Geschwind summarized the anatomical findings from aphasics patients in a model that outlined regions in the left hemisphere, and in particular their connections, that were critical for language.

As early as the 19th century, John Hughlings Jackson voiced an alternative account of Broca’s findings. According to Jackson, Broca had established a role of the left inferior frontal lobe in articulate language, not language per se. Significant Jackson’s differentiated conception of the functional neuroanatomy of language included an important role of the right hemisphere. This idea was in part reached through his careful observations of the spared language abilities of such aphasics patients as Tan, i.e., the “automatic” utterances of emotional expletives, words that could not be voluntarily repeated by the same patient on command: “The right hemisphere is the one for the most automatic use of words, and the left the one in which automatic use of words merges into voluntary use of words--into speech” (6). According to Jackson, the right hemisphere not only played a role in automatic language, but it also shared the ability of the left hemisphere to learn and comprehend speech. Despite Jackson’s clinical findings in support of a hemispheric balance of function, the general neurological maxim that conceptualized a “dominant” hemisphere as synonymous with the left hemisphere persisted.

A challenge to left hemisphere language dominance

The neurological axiom of an exclusive left hemisphere pre-eminence in language was fundamentally challenged by behavioral studies with callosotomy patients (11). In the “split-
brain” syndrome, unilateral sensory input is transmitted to the contralateral hemisphere, where, due to the lack of interhemispheric connections, it cannot be shared with the opposite hemisphere. For example, language stimuli transmitted to the right hemisphere were not available for processing in the left hemisphere. Thus callosotomy patients provided the neuropsychological community with an unequaled and unique opportunity to test the language functions of each hemisphere in isolation. So stunning were the findings from these patients that the principal investigator, the psychologist Roger Sperry, was later awarded the Nobel Prize.

The initial results from callosotomy patients seemed to confirm the neurological axiom of a language-incompetent right hemisphere: verbal information presented to the isolated right hemispheres could not be read aloud and language questions could not be verbally answered. However, later experimentation revealed that these findings merely reflected the right hemisphere’s lack of naming (articulatory) ability. Indeed, when nonverbal responses were required, a different picture emerged: the patients with disconnected right hemispheres demonstrated written and auditory word comprehension by, for example, selecting with their left hand the appropriate object from among an array of objects (4). These patients also evidenced competence on semantic (i.e., conceptual) tasks such as understanding synonyms and categorical (e.g., cat → animal) and functional (e.g., pencil → writing tool) relationships as well as more abstract language and conceptual abilities such as understanding metaphorical relationships.

Investigators thus began to more critically investigate language functioning in unilaterally right hemisphere brain-damaged patients. Consistent with the findings from callosotomy patients, right hemisphere brain-damaged patients appeared to have subtle semantic difficulties: they produced obscure responses on word-association tasks, displayed deficits in categorizing pictures of familiar objects into their respective categories, and lacked the normal tendency to cluster items according to superordinate category when recalling items from memory tasks. These patients also evidenced impaired metaphor appreciation, i.e., they had difficulties understanding the nonliteral, figurative meaning of verbal material (e.g., to be raining cats and dogs) (16). Indeed, patients with right hemisphere brain damage appear to rely primarily on literal meanings and neglect metaphorical relationships, whereas the opposite pattern is observed in left hemisphere brain-damaged patients (1). Correspondingly, right hemisphere brain-damaged patients have difficulties following indirect commands, drawing inferences, and understanding jokes.

Right hemisphere language competence: contributions from reading studies

The above reports of a right hemisphere involvement in language processing fueled experimental neuropsychological research with healthy subjects. These studies further functioned to rule out the possibility that the clinical findings were merely the result of developmental and/or postmorbid plastic changes in the language system. One common method to test the language functioning of each hemisphere is the split visual field paradigm, a method that induces a functional “split-brain” condition. Visual stimuli are presented extremenly by 10.220.33.1 on October 26, 2017 http://physiologyonline.physiology.org/ Downloaded from

| TABLE 1. Examples of right hemisphere language skills on split visual field tasks |
|-----------------------------|-----------------------------|-----------------------------|
| Factor                      | Explanation                                      | Examples                      |
| Grammatical class           | Processes nouns better than non-nouns.            | LAMP                         | DARK, JUMP, WHEN |
| Imageability                | Preferentially processes nouns for which an image can be retrieved. | TREE                         | IDEA               |
| Emotional valence           | Benefits from the emotional content of words.     | LOVE                         | DESK               |
| Pictographs                 | Benefits from the symbolic and pictorial word forms (e.g., logos, kanji, stenography). | TUBE                         |                    |
| Semantic relatedness        | Purportedly specialized for processing distantly as opposed to closely related material. | JOURNEY, LIFE                | FLOWER, TREE       |
| Task demands                | Performs better when asked a semantic than a lexical question. | TREE: “Plant?”               | TREE: “Word?”      |
briefly (i.e., for <180 ms) to the left and/or right visual field. If the individual fixates on the center of the screen, information falling in the left visual field will be transmitted to the right hemisphere and vice versa. These studies assume that the participant's response mainly reflects the cognitive processes in the hemisphere initially receiving the stimulus information.

Split visual field experiments have reported consistent right visual field-left hemisphere advantages on a test of written word recognition, the lexical decision paradigm (i.e., deciding whether a letter string represents a real word or not). Left visual field-right hemisphere performances, however, are typically better than chance and significantly improve under a number of experimental conditions (see Table 1). For example, words that elicit vivid images and nouns with high emotional valence, pictographic stimuli such as logos or kanji, and distantly related stimuli all boost left visual field-right hemisphere reading performance compared with their respective alternatives (7).

Split visual field experiments on the semantic processing capabilities of the hemispheres have under certain experimental conditions revealed comparable hemifield/hemisphere performances (13, 14). However, the results from another type of split visual field experiment, semantic priming, suggest that whereas both hemispheres participate in semantic processing, they do so in qualitatively different ways. These studies are based on the spreading activation theory of semantic processing, which represents concepts as nodes in a semantic network connected by relational links (e.g., fire → truck). Overall, the structure of the semantic network is organized along semantic similarity; the more properties two concepts share, the stronger they are related (2). A semantic priming task first presents a “prime” word that presumably activates the corresponding concept in the semantic network. This activation then spreads through links to related concepts. If a semantically related target word has been reached by the spreading activation by the time the target word is presented, the threshold for a response to the target word, and thus reaction time, is reduced (“facilitated” or “primed”). The semantic relatedness of two concepts can therefore be measured by response latencies to the target word: closely related prime-target words are in general responded to faster than distantly related prime-target words (see Fig. 1). The differential semantic capacities of the hemispheres were assessed using functional magnetic resonance imaging (fMRI) to identify brain regions associated with lexical and semantic processing.
spheres can thus be investigated by varying the semantic relatedness of prime-target word pairs in split visual field tasks, e.g., with either closely (fire → truck) or distantly (fire → flu) related prime-target word pairs. Such studies have generally found that close semantic relations are quickly primed in the left hemisphere, whereas distant semantic relations are slowly primed in the right hemisphere, suggesting that the left hemisphere focally and the right hemisphere broadly, or diffusely, activates the semantic network such that distantly or obliquely related concepts are available for processing (14).

Functional imaging studies have identified several key neuroanatomic sites involved in the reading process, regions largely restricted to the left hemisphere (inferior parietal, temporal, and inferior frontal lobes; see Ref. 9 for review). However, recent studies have begun to delineate the conditions under which the right hemisphere significantly participates in reading. For example, the split visual field findings reported above have been replicated in a functional imaging study (15) that administered three different types of tasks: semantic (e.g., “Is ‘dog’ an animal?”), lexical (i.e., word form recognition, e.g., “Is ‘b-u-v’ an English word?”), and complex visual tasks (e.g., “Does ‘A’ have an enclosed space?”). Whereas lexical processes were associated with primarily left hemisphere (inferior parietal) regions, semantic processes were associated with bilateral (frontotemporal) activations (see Fig. 2). Moreover, the evidence from semantic priming studies of more widespread semantic network activation in the right than in the left hemisphere has received support from functional imaging studies reporting more right hemisphere activation during the processing of obliquely related concepts, i.e., when reading semantically illogical words or verb-noun phrases (e.g., Ref. 12).

Dynamic models of hemispheric language

Until now, we have discussed static models of hemispheric language processing, i.e., when the brain is in a stable state. However, only recently have methodological advances confirmed earlier clinical observations that hemispheric participation in language processing is dynamic, regulated by interhemispheric inhibition. Indeed, experimental manipulations (see Table 1) and brain dysfunction that disturb this interhemispheric functional balance have demonstrated enormous latent language capacities, in particular in the right hemisphere.

Lesions, either permanent (e.g., cerebrovascular) or temporary (e.g., seizures), lead to a redistribution of resources in the language system. It appears that early functional recovery following left hemisphere ischemic lesions resulting in aphasia depends on the developmental stage of the brain and the site, size, and functional viability of the initially damaged left hemisphere tissue. However, with the advent of functional imaging technology, researchers could demonstrate that long-term recovery of language functions in, for example, Wernicke’s and Broca’s aphasia patients was associated with activity at right hemisphere sites homotopic to the lesion. The dynamic nature of hemispheric language processing was further illustrated in patients with unilateral and subclinical limbic seizures (10). Split visual field lexical and/or facial decision tasks were administered in three patients with left and one with right unilateral limbic seizures while seizure activity was bilaterally monitored with stereotactic EEG recordings. In

FIGURE 3. Performance in a divided visual field lexical decision task of a patient with unilateral left-sided limbic seizures with aphasia. Before seizure onset (run 1), a right visual field advantage, i.e., the expected left hemisphere dominance for this task, is documented. During the seizure (run 2), dominance shifts to the left visual field/right hemisphere, and it returns to normal following the seizure (runs 3–5; ~20 min). Hemispheric performances are shown in terms of percentage hits and reaction times. Figure is adapted from Ref. 9, with permission.
general, unilateral seizure activity disrupted the corresponding hemisphere's functioning on the task for which it is presumably specialized (i.e., left hemisphere, lexical decision task; right hemisphere, facial decision task). Strikingly, the disruption of right visual field-left hemisphere lexical decision performance by left limbic seizure activity in patient C was associated with a concomitant improvement in left visual field-right hemisphere lexical decision performance (see Fig. 3). Thus this finding demonstrates that the common left hemispheric functional language dominance can temporarily shift to the right hemisphere, an observation suggesting that latent right hemispheric language skills had been released from the inhibitory control of the left hemisphere.

Both the functional imaging findings from recovered aphasics as well as the performance of patients with unilateral limbic seizures can be accounted for by an interhemispheric callosal inhibition model (3). This model is based on neuroanatomic evidence that fibers of the corpus callosum are primarily inhibitory and homotopic in nature. Thus the hemisphere particularly suited to a given task will inhibit the activation of the same functions at mirror image sites in the opposite hemisphere. The model predicts that unilateral damage will “release” the functions of the opposite hemisphere from inhibition (see, e.g., Ref. 8).

Modern dichotomies and language in the right hemisphere

The findings from callosotomy and unilaterally brain-damaged patients and from healthy controls provide converging evidence of complementary hemispheric functions in language. For example, while the right hemisphere understands the pictographic meaning of the individual letter symbols in LH'GIL&AJE, the left hemisphere recognizes it as a familiar letter sequence according to the orthographic rules of the English language. Far from mere supportive tasks, the right hemisphere appears to be functionally dominant for some aspects of language processing (e.g., pictographic reading, metaphor appreciation, and other semantic functions). This dichotomy in hemispheric processing of language accounts for the complexity and flexibility of our language skills. Temporary or permanent disruptions of the left hemispheric language system release the opposite hemisphere from the inhibitory control. These instances have shown that the language capacity of the right hemisphere may extend far beyond pictographic or semantic processing to include language functions for which the left hemisphere has classically been deemed dominant.

The ultimate theoretical goal is to describe the interplay between the hemispheres while they store and process language. This goal is fundamental to conceptions of language processing and functional lateralization in the human brain. The understanding of right hemisphere contributions to normal language processing and recovery from aphasia will aid the development of neurorehabilitation programs for aphasic patients. Moreover, a comprehensive understanding of right hemisphere language ability is necessary to establish more appropriate and less invasive methods for assessing hemispheric language dominance in neurosurgical candidates. Finally, right hemisphere language processes are central to cognitive neuropsychiatric theories that implicate deficient left and disinhibited or “released” right hemisphere language functioning in the genesis of psychotic and schizotypal thought.

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