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DIFFERENT ORGANIZATION OF CONCEPTS AND MEANING SYSTEMS IN THE TWO CEREBRAL HEMISPHERES

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I. Introduction

The left and right sides of the brain, the cerebral hemispheres, are both anatomically (Galaburda, 1995) and functionally (D. Zaidel, 1993) asymmetrical, a neuroarrangement unique to humans in extent and scope (Sperry, 1974). Its adaptive evolutionary development can explain a great deal about the human experience, including speaking, writing, and reading. My research into brain organization has been driven by the assumption that in order to understand the human mind, as well as personality, emotions, and social behavior, it is critical to gain insight into the logic of hemispheric specialization and functional asymmetry. Thus, my findings emphasized left–right asymmetry in long-term memory (LTM) ascribing storage of common, prototypical, stereotypical, and cultural metaphors to the right hemisphere (RH) and the reverse of that to the left hemisphere (LH), that is, to storage of new, noncultural metaphors, creative, and modified familiar concepts whether reflected in artworks, single objects, or in pictorial semantics (D. Zaidel, 1986, 1987, 1988, 1990a; D. Zaidel & Kasher, 1989).

Ever since hemispheric asymmetry was accepted as a major principle of brain organization, starting in the early 1960s with the fascinating results from 'split-brain' patients, many researchers in neuropsychology focused on which mental functions are lateralized to one or the other hemisphere (Bogen & Vogel, 1962a; Bogen & Vogel, 1975; Bogen, Schultz, & Vogel, 1988; Finger, 1994; Sperry, 1974). Earlier, neurologists and neuropsychologists learned about functional asymmetry from patients with unilateral focal brain damage (McCarthy & Warrington, 1990). In such patients, damage in a localized brain region produces a profile of perceptual and cognitive deficits not seen following damage in other cortical regions. Data from split-brain patients confirmed and augmented those findings. The functional laterality picture has not changed much over the years, with the LH still considered to have the major control over language functions, including speech, writing, and comprehension, and the RH to have the major control over facial memory, visuospatial cognition, and musical appreciation (McCarthy & Warrington, 1990; Hiscock & Kinsbourne, 1995). However, various modifications have been added. For example, the fact that the main language centers are in the LH does not mean that the RH cannot extract meaning from sensations or cannot process abstract concepts. A good example is the findings of Cronin-Golomb (1986), who used a completely nonverbal test of picture associations in a study of three complete commissurotomy patients and found 82% correct responses controlled by the RH compared to 90% correct by the LH. So although the RH lacks a highly developed language system, it is still capable of abstract cognitive processing. The associative process need not necessarily be language-mediated in either hemisphere.

Confirmation for the functional specialization of each disconnected hemisphere soon followed in healthy subjects with the use of the hemi-field technique (Sperry, 1974; D. Zaidel, 1985). What has changed somewhat throughout the years are the experimental details, emerging mostly from hundreds of experiments in which one or two facets are altered. The most intriguing question still remains: how do the two hemispheres work together? Connected by over 200 million fibers in the corpus callosum and with additional interhemispheric fibers in the anterior and hippocampal commissures, the cerebral hemispheres communicate selectively, and together they represent asymmetric yet complementary mental functions (D. Zaidel, 1993).

A. The Puzzle of Functional Brain Asymmetry

At the same time, even as the understanding of the pattern of lateralized functions was developing, there was no attempt to understand the biological logic behind the particular hemispheric assemblages, that is, the grand logic behind the separation between speaking and visuospatial cognition. We still do not fully understand why these two functions are mutually exclusive and are specialized in opposite sides of the neocortex. Why do we even need functional asymmetry, besides efficiency in cognitive information processing?, I asked myself. Avoiding cognitive interference is an obvious answer. An additional clue must lie in the hemispheric meaning systems in LTM and in the nature of concept organization, I reasoned. Thinking, problem solving, and remembering proceed relative to what was experienced and stored previously (D. Zaidel, 1994), but even as we capitalize on what we have learned previously, we are also capable of learning new things. Thus, determining the nature of LTM or of knowledge of the world in each cerebral hemisphere could provide a glimpse into the biological logic behind functional hemispheric asymmetry.

B. Assumptions about Long-Term Memory

The mind in the brain creates order from experience with the aid of organized knowledge systems stored in LTM. Forms of knowledge organizations include serial organization, (e.g., alphabet, calendar, categorical organization [taxonomy]) (Medin & Coley, 1998; Medin, Lynch, Coley, & Atran, 1997) and schema organization (parts that together form a theme or a concept) consisting of some of our knowledge about objects, events, scenes, stories, or motor programs. Both organizations must be studied in parallel. LTM provides the framework for the meaning of what is sensed and perceived, as was shown long ago by Bartlett's famous experiments (Bartlett, 1932), regardless of whether we hear a verbal sentence and need to comprehend its meaning, when we navigate in a topographical terrain and need to know why we are there, or when we identify someone's face. The assumption here is that the same external experiences are available to both hemispheres but that each uses its own specialized knowledge system and its own strategy to store and retrieve these experiences. If LTM is the ink that colors sensations and perceptions, then I propose that the ink's shade is somewhat different in the two hemispheres. The ink's molecules and combinations could explain the particular assemblages in the left and right hemispheres.

II. Concepts, Schemas, and Categories in the Hemispheric Long-Term Memory

A. "Split-brain" (Commissurotomy) Patients: Findings on Schemas

The clue to hemispheric asymmetry in knowledge of the world emerged in testing commissurotomy patients ("split-brain"). The surgery disconnects the cerebral hemispheres by severing the interhemispheric commissures. The patients in my studies were from the Bogen–Vogel series (also known as the Caltech series). They underwent a procedure in which the neuronal fibers connecting the hemispheres are sectioned in a single-stage operation; the corpus callosum was sectioned in its entirety as was the anterior and hippocampal commissures (Bogen, 1992; Bogen & Vogel, 1962b). Apart from a nonamnesic yet persistent memory impairment (D. Zaidel, 1990b; D. Zaidel, 1995), the surgery alleviated the debilitating seizures and the patients function essentially normally in everyday life (D. Zaidel, 1993). The full effects of hemispheric disconnection on perceptual, cognitive, and mnemonic asymmetry can be shown only under special laboratory conditions when stimuli are presented to one or the other cerebral hemisphere (Sperry, 1974; Sperry, Zaidel, & Zaidel, 1979; E. Zaidel, Zaidel, & Bogen, 1996). With this technique, I was able to uncover some of the hemispheric meaning systems (D. Zaidel, 1990a, 1994).

1. Distorting a Familiar Schema to Obtain the First Clue

The first clue to the hemispheric LTM was a serendipitous finding. I designed tests in the 1970s to uncover the causes of unilateral ideomotor apraxia (the inability to execute verbal commands) in the complete commissurotomy patients (D. Zaidel & Sperry, 1977), consciously wondering whether or not the unilateral left arm and leg errors that I observed could be explained by the notion that each disconnected hemisphere "sees" the world differently. Some of the verbal commands demanded knowledge of face parts in conjunction with arm movements. In the tests designed to uncover the causes, line drawings of a face showing a head-on perspective as well a face profile were lateralized to each hemisphere at a time through the use of the Z-lens, a technique which permits long lateralized visual exposures (as opposed to quick tachistoscopic presentations) (E. Zaidel, 1975). One would expect that with exposure of the stimuli to the RH, pointing to facial parts upon verbal commands would produce errorless performance, because the RH specializes in facial processing and memory (DeRenzi, Faglioni, & Spinnler, 1968). Consequently, I was puzzled by errors with a face profile in contradistinction to no errors with the head-on face. The errors suggested that a mental representation of a head-on face controlled the responses on the face profile. Dramatically, no errors whatsoever in pointing to a face profile were observed during LH performance. Thus, a clue was obtained that different mental concepts represent the same external reality in each hemisphere (D. Zaidel, 1984, 1990a, 1994).

2. Distortion in a Famous Painting

Using Magritte's painting, "The Rape," I gained further support for the hypothesis that each hemisphere has a different view of the world (D.

Zaidel, 1984, 1990a, 1994). In this painting, the artist substitutes a female's nude torso for facial parts. What particularly fools the eye is the presence of a rich mane of hair and a normal-looking neck. Is it a face, then? In an experiment carried out in the 1970s, when I exposed a picture of this painting for a prolonged period to each disconnected hemisphere separately, with the Z-lens, the patients' RH failed to recognize the breasts, naval, and pubic for what they were but rather "acted" as if they were eyes, nose, and mouth, respectively. The LH, in contrast, was not "fooled" by the substitution, rather it recognized correctly the nude body parts even when asked to point to eyes, nose, and mouth (D. Zaidel, 1984, 1990a, 1994). The LH could view a highly familiar image, the face, and "accept" modification made to it, whereas the RH could "not accept" the deviations. Together, these results pointed to different concepts of reality in each hemisphere.

B. Natural Superordinate Categories

Several paradigms and methodologies developed by cognitive psychologists, particularly those pertaining to the category meaning system, are valid ways of measuring how knowledge is stored in each hemisphere.

1. *Synopsis of Previous Findings: Central Tendency in Natural Categories*

The study of the category knowledge system examines the relationships among concepts with reaction time (RT) paradigms (Medin & Coley, 1998; Medin et al., 1997). The RTs gauge "mental distances" among category members (Collins & Quillian, 1969; Rips, Shoben, & Smith, 1973; Rosch, 1975a, 1975b). Verification latencies in natural category membership tasks reflect the degree of similarity between items and the prototype invoked by the category concept (Rosch, 1975a). Prototypicality as the main organizing principle in LTM has been questioned (e.g., Barsalou, 1983), but for natural concepts there is ample evidence that it exists, and I have used the method of category membership decisions successfully to study the nature of the hemispheric LTM (D. Zaidel, 1987).

a. Participants In this experiment and in all subsequent experiments described in this paper, normal, right-handed participants were tested. They were all undergraduate students in introductory psychology courses at the University of California, Los Angeles, (UCLA), who volunteered in exchange for partial course credit.

b. Stimulus Presentation and the Hemi-Field Technique With this technique, each participant fixates the visual gaze on a red dot placed in the middle of the viewing screen while single images are flashed tachistoscopically, either to the left or right of the dot, in a pseudorandom order. Because of neuroanatomical arrangement of the visual system, this procedure effectively lateralizes the input to the left (LVF) or right (RVF) visual half-fields, from whence the visual information reaches the RH or LH, respectively.

In the central tendency in natural superordinate categories experiment, participants had to make speeded category membership decisions for natural superordinate categories (furniture, weapon, vehicle, fruit, vegetable) (D. Zaidel, 1987). As the statistical results were already published in full, a summary and graphic illustrations will be provided here in the interest of making a complete story. The typicality level of the exemplar was obtained from Rosch's (1975) norms. The accuracy rate was very high in both visual half-fields, indicating the existence of knowledge of the world in both hemispheres. The results for the RTs revealed a significant difference between high and low typicality exemplars in the RH but no difference in the LH (see Figure 1). If there were no statistical interaction, we would have concluded that hemispheric concepts are organized in highly similar ways. Rather, this outcome illustrated the asymmetry in the LTM category meaning system (D. Zaidel, 1987).

Subsequently, after testing three complete commissurotomy patients in two experiments, Cronin-Golomb confirmed presence of two qualitatively different semantic networks in both hemispheres (Cronin-Golomb, 1995). The task for the patients was to decide which member of a pair of pictures was more closely related to the target picture. Her findings suggested the presence of similar knowledge systems in both disconnected hemispheres but each operating with qualitatively different semantic organization.

2. *Instances of High Typicality Exemplars of Natural Categories*

a. Effect of Different Instances Given high typicality exemplars only, there may be a further hierarchy within this knowledge domain. To answer the question, pictures of instances from the categories furniture, weapon, and vehicle, with two different instances representing each of the categories, were used as stimuli. Thus, in this study there were six different pictures of chairs, drawers, guns, swords, cars, and trucks.

Sixteen subjects were tested individually in the hemi-field technique. Each subject viewed single pictures in the LVF or RVF for an exposure duration of 100 msec each. The subject's task was to decide with a button press whether or not the picture was a representation of a specific category named by the experimenter (i.e., of furniture, weapon, or vehicle).

The results revealed a very high accuracy rate in both visual half-fields, as in the previous experiment. Figure 2 is a graphic illustration of the mean RT data. The RTs were analyzed with a repeated measures analysis of

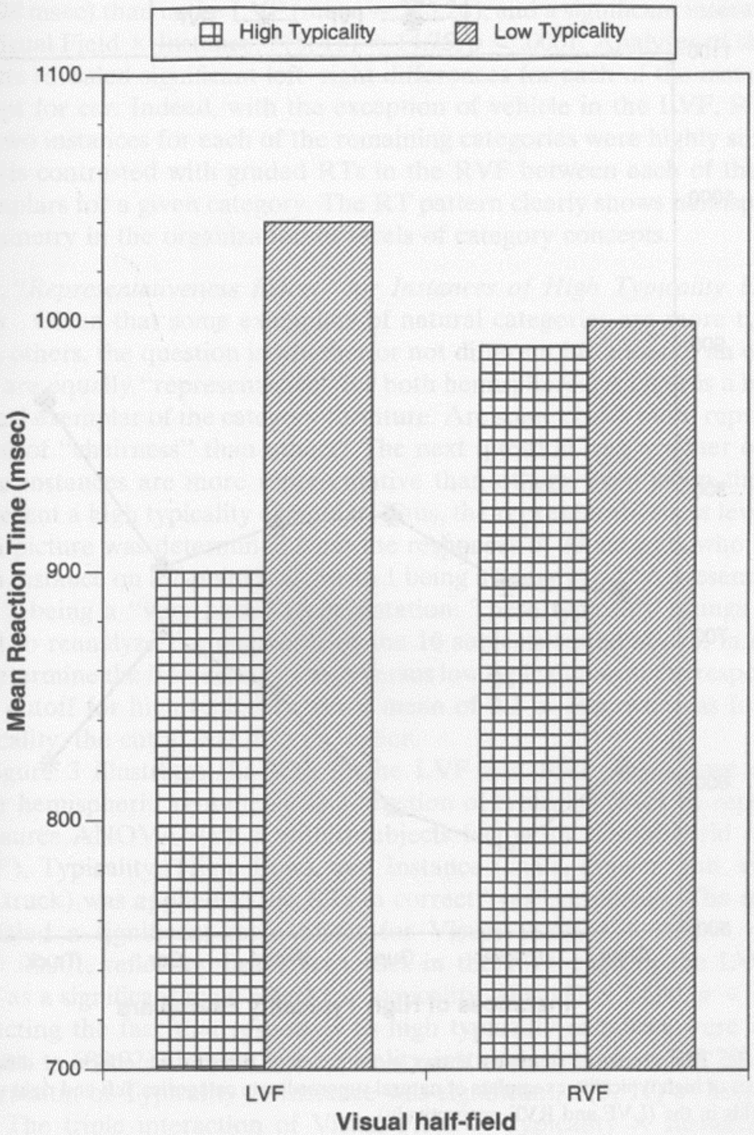

Fig. 1. Previously published results on central-tendency category decisions in the left and right visual half-fields (LVF and RVF, respectively). The stimuli were pictures representing high versus low typicality exemplars of natural superordinate categories (D. Zaidel, 1987). The dependent measure was reaction time. There were no differences in accuracy.

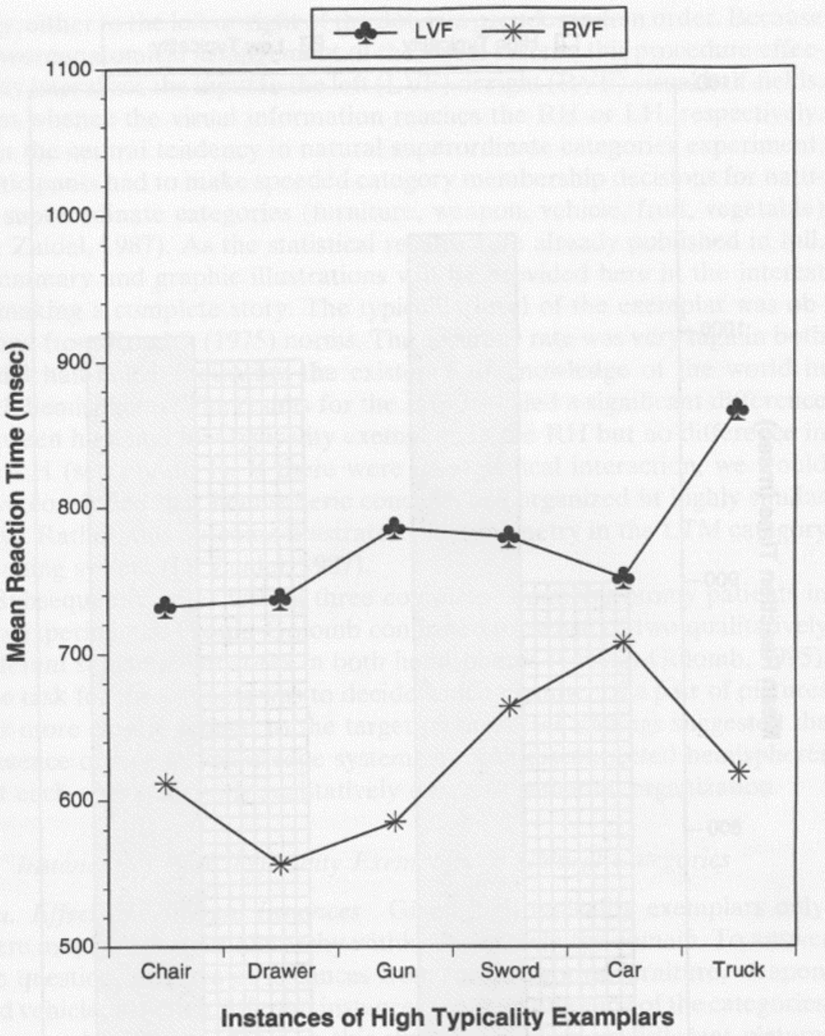

Fig. 2. This graphical summary shows mean reaction time to the effects of different instances of high typicality exemplars of natural superordinate categories, left and right visual half-fields in the (LVF and RVF, respectively).

variance (ANOVA) with a within-subjects factor of Visual Field (LVF, RVF) and a within-subjects factor for Instance (chair, drawer, gun, sword, car, truck). Only RTs to correct "yes" responses were analyzed. The results revealed a significant main effect for Visual Field $F(1, 15) = 37.77$, $p < .00001$, reflecting the fact that RT was faster in the RVF (mean =

623.98 msec) than in the LVF (mean = 775.26), and a significant interaction of Visual Field × Instance, $F(5, 11) = 14.75$, $p < .0001$. Analyses of simple effects revealed significant left–right differences for each of the instances, except for car. Indeed, with the exception of vehicle in the LVF, RTs to the two instances for each of the remaining categories were highly similar. This is contrasted with graded RTs in the RVF between each of the two exemplars for a given category. The RT pattern clearly shows hemispheric asymmetry in the organization of levels of category concepts.

b. "Representativeness Effect" for Instances of High Typicality Exemplars Given that some exemplars of natural categories are more typical than others, the question is whether or not different instances of an exemplar are equally "representative" for both hemispheres. A chair is a highly typical exemplar of the category furniture. Are some chairs more representative of "chairness" than others? The next question was whether or not some instances are more representative than others, even when they all represent a high typicality exemplar. Thus, the representativeness level for each picture was determined from the responses of 33 subjects who rated each instance on a 7-point scale, with 1 being a "very good" representation and 7 being a "very poor" representation. These typicality ratings were used to reanalyze the responses of the 16 subjects tested above, in order to determine the interaction of high versus low typicality with the responses. The cutoff for high typicality was a mean of 2.3 or less, whereas for low typicality, the cutoff was 5.75 or higher.

Figure 3 illustrates the RTs in the LVF and RVF. Again, we see a clear hemispheric asymmetry as a function of typicality level. A repeated measures ANOVA with a within-subjects factor for Visual Field (LVF, RVF), Typicality (High, Low), and Instance (chair, drawer, gun, sword, car, truck) was applied to the RTs in correct "yes" responses. The results revealed a significant main effect for Visual Field, $F(1, 15) = 41.88$, $p < .00001$, reflecting faster responses in the RVF than in the LVF, as well as a significant main effect for Typicality, $F(1, 15) = 24.80$, $p < .0002$, reflecting the fact that responses to high typicality instances were faster (mean = 608.92) than to low typicality instances (mean = 718.20). The interaction of Typicality × Instance was significant, $F(5, 11) = 5.30$, $p < .01$. The triple interaction of Visual Field × Typicality × Instance was significant as well, $F(5, 11) = 3.23$, $p < .01$. There were no other significant main effects or interactions. Subsequent analyses for simple effects revealed that Visual Field × Typicality for car was significant, $F(1, 15) = 6.97$, $p < .01$, and similarly a significant interaction for drawer dresser, $F(1, 15) = 8.52$, $p < .01$). This can be seen clearly in Figure 3. The fact that there was a significant interaction between instances and visual half-field suggests

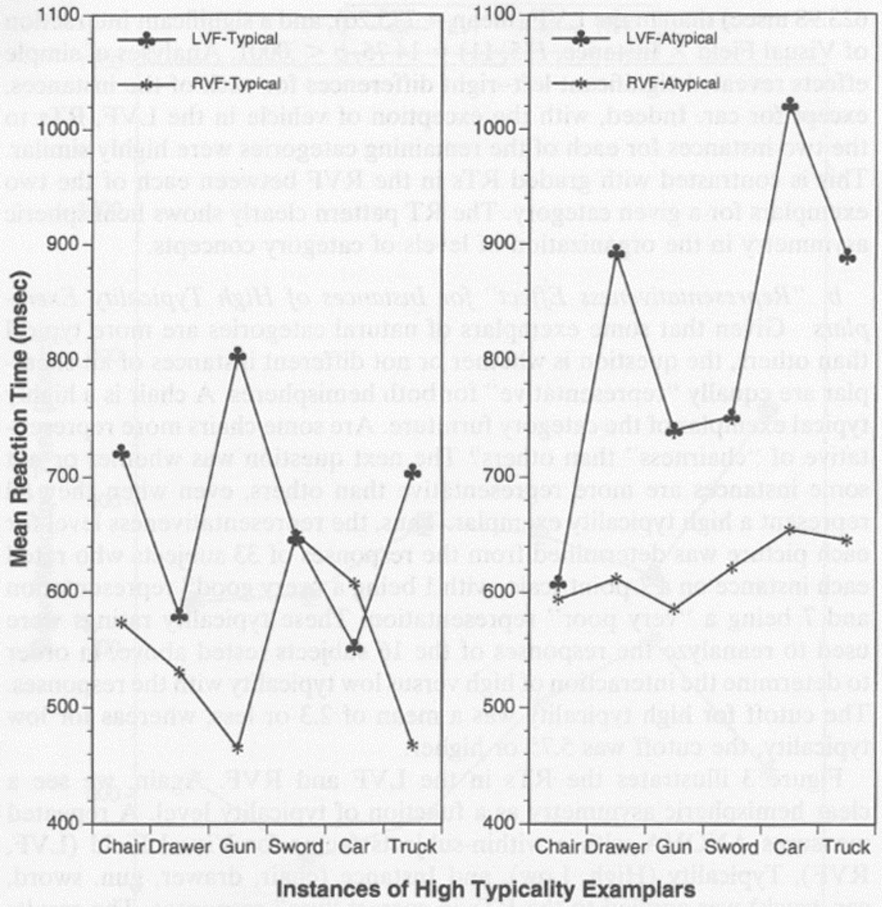

Fig. 3. Summary of the mean reaction time (RT) results investigating "representativeness effect" for instances of high typicality exemplars of natural superordinate categories, in the left and right visual half-fields (LVF and RVF, respectively).

that some categories are stored/retrieved preferentially in one versus the other hemisphere. And, as we saw earlier, representativeness had a greater effect in the LVF than in the RVF.

C. Logical Categories

1. Family Resemblance versus Logical Membership

Wittgenstein (Wittgenstein, 1953) is credited with alerting us to the complex structure of a meaning in a category name. Many objects fit under the natural category of furniture, all looking different than each other and yet unified in the concept we have of furniture. Perhaps they share only 1 feature, perhaps 20 features (e.g., their physical properties, functionality, spatial location). Wittgenstein offered that a family resemblance is what unites the features into a single concept. However, in contrast to natural categories whose boundaries are "fuzzy," logical categories are defined by a limited number of features that satisfy necessary and sufficient inclusion criteria (D. Zaidel & Frederick, 1988). The main interest here is whether or not hemispheric category meaning systems can be further understood and distinguished according to fuzzy versus strict inclusion criteria.

2. *Parity Category Membership*

I used the logical category of parity, odd and even numbers. There were 48 participants. On each of 40 trials, subjects viewed a pair of numerals and had to decide whether or not they belonged to the same category, odd or even, with a button press. The odd and even numerals were equally chosen from small (>1, <10), medium (>10, <20), and high (>40, <50) magnitudes. The following procedures were employed: the first number appeared in the center of vision for 500 msec, followed, after a 500-msec delay, by the second number, which was exposed in either the left or right side of the visual fixation point, for 100 msec. On 20 successive trials the task for the subject was to decide whether or not both members of the pair were even numbers, whereas on 20 different successive trials they had to decide whether or not both members were odd numbers. Both the hand pressing the button (right versus left) and the order of the parity trials were counterbalanced across subjects.

Accuracy was very high in both visual half-fields. The RT results are illustrated graphically in Figure 4. A repeated-measures ANOVA was applied to the RT data with a within-subjects factor of Visual Field (LVF, RVF) and Parity (odd, even). There was a significant main effect for Parity, $F(1, 47) = 29.93$, $p < .00001$, reflecting faster responses to odd than to even membership. The factor of Visual Field was not statistically significant. The interaction of Visual Field × Parity was significant, $F(1, 47) = 5.55$, $p < .02$, reflecting greater sensitivity to parity in the LVF than in the RVF, as well as a significantly faster RT to even numbers in the RVF than in the LVF. Analysis for simple effects revealed a significant difference between odd and even in the LVF, $t(47) = 28.68$, $p < .00001$, as well as within the RVF, $t(47) = 9.66$, $p < .002$.

Logical categories are defined by strict necessary and sufficient inclusion criteria, and yet we continue to find hemispheric asymmetry in RT. Thus, the fuzzy boundaries of natural categories and the tight boundaries of

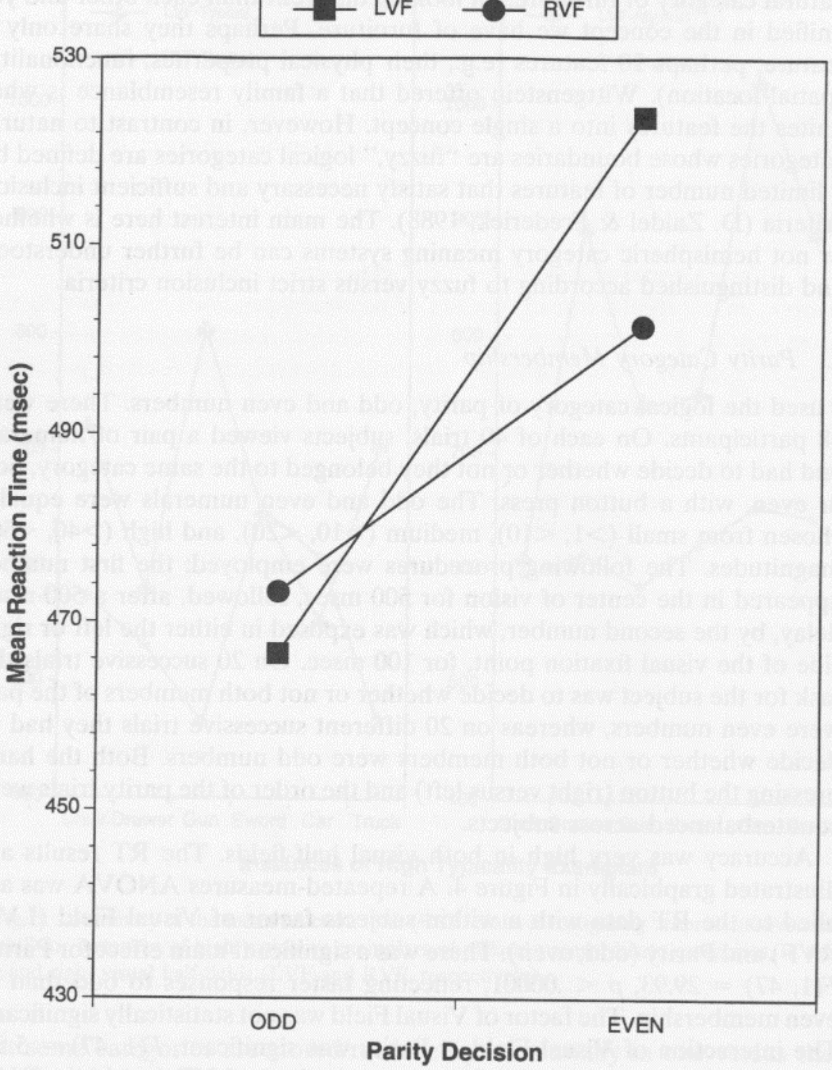

Fig. 4. Summary of mean reaction time (RT) in the left and right visual half-fields (LVF and RVF, respectively) to parity decisions ("odd" versus "even") in a logical category.

logical categories do not distinguish between the hemispheres. Rather, a similar principle of knowledge categorization seems to apply in the hemispheric LTM. The hemispheric distinction lies in the nature of the organization of the knowledge system.

D. Schemas of Faces: A Case of a Highly Familiar Visual Object

The human face is a unique visual percept. It is a highly familiar visual pattern and is already extremely important in infancy (Fantz, 1964; Johnson, Dziurawiec, Ellis, & Morton, 1991). It is critical in human social interactions, and, as language, it appears to be modular (both functionally and structurally). Moreover, there is neuropsychological evidence that facial processing is specialized principally in the RH (Beardsworth & Zaidel, 1994; McCarthy & Warrington, 1990; Milner, 1975). RH damage, particularly in posterior regions, may lead to prosopagnosia, a neurological disorder in which the patient exhibits the inability to recognize people by their faces alone. Further, RH specialization appears right after birth, in the early postnatal period (de Schonen & Mathivet, 1989; de Schonen & Mathivet, 1990). Importantly, self-recognition can occur in the disconnected hemispheres in commissurotomy patients (Sperry et al., 1979). Following right, but not left anterior temporal lobectomy, patients have selectively poor memory for newly presented faces (Beardsworth & Zaidel, 1994), and the selective hemispheric role is seen even before the lobectomy, while the patients still suffer from repeated, drug-resistant epileptic seizures. However, work with complete commissurotomy patients clearly showed that both hemispheres play a role in face processing and that the relative contribution of each can be manipulated with task demands (Levy, Trevarthen, & Sperry, 1972).

The findings described in section II revealed an idée fixe in the RH regarding the face's appearance as contrasted with flexibility in the LH. Those results invited the question, What makes a face a face in each cerebral hemisphere? Consider aspects of the face which could selectively activate the face schema: (a) the outline contour, (b) the internal features, and (c) the spatial location of individual features. If the relationships between all of these components were violated systematically, what effect will this have on each hemisphere? In the next experiment, the outline contour was either present or absent, the configuration of the internal features was realistic (e.g., eye, nose, mouth, ear), and the spatial location of individual features was always seen according to normal "T shape". What was varied systematically, however, was the position of the internal features within the T. Figure 5 shows some examples of the stimuli in this experiment.

In this experiment the participants (N = 24) saw a single target in the center of vision for a 500-msec duration. This target represented a facial feature (e.g., nose, eye, ear, lips). At this duration and spatial location, both hemispheres could see the target. After a 500-msec delay, a normal face or face-like array (distorted face) was projected for 130 msec either in the LVF or RVF. Although the lateralized image was still on the screen,

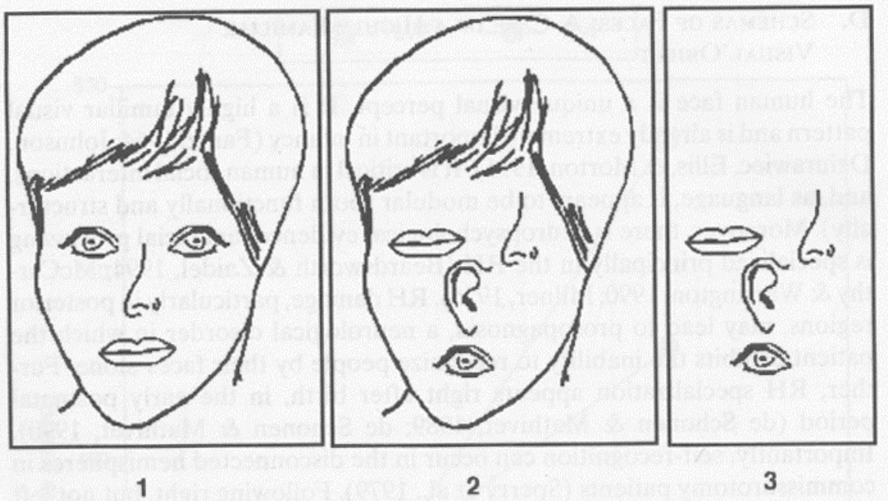

Fig. 5. Examples of the face stimuli and their distortions used in this experiment. 1 = a normal face (NF). 2 = a face distortion where the contour-frame is present but facial features are rearranged (PFR). 3 = a face distortion where the contour-frame is absent, only the internal features remain (AFR). Notice the rearrangement maintains the "T" shape of a normal face.

a small circular light cue appeared for 20 msec on top of one of the internal features in the lateralized array. This occurred 110 msec into the 130-msec exposure window. The task for the participant was to press the yes or no button to indicate whether or not the light cue had signaled a figure that matched the center-of-vision target.

The series of 48 trials consisted of normal faces (NF), face-like arrays where the contour frame was present (PFR), and face-like arrays (internal features only) where the contour frame was absent (AFR). In the face-like arrays, facial features were systematically rearranged. For every PFR, there was an AFR. These three types of stimuli were intermixed pseudorandomly within the series of trials.

The results are summarized in Figure 6. A repeated-measures ANOVA with a within-subjects factor of Visual Field (LVF, RVF) and Face Schema (NF, PFR, AFR) applied to the percent correct responses revealed a significant Visual Field × Face Schema interaction ($F(1, 23) = 4.12, p < .03$. The main interest was a distinction within each visual field between PFR and AFR. In the LVF, features in PFR were significantly less well localized than features in AFR ($t(46) = 8.83, p < .001$) or in the normal face ($t(46) = 7.23, p < .001$). In the RVF, there was no statistically significant difference between the three types of stimuli. Feature localization in the CFR was

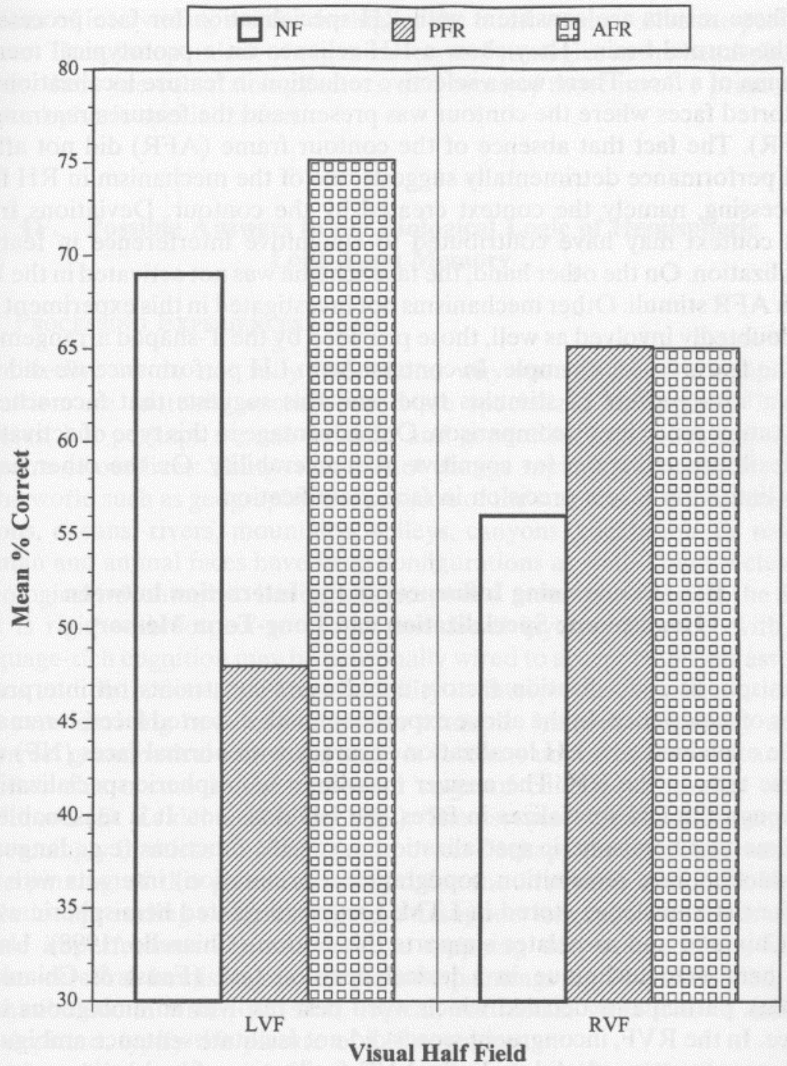

Fig. 6. Summary of mean accuracy in responding to face and face distortions in the left (LVF) and right (RVF) visual field of normal participants. Normal face (NF), contour-frame was present (PFR), contour-frame was absent (AFR).

significantly better in the RVF than in the LVF ($t(46) = 5.86$, $p < .002$), and for NF there was better localization in the LVF than in the RVF ($t(46) = 2.54$, $p < .01$).

These results are consistent with RH specialization for face processing in the normal brain. They show a RH reliance on a prototypical mental schema of a face. There was a selective reduction in feature localization for distorted faces where the contour was present and the features rearranged (CFR). The fact that absence of the contour frame (AFR) did not affect RH performance detrimentally suggests one of the mechanism in RH face processing, namely the context created by the contour. Deviations from this context may have contributed to congnitive interference in feature localization. On the other hand, the face schema was not activated in the RH with AFR stimuli. Other mechanisms not investigated in this experiment are undoubtedly involved as well, those provided by the T-shaped arrangement of the features, for example. In contrast, with LH performance we did not see a strong effect of stimulus type, and this suggests that face schema activation is fuzzier by comparison. One advantage in this type of activation is flexibility and room for cognitive maneuverability. On the other hand, one limitation is less precision in face identification.

III. Constraining Influences in the Interaction between Hemispheric Specialization and Long-Term Memory

Hemispheric specialization factors could exert constraints on interpretations of experience. In the above experiment with distorted faces, it remains to be explained why LH localization accuracy with normal faces (NF) was worse than in the RH. The answer may lie in hemispheric specialization: although the RH specializes in faces, the LH does not. It is reasonable to assume that hemispheric specialization in specific functions (e.g., language production, face recognition, topographical orientation) interacts with experiential knowledge stored in LTM. Language-related hemispheric work by Chiarello and associates supports this notion (Chiarello, 1998). Using the hemi-field technique in a lexical decision task (Faust & Chiarello, 1998a), participants decided which word best resolves an ambiguous sentence. In the RVF, incongruent words did not facilitate sentence ambiguity, only congruent words did so. In the LVF, facilitation of ambiguity occurred regardless of whether the word was congruent or incongruent. Thus, these results can be interpreted to show that when it comes to its nonspeciality, language, the RH can provide alternative word meanings flexibly, whereas the LH appears somewhat limited in that regard. In another sentence facilitation study (Faust & Chiarello, 1998b), the specialization of the LH in syntax emerged: Sentence completion was facilitated in the RVF regardless of the number of intervening words between the critical word in the sentence and a target word; in the LVF performance was limited by the number of intervening words: the higher the number, the worse the performance. Thus, independent of organization and strategies in the hemispheric LTMs, there are constraining factors, and some of those involve principles of hemispheric specialization.

IV. Possible Answers to the Biological Logic of Hemispheric Long-Term Memory

A. Processing Experiences

Admittedly, we do not fully understand why speaking and visuospatial cognition are mutually exclusive and are specialized in opposite hemispheres, but perhaps we can be bold and generalize to various cognitive domains of our lives: Things that do not change rapidly are spatial layouts of the world such as geography, the position of the sun, moon, stars, constellations, oceans, rivers, mountains, valleys, canyons, vegetation, or roads. Human and animal faces have fixed configurations as well. There is clearly a biological advantage to having a concept and meaning system in the RH that is rigid with respect to spatial and facial layouts. The LH with its language-rich cognition may be neuronally wired to accept countless associations and distortions, allowing flexibility in interpretations of experience and even deriving new meanings. For example, humans frequently utter incorrect grammatical sentences and yet listeners understand the meaning, whether this occurs in the one-word stage of child development or in adulthood (D. Zaidel & Kasher, 1989). The essence of human language is its seemingly limitless combinatorial power. Perhaps the neuroanatomical underpinning of this power developed for the first time in human brain evolution, providing a cognitive system to support language communication where imperfections can still lead to meaning derivation. In my view of the cerebral hemispheres, surrealistic paintings by Magritte, Dali, or Archimboldo, in which physical, logical, and social violations of reality are depicted, typify this picture of LH cognition.

Although it is neither intuitive nor obvious why rigid and flexible cognitive systems need to be separated in the brain, this may have been the prerequisite in the evolution of human hemispheric specialization. The RH is vigilant with regards to what is well known in the geography, the terrain, faces, or etiquette, and the LH is receptive to new possibilities and interpretations of that which is known, familiar, or established in these very same domains. Hemispheric independence of such cognitive processes may in the long run be cognitively more efficient than if these processes occurred intra hemispherically.

B. Processing Facial Attractiveness in an Evolutionary Perspective

Mate selection strategies are critical features of biological survival. Consider the face of the owner and the brain of the observer. We have found that the organization of attractiveness in the face is sex-related; specifically, in women's faces the right half is significantly more attractive than the left half, whereas in men's faces there is no left–right difference in this regard (D. Zaidel, Chen, & German, 1995). On the other hand, we found that smiling is more salient in the left half of the face, and this is so in both women's and men's faces. What is the biological advantage of such arrangements? Surely it is not coincidental. We proposed that the arrangement is adaptive, having evolved in concert with brain evolution, with the progression in mammalian brains toward anatomical and functional asymmetry of the cerebral hemispheres. The context for the development of asymmetric functionality in the face is mate-selection strategies in humans. In the animal kingdom, attractiveness and health are highly linked and are essentially synonymous. We investigated this link in another study of human faces (Reis & Zaidel, 2000) and found that the pattern of judging left and right halves of women's and men's faces on the appearance of health was essentially identical to the pattern observed for judging the same faces on attractiveness. In humans, as in a large variety of nonhuman mammals, what is healthy is also attractive. However, because decision is made in the brain of the observer, there must be neuroanatomical features that process what is necessary. A woman's face has evolved to be what it is in response to the unique features of a male's brain, whatever they are. Similarly, a man's face has evolved to be what it is in response to a female's brain. Thus, we have proposed that the brain of the observer is biologically linked to the face of the observed, the two having evolved in concert.

V. Conclusions

Despite the fact that in humans the cerebral hemispheres are interconnected with the largest fiber tracts in the brain, the experiments described here show that they have separate strategies for handling knowledge stored in LTM. Considering millions of years of primate and human evolution in which the corpus callosum grew enormously in size and presumably so did interhemispheric communication, distinctiveness of the hemispheric LTMs suggests adaptive functional complementarity. It is not as if the hemispheres have wholly different stores in LTM, rather, the differences lies in their organization. Within each store, there must also be an interaction with principles of hemispheric specialization *per se* (language in the LH and spatial cognition in the RH).

Convergent support for my characterization of the LH and RH knowledge-of-world systems has now been reported by others. Cronin-Golomb (Cronin-Golomb, 1995) studied the semantic networks of picture associations in the disconnected hemispheres of three complete commissurotomy patients (Bogen–Vogel, Caltech series). She concluded that the RH made typical and conventional associations and thus specializes in conventional meaning, whereas the LH made unusual associations to the target and thus specializes in processing deviations from standard meaning. Metcalfe and colleagues (Metcalfe, Funnell, & Gazzaniga, 1995) studied J. W., a collosotomy patient (who underwent a two-stage surgery), and based on six experiments concluded that the RH's specialization in veridical, literal information contributes to correct categorization of related events, whereas the LH's specialization in language contributes to inferences that deviate from veridical information.

Except for principles of hemispheric specialization where there can be sharp boundaries, there is by now little doubt that the cerebral hemispheres are not functionally as different from each other as "night and day." LTM may contribute to interhemispheric communication, and LTM's organization and strategies may be the mental space where the colors of experience are combined with functional hemispheric specialization.

References

Barsalou, L. W. (1983). Ad hoc categories. *Memory and Cognition, 11,* 211–227.

Bartlett, F. C. (1932). *Remembering: A study in experimental and social psychology*. Cambridge, UK: Cambridge University Press.

Beardsworth, E., & Zaidel, D. W. (1994). Memory for faces in epileptic children before and after unilateral temporal lobectomy. *Journal of Clinical Experimental Neuropsychology, 16,* 738–748.

Bogen, J. E. (1992). The callosal syndromes. In K. M. Heilman & E. Valenstein (EDs.), *Clinical neuropsychology*. New York: Oxford University Press.

Bogen, J. E., Schultz, D. H., & Vogel, P. J. (1988). Completeness of callosotomy shown by magnetic resonance imaging in the long term. *Archives of Neurology, 45,* 1203–1205.

Bogen, J. E., & Vogel, P. J. (1962a). Cerebral commissurotomy in man. Preliminary case report. *Bulletin of the Los Angeles Neurological Society, 27,* 169–172.

Bogen, J. E., & Vogel, P. J. (1962b). Cerebral commissurotomy in man. Preliminary case report. *Bulletin of the Los Angeles Neurological Society, 27,* 169–172.

Bogen, J. E., & Vogel, P. J. (1975). Neurologic status in the long term following complete cerebral commissurotomy. In F. Michel & B. Schott (Eds.), *Les syndromes de disconnexion calleuse chez l'homme*. Lyon: Hospital Neurologie.

Chiarello, C. (1998). On codes of meaning and the meaning of codes: Semantic access and retrieval within and between hemispheres. In M. Beeman & C. Chiarello (Eds.), *Right* *hemisphere language comphrehension: Perspectives from cognitive neuroscience*. Mahwah, NJ: Earlbaum.

Collins, A. M., & Quillian, M. R. (1969). Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior, 8,* 240–248.

Cronin-Golomb, A. (1986). Comprehension of abstract concepts in right and left hemispheres of complete commissurotomy subjects. *Neuropsychologia, 24,* 881–887.

Cronin-Golomb, A. (1995). Semantic networks in the divided cerebral hemispheres. *Psychological Science, 6,* 212–218.

de Schonen, S., & Mathivet, E. (1989). First come, first served: A scenario about the development of hemispheric specialization. *European Bulletin of Cognitive Psychology, 9,* 33–44.

de Schonen, S., & Mathivet, E. (1990). Hemispheric asymmetry in a face discrimination task in infants. *Child Development, 61,* 1192–1205.

DeRenzi, E., Faglioni, P., & Spinnler, H. (1968). The performance of patients with unilateral brain damage on face recognition tasks. *Cortex, 5,* 274–284.

Fantz, R. L. (1964). Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science, 46,* 669–670.

Faust, M., & Chiarello, C. (1998a). Sentence context and lexical ambiguity resolution by the two hemispheres. *Neuropsychologia, 36,* 827–835.

Faust, M., & Chiarello, C. (1998b). Constraints on sentence priming in the cerebral hemispheres: effects of intervening words in sentences and lists. *Brain and Language, 63,* 219–236.

Finger, S. (1994). History of neuropsychology. In D. W. Zaidel (Ed.), *Neuropsychology* (pp. 1–28). San Diego: Academic Press.

Galaburda, A. M. (1995). Anatomic basis of cerebral dominance. In R. J. Davidson & K. Hugdahl (Eds.), *Brain asymmetry* (pp. 51–73). Cambridge, MA: The MIT Press.

Hiscock, M., & Kinsbourne, M. (1995). Phylogeny and ontogeny of cerebral lateralization. In R. J. Davidson & K. Hugdahl (Eds.), *Brain asymmetry* (pp. 535–578). Cambridge, MA: The MIT Press.

Johnson, M. H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborn's preferential tracking of face-like stimuli and its subsequent decline. *Cognition, 40,* 1–19.

Levy, J., Trevarthen, C., & Sperry, R. W. (1972). Perception of bilateral chimeric figures following hemisphere deconnexion. *Brain, 95,* 61–78.

McCarthy, R. A., & Warrington, E. K. (1990). *Cognitive neuropsychology*. London: Academic Press.

Medin, D. L., & Coley, J. D. (1998). Concepts and categorization. In Julian Hochberg (Ed.), *Perception and cognition at century's end*. San Diego: Academic Press.

Medin, D. L., Lynch, E. B., Coley, J. D., & Atran, S. (1997). Categorization and reasoning among tree experts: Do all roads lead to Rome? *Cognitive Psychology, 32,* 49–96.

Metcalfe, J., Funnell, M., & Gazzaniga, M. S. (1995). Right-hemisphere memory superiority: Studies of a split-brain patient. *Psychological Science, 6,* 157–164.

Milner, B. (1975). Psychological aspects of focal epilepsy and its neurosurgical management. In J. K. Purpura, R. D. Penry, & R. D. Walters (Eds.), *Advances in neurology*. New York: Raven.

Reis, V. A., & Zaidel, D. W. (2000). Brain and Face: Communicating Signals of Health in the Left and Right. *Brain and Cognition, in press.*

Rips, L. J., Shoben, E. J., & Smith, E. E. (1973). Semantic distance and the verification of semantic relations. *Journal of Verbal Learning and Verbal Behavior, 12,* 1–20.

Rosch, E. (1975). Cognitive representation of semantic categories. *Journal of Experimental Psychology: General, 104,* 192–233.

Rosch, E., & Mervis, C. B. (1975b). Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology, 7,* 573–605.

Sperry, R. W. (1974). Lateral specialization in the surgically separated hemispheres. In F. O. Schmitt & F. G. Worden (Eds.), *The Neurosciences Third Study Program.* Cambridge, MA: MIT Press.

Sperry, R. W., Zaidel, E., & Zaidel, D. (1979). Self-recognition and social awareness in the deconnected minor hemisphere. *Neuropsychologia, 17,* 153–166.

Wittgenstein, L. (1953). *Philosophische Untersuchungen [Philosophical investigations].* Oxford: Blackwell.

Zaidel, D. W. (1984). Cognitive functions in the right hemisphere. *La Recherche, 15,* 332–340.

Zaidel, D. W. (1985). Hemi-field tachistoscopic presentations and hemispheric specialization in normal subjects. In D. F. Benson & E. Zaidel (Eds.), *The dual brain: Hemispheric specialization in humans.* San Diego: Guilford Press.

Zaidel, D. W. (1986). Memory for scenes in stroke patients: Hemispheric processing of semantic organization in pictures. *Brain, 109,* 547–560.

Zaidel, D. W. (1987). Hemispheric asymmetry in long-term semantic relationships. *Cognitive Neuropsychology, 4,* 321–332.

Zaidel, D. W. (1988). Hemi-field asymmetries in memory for incongruous scenes. *Cortex, 24,* 231–244.

Zaidel, D. W. (1990a). Long-term semantic memory in the two cerebral hemispheres. In C. Trevarthen (Ed.), *Brain circuits and functions of the mind.* New York: Cambridge University Press.

Zaidel, D. W. (1990b). Memory and spatial cognition following commissurotomy. In F. Boller & J. Grafman (Eds.), *Handbook of neuropsychology* (pp. 151–166). Amsterdam: Elsevier.

Zaidel, D. W. (1993). View of the world from a split-brain perspective. In E. M. R. Critchley (Eds.), *Neurological boundaries of reality.* London: Farrand Press.

Zaidel, D. W. (1994). Worlds apart: Pictorial semantics in the left and right cerebral hemispheres. *Current Directions in Psychological Science, 3,* 5–8.

Zaidel, D. W. (1995). Separated hemispheres, separated memories: Lessons about memory from split-brain patients. In R. Campbell & M. Conway (Eds.), *Broken memories.* Oxford: Blackwell.

Zaidel, D. W., Chen, A. C., & German, C. (1995). She is not a beauty even when she smiles: Possible evolutionary basis for a relationship between facial attractiveness and hemispheric specialization. *Neuropsychologia, 33,* 649–655.

Zaidel, D. W., & Frederick, K. (1988). Hemispheric asymmetries in logical categories: Convergent evidence from normal and split-brain subjects. *Society for Neuroscience Abstracts, 14,* 1138.

Zaidel, D. W., & Kasher, A. (1989). Hemispheric memory for surrealistic versus realistic paintings. *Cortex, 25,* 617–641.

Zaidel, D. W., & Sperry, R. W. (1977). Some long-term motor effects of cerebral commissurotomy in man. *Neuropsychologia, 15,* 193–204.

Zaidel, E. (1975). A technique for presenting lateralized visual input with prolonged exposure. *Vision Research, 15,* 283–289.

Zaidel, E., Zaidel, D. W., & Bogen, J. E. (1996). Disconnection syndromes. In J. G. Beaumont, P. M. Kenealy, & M. J. C. Rogers (Eds.), *The Blackwell dictionary of neuropsychology* (pp. 279–285). Oxford: Blackwell.