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CEREBRAL LATERALITY AND HANDEDNESS IN AVIATION: Performance and Selection Implications

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Humans may have preferred to use the right hand more than the left since prehistoric times. Despite the persistence of this almost uniquely human characteristic, handedness has never been examined as a demographic variable in aviators. Cerebral laterality, a psychological field which deals with the cognitive functions of the cerebral hemispheres, is closely related to handedness, a peripheral manifestation of human laterality. Recently, there has been aeromedical research published which examines the cognitive functions within, and interactions between, the two hemispheres. This paper reviews the general psychology literature related to handedness and cerebral laterality, beginning with a brief discussion of the research methods employed. Aspects of laterality, including vision, audition, tactile perception, spatial ability, and language are reviewed, as well as theories of cerebral dominance patterns. The handedness literature is examined, with attention to

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measurement, theories of genesis, sociocultural factors, and sex differences. There are many postulated correlates of human laterality, including performance, occupation, emotions, and various diseases. There have been few references to handedness over the 85-year history of aviation; what little that exists seems to suggest that pilots who have no strong hand preference may be at a slight disadvantage in the cockpit, whereas those who are consistently right-side dominant tend to do well. However, since there is great variance in ability across the spectrum of handedness, this parameter has limited usefulness as a selection tool. Current neuropsychological theory would suggest that the "ideal aviator brain" should be well lateralized, to minimize competition for hemispheric resources. There is evidence that pilots who are poorly lateralized may exhibit traits of right-left confusion. Several aircraft accidents have been attributed to pilots failing to correctly distinguish between "left" and "right." Performance in flight school seems to be associated with right hemispheric (visuospatial) ability, as measured by tests of cognitive function. These tests have utility in the selection of aircrew; techniques for enhancing cognitive laterality may also prove useful.

PREFACE

I would like to acknowledge a few colleagues who contributed to this paper. Pat Sanner provided valuable input regarding the laterality of horses, and Kevin Mason helped in testing various right brain functions. Harold Gordon and Gail Marsh were kind enough to respond to my letters with copies or preprints of their latest publications. The translation service at USAFSAM, Brooks AFB, provided essential translation of the Soviet literature. Also, Fred Previc contributed valuable criticism of my review of the cognitive psychology literature. Finally, thanks are due to Robert Crowley for his proofreading talent throughout the paper's gestation.

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INTRODUCTION

Humans may have preferred to use the right hand more than the left since prehistoric times. Based on examination of fossilized fractured skulls, Levy concluded that Australopithecus (5 million B.C.) was probably right-handed (146). In 1958, Dennis noted that people represented in Egyptian tomb paintings (4.000 B.C.) were usually engaged in right-handed activities (112).

In a more recent analysis, Coren and Porac examined 1,180 instances of artwork dating back to 15,000 B.C., from the European, Asian, African, and American continents (48). They found that 92.6% depicted the use of the right hand, and that this figure was stable over all the centuries examined. Some researchers, however, noting that a great deal of prehistoric evidence suggests a lack of distinct hand preference, declare that dextrality became established in the bronze age (3,000-1,000 B.C.) (22) when complicated metallic tools were designed for one hand. These instruments would have become treasured family possessions, handed down from generation to generation, perpetuating the preferred use of one hand.

It has been suggested by many researchers that the right hand was selected for complex tasks for the simple reason that the left hand was needed to shield the heart in battle, leaving the right hand to wield a weapon. The English essayist and historian, Thomas Carlyle, suggested that those who fought in this fashion were more likely to survive in battle, perhaps creating a natural selection process, or at least encouraging other warriors to adopt this tactic (64). All such theories are plagued by exceptions, however, and the essential questions regarding the evolution of hand preference remain unanswered. Certainly, the Industrial Revolution meant further trouble for those preferring to use the left hand, as skill with a tool became even more important.

A plethora of myths, legends, and prejudices arose from the dextral majority, exerting social pressure on the sinistral minority to conform. These prejudices persist even today: The English language has given derogatory meaning to the Latin and French words for left: sinister and gauche, respectively. Even today, left-handers are frequently urged to abandon the use of their preferred hand (216). That handedness is not an option was expressed well by Witelson (110):

"Derided, chided--the offending hand smacked with a ruler, even tied behind the back. Shamed and blamed, left-handers did not quietly wither away. They survived. Why? Because they do not choose their preference; they follow a neurological imperative (p. xiii)."

Apparently, the younger generations of American society are more tolerant of left-handedness. A 1987 Washington Post/ABC News poll asked 1,509 people of various age groups, "Are you right-handed or left-handed?" Thirteen percent of the 18- to 30-year-old group said they were left-handed, whereas only 6% of people 61 and older admitted to preferring their left hand. More of the 61 and older group stated they were ambidextrous (6%) than did those of the 18- to 30-year-old group (3%). These differences probably reflect the pressure on left-handers during the early 20th century to convert to the right hand (16). Although this type of survey has been shown to correlate poorly with actual hand use, it is often the only data available.

Long ago, Hippocrates noted that convulsions which followed head injury usually occurred on the side of the body opposite to that of the injury (204). Over a century ago, it was recognized that the neurological basis for hand preference lay, not in differences between the right and left hands, but in an advantage of one cerebral hemisphere over the other. Because a given hemisphere controls most of the voluntary movement of the opposite side of the body, the "preferred" hemisphere in 90% of the population was deduced to be the left (64).

Since the mid-1960s, researchers have been unravelling the complex details of specialized cerebral hemispheric function. Each hemisphere can be shown to possess specific attributes and skills. For example, the left hemisphere has been characterized as verbal, sequential, analytic, logical, rational, and temporal. The right hemisphere, on the other hand, is usually described as holistic, synthetic, visual, spatial, and emotional (165). Most right-handers have the same general geographical layout of cerebral function. However, left-handers can be shown to have a more variable organization of such lateralized functions as speech or visuospatial skills.

The past two decades have seen a resurgence in laterality research after a long interim since the turn of the century (272). Most of this research is laboratory-based cognitive performance research, which has much improved our understanding of brain function. However, practical applications are for the most part still on the horizon. This paper will review potential applications of cerebral laterality research to aerospace medicine and engineering. For example, it has been suggested that cerebral laterality, perhaps manifested as handedness, might be useful as a selection parameter for pilots (165). Lateralization of other organs also has been well studied; eye, ear, and foot dominance will be briefly reviewed later in this paper.

Current theory suggests that optimum cognitive efficiency is achieved by maintaining functional separation of the two cerebral hemispheres (14). Theoretically, a pilot candidate having poor separation of cerebral function might therefore display inferior psychomotor skills; the idea will be presented later in this paper that left-handedness might serve as a marker for such a less-lateralized population.

The 25 million left-handed people in the United States (U.S.), roughly 10% of the population, continue to encounter special problems in their daily lives because most utensils, tools, and appliances are designed for right-handers. Lefties can adapt, and learn to do things with the right hand, but they might thereby give up the sure touch of the "better" hand, and the control of the "better" hemisphere (3).

What relevance does neurobehavioral laterality research have to practical occupational and aerospace operations? The most visible evidence of cerebral laterality is hand preference. The fact that one-tenth of the population prefers to use the left hand would seem to have significant design implications. If left-handers have such difficulty with normal playing cards that they will buy cards specially designed for "lefties" (3), it makes sense that more complex tasks, such as those found in industry or aviation, also are problematic for them. Assuming this to be true, the significance of left-handedness would seem an important area for safety research. Nonetheless, upon reviewing the literature, it appears that the problem of left-handedness as an individual characteristic related to industrial or aviation safety has not been subject to any extensive study (117). The lack of consideration of this interesting topic is remarkable.

Two relevant questions arising from these considerations are: First, do left-handers (i.e., those people exhibiting left-handedness as a marker for unusual patterns of hemispheric function) in the cockpit learn and perform as well as right-handers, under all possible conditions? Second, is the left-hander put at a significant disadvantage by flying in a cockpit designed for a right-hander? A knowledge of differential hemispheric function may enhance cockpit design, so as to more efficiently present information to the pilot. The purpose of this paper is to review the basic literature concerned with hemispheric laterality and handedness, and apply this research to the aviation arena, in an attempt to answer these two key questions.

THE STUDY OF BIOLOGICAL ASYMMETRY

History

As discussed previously, the predominant use of the right hand has been observed for many centuries. It has also long been recognized that motor control of the extremities is exercised by the contralateral cerebral hemisphere. However, it was not until Broca noted in 1861 that aphasia was linked to localized lesions in the left cerebrum that the concept of hemispheric specialization emerged (30). For years thereafter it was assumed that language and manual dominance were aspects of the same brain function, and the left hemisphere was considered to be the "dominant hemisphere," controlling all important psychological functions. It was assumed that the left-hander's cerebral function was completely reversed, with control of the dominant hand and speech residing in the right hemisphere. In the early part of this century, many scientists still believed that left-handedness was musculoskeletal in origin, rejecting theories citing a hemispheric etiology (231).

World Wars I and II generated many patients with relatively well-defined brain injuries who provided much of the neuropsychological data during the first half of the 20th century. Based on these reports, it became evident that left-handers sometimes developed aphasia after left-sided cerebral damage, and right-handers occasionally became aphasic after right-sided brain injury. It also became clear that each hemisphere could be specialized for functions other than speech. For example, it was noted by several authors that spatial disability resulted more often from right than left brain damage (53); the idea that the right hemisphere dominated some functions was gradually accepted. In addition to the functional asymmetry of the brain, anatomic or structural asymmetries have been convincingly demonstrated by several investigators. Asymmetry, mainly around the Sylvian fissure, has been found in human adults (81), fetuses (262), and fossil skulls (143).

New experimental methods have been devised over the last 30 years to further elucidate the nature of hemispheric function, producing a wealth of often confusing data. As will be discussed, handedness has been commonly used as an obvious and easily measured indicator of cerebral laterality. However, the basic principles of the complex interactions among hemispheric function, handedness, and performance remain elusive.

Laterality in Animals

Anatomic asymmetry is frequently encountered in the animal kingdom. The bottom-dwelling flatfish such as the flounder and sole, which have both eyes on the same side, either the right or the left, and the one enlarged claw of the fiddler crab and the lobster are well-known examples of external asymmetry (64). Internal asymmetry of the non-human brain, however, has only recently become accepted. As early as 1906, asymmetry in the optic chiasm of trout was reported, but largely ignored (140). Geschwind attributes this lack of interest to the prevailing belief that functional asymmetry was an attribute solely of man, and also to the rejection of anatomical asymmetry as the basis for human dominance (80).

Actually, functional asymmetry of unicellular species had been convincingly demonstrated in the 19th century. Jennings had noted that each species of ciliated microbe rotates around the long axis of the body in one direction (120). Of 162 species examined, 100 rotated exclusively to the right, and 62 rotated to the left. In 1928, Schaeffer noted these observations and gave many other examples of functional asymmetry in oligocellular animals. For instance, he noted that amoebas move around a glass rod more frequently in one direction than the other (231).

Prevailing scientific opinion through the 1960s held that non-human species did not demonstrate functional cerebral asymmetry. Typically, animal studies of handedness revealed consistent forelimb preferences which were evenly distributed across the population; orangutans, rhesus monkeys, and mice demonstrated this seemingly random pattern (253). Chimpanzees have recently been tested for asymmetry of hand performance (163). Although a clear practice effect was seen for the right hand in all subjects, and there were individual patterns of handedness, there was no evidence of hand preference for the group as a whole.

Collins demonstrated that paw preference in mice is strongly dependent on directional bias in the environment. The location of the water bottle in cages of baby mice was found to determine lifelong paw preference (46). Similarly, the development of a crushing claw in the lobster is extrinsically controlled. Young lobsters have symmetrical small claws, called pincers; one of these will develop into a heavier claw called a crusher. Govind and Kent showed that the pincer allowed to crush an oyster shell will develop into the crusher, and the other will remain a pincer (91). It appears that some afferent neural signal from the crushing claw suppresses the development of the crusher in the claw destined to become nondominant.

These observations supported the view that genetic control of functional laterality did not occur in nonhumans. Recently, the first report of paw preferences in dogs purported to show a genetic effect. Tan found 57.1% of 28 dogs preferred the right paw, 17.9% preferred the left paw, and 25% were ambidextrous. There was no control or observation of the rearing of the subjects, however, as they were collected strays (253). Other examples of non-random behavioral asymmetry are apparent. Denel and Lawrence reported that horses show a strong preference for the left lead for a gallop, and took longer strides with the left lead (56). However, forefoot preference for pawing movements does not appear to show lateralization (186). Mountain gorillas tend to begin beating their chests with their right hand (232), and chimpanzees have been noted to look more to the left than the right after breaking eye contact with their caretakers (194). The Japanese macaque monkey has been reported to discriminate macaque calls better with the right ear. However, since only five animals were used, Beaton regards the evidence as tentative (14).

The first clear evidence of cerebral specialization in a manner similar to humans emerged in 1976, involving the neural control of song in the canary (193). Lesions of the left hyperstratum ventrale were found to abolish song to a far greater extent than identical lesions on the right. Interestingly, an anatomic difference between the right and left song centers was not found. Subsequently, the right archistriatum of domestic chicks was found to control fear behavior more frequently than the left (212). Less clear is recent evidence that lesions in the right hemisphere of the rat brain, as in the human, affect emotional behavior (57).

Over the past 20 years, many examples of neuroanatomical asymmetry have been recorded. Among these examples are: a higher right Sylvian point in the brains of chimpanzees and orangutans (as in humans) (144), a larger right frontal lobe in the baboon (34), and the earlier myelination of the rabbit's right optic nerve compared to the left (191). Animal and human studies have also demonstrated lateral asymmetries in brain content of enzymes and neurotransmitters (80).

Apparently, asymmetry does exist in non-human species, as Geschwind states (p. 677), "Indeed, anatomical and/or functional asymmetry has now been found in the brain of every species in which it has been looked for carefully" (78). It should be evident that there is no suitable animal model for the study of human cerebral laterality and performance; such research must rely on human data. It is interesting, in closing this section, to take note of one observation that may have real application in the study of human performance: the poorer maze performance of rats who do not show strong turning tendencies to either side (280). Some human data also suggest the importance of lateralization in optimizing performance.

Sources of Laterality Data

Since a good animal model is not available, students of laterality must rely on human data, thus severely restricting experimental design. This situation is particularly true in studies of neuroanatomical correlates of hemispheric function, where much of our knowledge is based on observational reports of patients with brain damage resulting either from surgery or trauma. Much functional (as opposed to anatomical) laterality research is done on normal subjects, but it is very difficult to ensure that all subjects are using the same neural strategy to perform the task at hand, since little is known about internal information processing. Also, hand preference has been overused in the past as the marker for degree and direction of cerebral lateralization of speech. For these and other reasons, investigators are frequently unable to reproduce each other's findings. The major methods of both functional and anatomical laterality research will be briefly reviewed, and the state of current knowledge will be summarized in a later section.

Human Brain Lesions-- Much of the early laterality research was based on observation of World War I and II veterans who had suffered penetrating head trauma. A number of case reports of patients with cerebral hemorrhages and brain tumors also appear in the literature. These data are plagued by a number of deficiencies.

First, until recently, it was almost impossible to determine the exact nature and extent of a brain lesion, even after subjecting the patient to painful and invasive studies, such as pneumoencephalography and arteriography. Often it was not ethically possible to pursue these primitive studies in essentially asymptomatic patients, and anatomic localization of the cerebral damage was done postmortem, if at all. More recently, much more accurate and noninvasive diagnostic tools have been developed. These tools include Computerized Axial Tomography (CAT), Positron Emission Tomography (PET), Nuclear Magnetic Resonance (NMR), and most recently, the magneto-encephalogram (MEG). Unfortunately, each of these tools is expensive, and none has been available for large-scale research. These methods do, however, represent immense improvements in diagnostic accuracy.

Second, since the researchers had no control over the nature of these patients' lesions, no two brains had exactly the same pattern of damage; the resulting neuropsychological changes were similarly variable.

Third, it is always dangerous to extrapolate from the damaged brain to the normal brain. Functions may be shifted to normally quiescent undamaged areas of the brain, or test performance may be impaired due to reduced intellect.

Even with improving diagnostic tools, the second and third flaws just cited will persist in studies of random brain pathology. However, a specific and more uniform type of brain damage, absence of the corpus callosum, has yielded more useful data. Careful study of the normal brain through neuropsychological research has also produced much useful information.

Split-brain Research-- The two cerebral hemispheres are normally connected in the midline by a large associative bundle, the corpus callosum. Other structures of lesser importance which connect the right and left hemispheres are the anterior and hippocampal commissures, and in 70% of human brains, the massa intermedia (36).

Patients who are missing the corpus callosum represent a fairly homogeneous study group, and much has been learned from this small population. In the normal brain, it has been difficult to isolate the functions of the two hemispheres, since they so readily exchange information.. When the connecting bundles are missing, however, the hemispheres must act independently, and are more easily tested. The defect may follow "split-brain" surgery, which was described by Van Wagenen in 1940 as a treatment for intractable epilepsy (261), or may result from callosal agenesis, a congenital absence of the corpus callosum. Beaton has extensively reviewed these studies, and notes that although these studies have added much to our knowledge, they still describe abnormal brains, and exact anatomic verification is usually lacking (14). All of the post-surgical subjects had suffered years of severe seizures, and also the trauma of brain surgery; intelligence quotient (IQ) scores and reaction times are generally worse for these patients. Callosal agenesis subjects tend to show much less marked split-brain symptoms. Frequently, the smaller commissural tracts are enlarged, and compensate to a degree for the missing corpus callosum.

Split-brain patients frequently exhibit no behavioral or cognitive impairment on casual observation, and lead surprisingly normal lives. On careful testing, however, profound deficiencies are found. In their day-to-day activities, split-brain patients display a variety of clever methods of cueing the other hemisphere about important information. Bimanual tasks such as tying one's shoes require communication between hemispheres, which may be accomplished visually by the patient. It is even possible for a patient to transfer information from the right hemisphere to the left by tracing letters on the back of the right hand; the left hemisphere, having control of speech, can then vocalize the word (71).

Research with Normal Subjects-- Neuropsychological research with normal humans is often much more difficult to interpret. Frequently, testing of the visual or auditory systems has very poor reliability and validity (214, 229). Even within a single experiment, subjects can change laterality direction and magnitude (137). The most simple explanation for this change is that the normal subject can utilize both hemispheres, which allows for many more variations in information processing strategy. Researchers must attempt to control the thought processing in subjects in order to reduce "noise" to a minimum.

A problem encountered in laterality testing is "stimulus-response" (S-R) compatibility. Common sense dictates that a manual response with a given arm will be faster when the target is on the same side as the stimulus; in such a case, the response is said to be compatible with the stimulus, thus interfering with the experiment. This interference can often be overcome with maneuvers such as crossing the arms, or intertwining the fingers, but these types of data are difficult to interpret (14).

Although the testing of split-brain patients or normal subjects each requires special analysis, the basic methods are the same.

Research Methods

Laterality research generally attempts to engage specific parts of the brain via stimulation of a specific lateralized sensory modality, and subsequent recording of a motor output (e.g., speech or peripheral muscle movement). By comparing the motor output to normal performance, or to performance with a contralateral stimulus, conclusions can be drawn regarding function. The common methods of studying laterality will be briefly presented.

Vision-- Visual processing is usually assessed using tachistoscopic presentation. That is, a stimulus is presented to only one visual hemifield, or different stimuli may be presented to each hemifield. If the subject does not shift visual fixation, the stimulus will be transmitted exclusively to the contralateral visual cortex. A letter presented to the right hemifield will, therefore, reach the left occipital cortex via the optic pathways. Subjects may then be asked about the nature of the stimulus, or they may be required to compare two stimuli from competing visual fields. Split-brain patients frequently show an inability to compare symbols from different visual fields, but are able to compare them if they are presented within the same visual field (14). This phenomenon is due to the occipital lobes inability to "talk" to each other about visual field content. Normal subjects can be shown to display a variety of hemifield superiorities for different types of stimuli. Some of these functions may have application to enhancing cockpit performance.

Hearing-- Auditory function can be assessed using a technique called dichotic listening, in which different words are spoken simultaneously to each ear. Subjects might be asked to speak or write the words that they hear through the headphones, in an experiment attempting to determine the hemisphere dominant for speech. This method serves to overwhelm the weaker connection to the ipsilateral temporal lobe, and allow testing of the predominant contralateral pathway. In the hypothetical experiment just described, the expectation would be that the words presented to the ear opposite the hemisphere dominant for speech will be recalled more accurately.

Tactile Perception-- As might be expected, split-brain patients have demonstrated an inability to cross-localize a tactile stimulus; that is, to indicate with the opposite hand an area previously touched by the examiner. This inability is especially true as more peripheral extremities are touched (72). Normal subjects have been tested extensively to determine relative sensitivity of the hands to various stimuli, including shapes and braille. These studies may have application to cockpit design, and will be reviewed later in this paper.

Electrical Activity of the Brain-- A popular method of localizing brain activation has been the electroencephalogram (EEG). The EEG will indicate changes in the electrical activity under electrodes placed in standard locations on the scalp. These changes reflect the electrical activity of the underlying cortex. For example, the normal 10 cps alpha rhythm is suppressed and replaced in the right hemisphere by faster activity with lower amplitude, during the solving of spatial puzzles (68). Research using EEGs has been criticized for failing to exert control over subjects' mental activities (14), and for various statistical difficulties (165). This device remains a useful tool, however, and methodologies are improving. A type of EEG specifically evoked by stimuli presented to the subject is the event-related potential (ERP). Decision making and sensory experiences have been shown to cause specific waveforms that allow the location and temporal sequence of the lateralized process to be deduced.

Lateral Eye Movements-- In 1969, Bakan suggested that the direction of lateral gaze reflects contralateral cortical activation, and therefore the direction of gaze following a question reflects the hemisphere utilized to answer (12). This concept has been used in a number of investigations, which were criticized by Ehrlichman and Weinberger (62), and appear difficult to interpret, for a variety of reasons. Nonetheless, some interesting results did attain statistical significance.

Dual-Task Methodology-- This concept has been used widely in psychology, and in laterality research it holds that mental processing will be relatively impaired when more than one information processing task is required in one hemisphere. By including the proper tasks (127), this performance decrement can be used to determine the hemisphere being used for the task under study. Kinsbourne and Hicks used this technique to demonstrate the left hemisphere's role in language (138). Their subjects balanced a stick in one hand while reciting letters of the alphabet. Stick-balancing times were reduced for the right hand, but not the left, implying that the balancing and speaking competition for neural space was taking place in the left hemisphere. Much research has successfully used this strategy.

With the concept of task interference taken to its extreme, it may be that performance would be optimized by causing the two hemispheres to act completely independently, thereby increasing the capacity of the person to perform. Research in split-brain patients does not support this contention, however, as both hemispheres seem to become involved in difficult tasks (165). In fact, Sergent has recently suggested that split-brain patients' hemispheres communicate through subcortical structures more than was previously realized (237).

The Wada Test-- A famous research methodology employed first in the 1950s is the Wada Test. This test involves the injection of sodium amytal into the common carotid artery, with the objective of anesthetizing the ipsilateral cerebral hemisphere. During the brief period that the hemisphere is depressed, the patient may be tested for deficits, which would then be due to the impaired function of the drugged hemisphere. If the patient counts aloud during the injection, he will become aphasic if the side being injected contains the speech center, thus allowing the localization of language control. This procedure has significant risks, and for this reason, is limited to patients being evaluated preoperatively to determine the dominant hemisphere for speech. This result is useful information to the neurosurgeon, who may be contemplating removal of a temporal lobe, or entire cerebral hemisphere, for intractable epilepsy. These data are, therefore, not based on totally normal subjects, but have provided much insight into hemispheric function.

After this brief review of the major research methodologies found in the laterality literature, the next section of this paper will discuss the current state of knowledge in the field of cerebral laterality.

HUMAN CEREBRAL LATERALITY

In this review of the human laterality literature, three main areas will be discussed. In this section, evidence of cerebral anatomic and functional asymmetry will be presented. Handedness, which is a manifestation of cerebral asymmetry, will then be explored, along with other human systems which manifest functional asymmetry. Finally, these concepts will be brought together in a discussion of the interactions among cerebral laterality, handedness, and psychophysical performance.

Anatomic Asymmetry

It has been well documented that the human brain exhibits structural asymmetry in the adult, as well as the fetus and newborn infant (80). A higher Sylvian point can be seen at least by the 16th week of gestation in humans (142). There is evidence that human brains have always possessed this specialization. Fossil human skulls have asymmetry of the Sylvian fissures, much as is present in the skulls of modern humans (143). Over a century ago, it was noted that the left pyramidal tract decussates above the right in 82% of human brains (80). The functional significance of this fact remains unknown.

There are many more examples of asymmetry in the human brain. Some variations reflect hand preference. For example, in right-handers, the left occipital lobe of the brain is wider and/or longer than the right (142).

Functional Asymmetry

Neuropsychological research over the years has led to a characterization of the two hemispheres as having different cognitive "modes" (197). The left hemisphere has been described as verbal, sequential, analytic, logical, rational and temporal. Fine motor movements are largely initiated and guided from the left hemisphere (165). The right hemisphere modes are holistic, synthetic, visual, spatial, and emotional. Visuospatial relationships, humor, facial recognition, and some aspects of musical ability reside in the right hemisphere (165).

It is interesting to note that the complementary functioning of the two hemispheres of the brain is not a new concept at all. The 17th century philosopher Blaise Pascal speculated that there were two types of mind: esprit de geometrie (mathematical and concrete), and esprit de finesse (intuitive and common). Van den Hooff (260) inferred that Pascal considered the esprit de geometrie to be localized in the dominant hemisphere, and esprit de finesse in the minor hemisphere. Although not based in science, his concepts were amazingly accurate.

Vision

The visual field of each eye is divided into nasal and temporal hemifields. Through a system of partial decussation in the optic chiasm, all of the left side of space is carried to the occipital lobe of the right hemisphere, and vice-versa, with the exception of a small area perhaps one degree wide at the vertical meridian (185).

Tachistoscopic Research-- Each cerebral hemisphere can independently perceive and respond to tachistoscopic visual stimuli in its own visual hemifield. Split-brain patients, when presented the word "RAILROAD," and asked to fixate on a point between the "L" in RAIL and the "R" in ROAD, will say they saw "road" but will point with the left hand to the picture of a rail (165). This illustrates the inability of the split-brain patient to communicate information from the right hemisphere to the speech center in the left.

It is now clear that most intact subjects exhibit a right visual field superiority in recognition or recall of words and letters, and a left hemifield advantage in visuospatial tasks (14). First-graders display a left visual field (LVF) superiority for single-letter recognition (the reverse of the pattern observed in adults), which is thought to represent the nonverbal processing strategy utilized by young children. A similar pattern is seen in adults analyzing letters in unusual typefaces. Superiority of the right visual field (RVF) in recognizing words has been detected as early as 8 years of age. This asymmetry increases with age, into adulthood (53).

Tachistoscopic presentation has been used to search for hemifield asymmetries of different types of visual perception. A superiority has been found for the left field discrimination of curvature and in perception of the spatial orientation of a single line. However, recognition of geometric shapes has not shown a consistent hemifield advantage on tachistoscopic testing (14). The left hemifield/right hemisphere does appear to dominate in tasks which stress the spatial arrangement of elements in a stimulus display (213).

These visual laterality effects in the normal brain probably arise because one hemisphere is relatively inefficient at processing the stimulus presented to it, and may have to transmit the information across the corpus callosum to the opposite hemisphere. The nature of this processing difference is unknown, and is the subject of much speculation.

Spatial Frequencies-- Sergent has attempted to resolve the discrepancies among the many studies of hemispheric specialization (236). She concluded that the left hemisphere better processes stimuli with high spatial frequencies, while the right hemisphere is superior for stimuli with low spatial frequencies. Marsh (165) provided the example of human faces, which contain most of their information a+ moderate and low spatial frequencies, and noted that the right hemisphere is much more effective at dealing with faces than is the left. This may be a way that the hemispheres separate incoming data for processing (124). The lowest spatial frequency channels, which are right hemispheric, are thought to detect motion in the visual field.

The concept of an "ambient" visual system, separate from the "focal" system, draws on these observations regarding spatial frequencies (258). The focal system is thought to have evolved relatively recently to allow close observation, fine detail, and hand-eye coordination. Objects of regard for the focal system involve high spatial frequencies, and are well-represented in the subject's consciousness. The information gleaned using focal vision can be described as unusual features, details, and patterns; the left hemisphere has shown superiority in using this type of information.

The ambient system, on the other hand, is thought to be phylogenetically older, subserving spatial localization and orientation. This system senses coarse detail and low spatial frequencies, and what is commonly referred to as peripheral vision. Stimulation of the ambient system frequently is without conscious awareness (154). It seems that these systems are separately controlled. Note that one can walk, completely oriented, while reading. Also, patients and animals that have had the focal system destroyed are able to maintain orientation (83, 259). The ambient system appears to be controlled through thalamic (superior colliculus and pulvinar) as well as right parietal contributions (165).

Ocular Dominance-- The term "ocular dominance" (or "eyedness") may refer to a number of different aspects of vision. "Acuity" dominance describes an eye with superior acuity, whereas "sighting" dominance refers to a tendency to use one particular eye in preference to the other during monocular viewing (14). Approximately 70% of dextrals are right eye dominant, whereas about 60% of sinistrals prefer sighting with the left eye (178).

Right eye sighting dominant subjects were more accurate on a tachistoscopic verbal task, while left-dominant subjects were superior on a nonverbal task (130). This effect would suggest some advantage for the crossed optic pathways, since the contralateral hemisphere appears to be preferentially engaged. However, one study found that right-eye dominant subjects showed a left-hemifield advantage for a facial expression matching task, while left-eye dominant subjects manifested a right hemifield advantage (249). Dominance of the right eye also weakly predicted a left ear advantage on a dichotic listening task.

There appear to be sex interactions involved in eye dominance. In males, handedness is associated with the sighting type of eye dominance, whereas the hand preference of females has been associated with acuity dominance (96). Overall, there is a weak association between generic eye dominance and hand preference (39, 200).

Stereopsis-- The successful fusion of the two disparate retinal images, cortical integration, and subsequent perception of the spatial relationships of the scene components is necessary to achieve stereopsis. Research into the functional lateralization of depth perception has produced conflicting results, although a recent explanation appears reasonable (141).

In studies of brain-damaged patients, investigators measuring depth perception with random letter stereograms have generally found a right hemisphere superiority, in the absence of monocular form and depth cues (60). Other researchers, using the Titmus test of stereoacuity, have found impairment worse with left parietal lesions, and concluded that this region was dominant for stereopsis (185). Apparently, the reason for these inconsistencies was that the different tests of stereoacuity are actually measuring different aspects of stereopsis, which Julesz originally called "local" and "global" (125).

"Local" stereopsis is the point-by-point matching of corresponding stimulus elements in the two half-images, and the assignment of a depth value for each. The Titmus test, which presents monocular form cues, measures this type of stereopsis, which is thought to occur at the level of the visual cortex by disparity-detecting neurons.

"Global" stereopsis represents the non-stereoscopic ability to construct from the binocular input the overall form of an object on the basis of interposition cues alone (53). The right hemisphere is dominant for "global" stereopsis, receiving "local" stereoscopic input from the visual cortex of both hemispheres and integrating it with right hemispheric visuospatial mechanisms (185).

Bilateral injury of the occipital lobes can produce a profound impairment of depth perception. A patient reported by Holmes and Horrax in 1919 was unable to tell a flat sheet of cardboard from a cardboard box, or a pencil held 30 cm (12 in.) from his face from one held at a distance of 60 cm (23.6 in.) (115). This lack of depth awareness is interesting but rare.

Face Recognition-- Especially when the faces are highly discriminable and/or unfamiliar, a superiority of the left visual field has usually been reported for simple same/different facial identification tachistoscopic tasks (14). As discussed previously in terms of the spatial frequency processing model, more detailed analysis of facial features seems to be a left hemisphere function.

Audition

In 1961, Kimura published two reports that provided evidence of auditory asymmetry. In the first report, she found that patients who had had surgical removal of the temporal lobe had a deficit in recalling digits presented under dichotic conditions to the ear opposite the side of the surgery (132). This finding supported the view that the auditory pathways from each ear to the contralateral cerebral cortex are more effective than ipsilateral pathways.

In the second report, normal right-handed subjects were found to have an advantage in recall of verbal material presented to the right ear (133). This right-ear advantage is presumably due to activation of the left hemisphere, which is more efficient at language tasks in right-handers.

While there does seem to be an advantage to the crossed auditory pathways, the side of space generating the sound does not determine the hemisphere activated. The left hemisphere appears to dominate, regardless of the side of space from which the sound originates, and this interhemispheric difference appears to increase as the stimulus becomes more complex (14).

Nonverbal auditory stimuli have also been studied, and reveal an interesting effect of proficiency. While the expected right ear superiority was found in inexperienced Morse code listeners, a left ear advantage for longer sequences was seen in experienced operators. This finding may reflect a more holistic processing strategy (200). Conversely, musically naive listeners have been shown to have a left ear superiority, whereas experienced listeners have a right ear advantage for music (121). It is generally conceded that music is multidimensional, however, and resistant to easy characterization and cognitive study.

Surprisingly, split-brain patients do not show an impairment in localizing a sound source, an ability dependent upon a comparison of the phase, intensity or time of arrival of the sound at the left and right ears. This implies that the integration and comparison of some aspects of sound from the two ears occurs at a sub-callosal level (71).

The auditory system, while displaying strong evidence of laterality, is somewhat more variable than other sensory systems. The fact that there is a 10% projection to the ipsilateral hemisphere, in addition to the 90% projection to the contralateral hemisphere, has limited the experimental use of the auditory system, since vision is just as readily tested and has relatively "pure" contralateral projection. Bryden found that 15% of right-handers did not show the expected pattern of right-ear superiority (32, 229), suggesting that dichotic listening is a poor method for ascertaining the hemisphere controlling language in an individual. More recently, some authors have contended that dichotic listening may be reliable (165).

In close proximity to the auditory system, the vestibular system has been reported to exhibit asymmetrical function. Bodo et al. found the slow phase rate, in response to caloric irrigation of the ear canal, to be more active on the left (24). They also noted a preponderance of the nystagmic reaction to the right, as measured by duration, frequency, amplitude, and the slow phase rate. Hand preference was not reported.

Tactile Perception

The afferent neural pathways of tactile sensation transmit information to the brain from the contralateral body (55). Because of this, split-brain patients are usually unable to point with one hand to where they had been touched on the opposite side of the body, when visual cues are excluded (72). The hemisphere feeling the sensation of touch is unable to pass that information to the hemisphere controlling the pointing hand, due to the absence of callosal fibers. This phenomenon occurs regardless of which side is touched, provided that the required response is contralateral.

There is evidence of hemispheric differences in information processing abilities. The left hand has been shown to be superior in discriminating the orientation of lines, and perceiving meaningless three-dimensional forms (271); however, the right hand is superior in recognizing letters traced on the palm (199). A left-hand advantage has also been shown for the individual sensory modes of point localization, kinesthesis, but not for pressure or vibration sensitivity (53).

In 1971, the case of a blind boy who lost the use of his left hand was reported (109). The observation that he was unable to read braille with his remaining right hand spurred a series of experiments examining the processing of tactile language; several investigators subsequently confirmed the left-hand superiority for braille reading. In fact, most right-handed blind subjects read braille faster or more accurately with the middle finger of the left hand than with the right, although there are large individual differences that depend importantly on initial hand preferences. However, fluent readers use both hands independently to read, the division of text seeming to depend mostly on convenience of movement (182). Fast reading seems to require the rapid alternation of function between the two hands.

Since the left hemisphere is classically cited as being specialized for language, this left-hand superiority may appear counterintuitive. It is currently believed that in order to process braille information, the spatial arrangement of the dots must be first appreciated by the right hemisphere, which is believed to specialize in visuospatial tasks (53). At least this is so for right-handed people, whether in the blind or in sighted people when they shut their eyes. For left-handers, however, the hands appear to be more nearly equal in skill, although the data are less clear (102). It has also been proposed that the sensory modality of touch requires right hemispheric processing more than similar patterns encountered visually.

De Renzi, in reviewing the literature of tactile perception laterality, concluded that the weight of evidence supports a right hemispheric superiority in simple space perception tasks (such as the orientation of a line or rod). However, as the tasks became more complex (e.g., when identifying unfamiliar shapes), the left hemisphere contribution increased (53).

Language

Much of the evidence indicating a lateralization of cerebral language function has already been discussed. As language is the most well-studied aspect of functional cerebral asymmetry, it is difficult to discuss other aspects of laterality without referring to this striking pattern of left-hemispheric speech dominance in most humans.

Lateralization of Language-- Many studies of patients with unilateral cerebral lesions have established the left hemisphere as the site of language in right-handers. Results from several experimental paradigms suggest that linguistic functions are localized in the left hemisphere from birth, for both male and female children (98). It is evident, however, that handedness is associated with this lateralization. Adult left-handers and those right-handers with a family history of sinistrality were noted to show better recovery from aphasia than unequivocal right-handers (157). This finding, coupled with the observation that left-handers could develop aphasia from damage to either hemisphere (278), suggested that left-handers were more variable than right-handers in their hemispheric control of language. Further, rare cases were reported of visuospatial deficits, but not aphasia, following left-hemisphere damage (126). This implied that language was not the only cerebral function that was subject to variability. These findings contributed to the decline of the universal left hemisphere dominance concept.

Gazzaniga et al. examined patients following callosotomy, and found that in the immediate post-operative period, all patients were unable to carry out actions of the left arm in response to verbal instructions. They were able to imitate the movement if demonstrated (74). This evidence supported the existence of a left-sided cerebral receptive language center, and bilateral visual representation. For several weeks after the operation, patients generally show marked deficits in naming objects presented to the left visual field or placed in the left hand (73), thus providing evidence of a left-sided expressive language center as well.

In split-brain patients, the lateralization of speech control has been investigated using various means to engage the hemispheres separately. This research has shown that, when verbal output is required, the left hemisphere has no difficulty, whereas the right hemisphere has almost no means of responding. Only one of the reported split-brain patients had language production capability in the right hemisphere (75).

The Wada Test-- Probably the most famous method used to localize cerebral control of language has been the Wada test. Beaton (14) summarized the Rasmussen and Milner data (218), noting that these subjects were all candidates for brain surgery, and had some degree of neurologic impairment. Of 140 right-handers showing no evidence of early injury to the brain, 134 (96%) had speech controlled in the left hemisphere and 6 (4%) had right hemisphere speech. Among 122 non-right-handers (left and mixed handers being considered together), the left hemisphere controlled speech in 86 patients (70%), while 18 (15%) had right hemisphere speech, and in 18 (15%), speech was bilaterally represented. The high proportion of right-handers with right hemispheric speech is attributed to the preselection of patients suspected of unusual patterns of speech representation (14). Rossi and Rosadini found that only one of their 74 right-handed patients did not have speech controlled exclusively from the left hemisphere (225).

Other Research-- Unilateral electro-convulsive therapy (ECT) has produced corroborative data. In right-handers, shock to the left side of the head impairs verbal performance, whereas right-sided ECT is more likely to impair spatial performance. The ECT-based research has not accumulated enough left-handers to contribute much to the body of laterality research (14).

Much recent research focuses on completely normal subjects, since it is widely acknowledged now that information processing is altered even in the mildly damaged brain. Tachistoscopic visual research has established the right visual field superiority in recognition or recall of words and letters (14).

A variety of dual-task experiments have shown that concurrent verbal tasks interfere with right-hand performance, and visuospatial tasks interfere with left-hand performance. This is true especially when the motor task involves rapid positioning of the contralateral limb, such as tapping (50).

At present, it is believed that in almost all right-handers, and in most left-handers, production of speech is limited to a small area of the left frontal lobe (Broca's area) which is just anterior to the tip of the temporal lobe. Receptive language functions, which appear to be less well lateralized than executive aspects, are located in the left hemisphere at the conjunction of the frontal, parietal and temporal lobes, (Wernicke's area). Besides controlling most aspects of language, the left hemisphere has a major role in the fine movements of the speech and oral musculature (252).

Recent studies have shown some language capability in the right hemisphere; these and other functions of the right hemisphere will be discussed in a later section.

Sign Language-- The manual sign language of the deaf is a fascinating form of communication, which is simultaneously a language and a spatially presented and perceived set of complex gestures. There are at least fourteen known true sign languages in the world, which often bear no resemblance to the local spoken language (167). American Sign Language (ASL), for example, is a separate language, much more than simple finger-spelling or a manual facsimile of English.

Some investigators have suggested that structures in the right hemisphere are responsible for formation, expression, and reception of these spatially mediated languages. However, evidence accumulated from brain-damaged deaf patients has convincingly demonstrated that it is the left hemisphere that controls language in both spoken and signed communication (135, 167).

Recently, Damasio et al. studied a female right-handed patient who was fluent in both English and ASL (51). This hearing patient was being evaluated to determine which temporal lobe should be resected for the treatment of intractable epilepsy. Determination of the hemisphere dominant for language would allow the removal of the contralateral temporal lobe without the risk of post-operative aphasia. A Wada test was performed, during which all left language areas were chemically temporarily ablated. This produced an aphasia of both spoken language and ASL. Removal of the right temporal lobe ensued, with no subsequent impairment of language abilities, spoken or sign. Clearly, in right-handers, the left hemisphere controls linguistic aspects of communication, regardless of the mode of transmission.

Standard and Anomalous Dominance

The "standard dominance pattern," displayed by most of the population, is a strong left hemisphere dominance for language and handedness, and strong right hemisphere control of other functions . All other variations of cerebral lateralization, which occur in about 30% to 35% of individuals, represent "anomalous dominance" to some degree (80).

Much of the literature examining the topic of anomalous dominance searches for relative advantages or disadvantages to various permutations of handedness, family history, eye dominance, etc. It should be emphasized that a finding of impaired performance or a higher rate of disease in such a group of people should not imply that all the members of that group are identical, nor should it follow that a specific individual has poor job (or flying) performance, or an overall increased risk of death.

Stuttering and Dyslexia-- The association between reading disabilities, stuttering, and faulty cerebral dominance patterns was first noted in a theory of mirror writing and reading by Samuel Orton (1925), who noted that some children could read better in a mirror, or with the page inverted, and observed that dyslexic children often reversed letters while writing. He termed this phenomenon "strephosymbolia," or "twisted symbols." (198). He proposed that letters are represented backward in the nondominant hemisphere, and correctly in the dominant hemisphere; in effect, one hemisphere formed the mirror image of the other. Incomplete suppression of the nondominant hemisphere, therefore, would cause the child to produce mirror images of the correct letters. It was thought that one with strephosymbolia might have a lowered degree of manual or mental dexterity (101).

More recently, Beaton concluded that there was "no evidence whatsoever" for belief in Orton's theory that symbols are recorded in a mirror image fashion in the two hemispheres (14). Although Orton's explanation for mirror-writing has been discarded, there has been a resurgence of interest in the phenomenon.

Stuttering and dyslexia are popularly associated with left-handedness (8). This association has received some experimental support, but the topic is controversial. Numerous investigators have observed that natural left-handers may begin to stutter when forced to use the right hand for writing, and this dysfluency may resolve following a return to left-handed writing (250).

There is evidence that the dominant hemisphere may somehow fail to inhibit the nondominant hemisphere during speech, producing stuttering as a consequence of this atypical excitation and competition (94). Studies using a variety of research techniques have frequently shown that stutterers are not as well lateralized for language as controls (105). This has been suggested by anatomical data as well. Hier et al. found that 10 out of 24 adult dyslexics showed a reversal of the normal pattern of cerebral asymmetry on the CAT scan, the right parieto-occipital region being wider and not smaller than the left as is usual (114). Geschwind and Behan have found higher rates of dyslexia and stuttering among strong left-handers than among strong right-handers (79). However, recent evidence has cast doubt on the association of stuttering with left-handedness (230, 266).

Similarly, the literature does not approach a consensus regarding the interaction between cerebral laterality and reading disability. Beaton reviews seven major theories attempting to account for the available experimental results, and concludes that there is probably a slightly higher incidence of non-right-handedness in dyslexics than in the population at large. A popular explanation for this is that some degree of global left hemisphere damage predated the development of both the handedness and dyslexia (14).

Geschwind and Dyslexia-- Geschwind believed that the brain abnormalities in dyslexia were developmental in nature and attributable to disturbances in neuronal migration during cortical embryogenesis. The developing cortex is characterized by neuronal redundancy, which may confer protection against neuronal damage in utero. Normally, these excess neurons die when they fail to achieve integration in the embryonic neural tissue (99). Geschwind speculated that the brain may be able to compensate for mild neuronal damage by shifting the specialization of the damaged area to another region of developing cerebrum. This remodelling may have a price, however, as the restructured brain may be predisposed to autism or dyslexia (80).

Geschwind et al. reported two cases in which speech fluency was changed by brain damage in adulthood (107). The first patient was an ambidextrous man who suffered a head injury and thereafter ceased stuttering. The second case was a converted sinistral man, who returned to stuttering after a cerebrovascular accident. Both of these patients' clinical courses could be explained by a major change in the balance of speech control.

Geschwind also suggested a fascinating mechanism for mirror-writing that draws on evidence that left-handers exhibit a left-hemifield preference for language, relative to right-handers. When reading a word, regardless of hand preference, the image falls on the fovea, and is available to both hemispheres. Since English is written left-to-right, the next word lies to the right of the fixation point and is transmitted to the left hemisphere. If the individual has right hemispheric specialization for language, the information will be relayed across the corpus callosum for processing. There is speculative evidence that the callosal fibers may be poorly formed in many dyslexics (23, 80), resulting in a clear advantage for lexical information that is presented to the left hemifield. When mirror-reading, words to the left of fixation are transmitted to the right hemisphere, which would be the most efficient mode of processing for these individuals. Geschwind noted that the ability to read and write in mirror fashion is much more common in left-handers. Some left-handers, such as Leonardo da Vinci, have been able to mirror-write easily; this may make reading easier for the right hemisphere.

Right Hemisphere Functions

The dogma of left hemispheric "dominance" persisted for many years, fueled by the late 19th century work of Broca and Jackson. In fact, it was not until 25 years ago that the scientific community acknowledged that the right hemisphere was superior to the left hemisphere in certain functions (14), despite the 1876 writings of Hughlings Jackson (118). Studies of right brain lesioned patients and normal subjects have contributed much to this understanding of the various functions of the right hemisphere.

Although the prevailing view held that language in right-handers was exclusively located in the left hemisphere, patients with extensive left brain lesions were shown to retain a few definite language skills (245). Further, patients with right brain lesions were found to have subtle evidence of language impairment (61). More easily accepted was research revealing that most complex spatial processing was carried out in the right hemisphere.

Research methods that selectively activate one hemisphere have made it quite clear that each half of the brain can, when required to do so, independently perceive, remember and respond to stimuli presented to it (14). This capacity is thus not an exclusive function of the left hemisphere. However, this remarkable degree of independence is probably only possible in the split-brain patient, in whom the corpus callosum is absent and cannot conduct information from one side of the brain to the other. In the intact brain, the right hemisphere usually controls attentional functions (165).

Perception of Space-- The weight of evidence in split-brain patients points to a right hemisphere superiority for visual and tactile pattern perception and memory (192). The left hand of these patients is superior to the right hand in spatial subtasks of the Weschler Adult Intelligence Scale, while the right hand is "barely able to do the simplest problems" (73). Drawing simple geometric shapes or copying a design is extremely difficult or impossible for the left hemisphere. The right hemisphere, by contrast, has no trouble with block construction or drawing shapes (150).

Spatial functions, such as the processing of visual stimuli and their spatial relationships to each other, the mental manipulation of geometric forms and objects, puzzle assembly and map reading, either on paper or in mental images, are all controlled from the right hemisphere. This is also true of the ability to recognize faces, especially contours and profiles, and the "sense of humor," especially with sexually oriented jokes (165), although there is evidence that some spatial functions are subserved by the left hemisphere (177).

Language-- Many patients retain the ability to sing despite their left hemispheres being incapacitated by disease, surgery, or amytal, suggesting that the right hemisphere does have some capacity for language (14). The capacity of the right hemisphere for speech has been the topic of much research. Right hemispheric speech has been described as different from left hemispheric speech. The speech of patients with left hemisphere lesions is often automatic and stereotyped, containing expletives and bursts of common phrases (55, 129). Lesions restricted to the right half of the brain have been shown to cause "higher-level" linguistic difficulties (263).

Apparently, the appreciation of the prosodic nature of speech (both receptive and expressive) and the comparative and metaphorical aspects of language reside in the right hemisphere

(61). The right hemisphere interprets a word based on a holistic impression, rather than a phonetic analysis. Patients with brain damage to the right temporal area can demonstrate a tonal agnosia, or "aprosodia," which renders them unable to infer the expressive qualities of language (227). [For a fascinating, brief, and readable account of the effects of left and right brain damage on language, the reader is referred to Sacks (227), chapter 9.]

Concrete, highly imageable words, (i.e., book, rock, girl), are represented in the right hemisphere, as well (176). It appeared initially that the right hemisphere's vocabulary was restricted to a single grammatical class, namely nouns (74). More recently, Zaidel has shown that if given sufficient time to decode a message, the right hemisphere is able to understand many aspects of language, including verbs. He estimated the right hemisphere's capacity for language to be approximately the level of a normal 5-year-old child (276).

It appears that while left-handers have more variable lateralization of language than dextrals, spatial skills usually remain lateralized to the right hemisphere in both groups (53). Language thus appears to be the main functional asymmetry that is subject to variability. However, Junque et al. recently reported a case of a right-handed man with a massive left-hemisphere infarct, who had deficits more compatible with a right-hemisphere lesion (126). He was found to have neglect, visuoperceptive and visuoconstructive deficits, and disturbed voluntary expression of emotion, but no aphasic symptoms at all. Clearly visuospatial function can be located in the left hemisphere, although this is rare.

Other Functions-- The recognition and appreciation of music have usually been associated with the right hemisphere; however some professional musicians have recently been found to analyze music much like a language, suffering a larger performance decrement from damage to the left than to the right hemisphere (121, 128). As noted in a prior section, a similar phenomenon has been observed in Morse code operators (200).

The right hemisphere also appears to dominate in depth perception, ambient vision, and other visual stimuli composed of low spatial frequencies. These aspects of vision have been discussed previously.

Information Processing Theories

The efficient management of cockpit resources is often dependent on the pilot's ability to absorb a large amount of data in a short time, and react appropriately. A knowledge of the various mechanisms used by the brain to process information could greatly enhance cockpit design. Unfortunately, little is known about these complex interactions. The major theories of information processing will be briefly reviewed here, and potential applications discussed in a later section.

There are several ways of contrasting the processing strategies of the two hemispheres. Some investigators have attempted to dichotomize processing into a left hemispheric serial mode, and a right hemispheric parallel mode (161). Attempts to experimentally verify these strategies have been supportive, but difficult to interpret (14). Another approach has been to assign an analytic processing mode to the left hemisphere, and a holistic, or gestalt, mode to the right hemisphere. In a well-known experiment, Martin used a large letter made up of many small letters. When subjects were asked to respond based on the smaller letters, the left hemisphere was superior; when responding to the larger, more holistic letter, the right hemisphere was superior (168).

Information processing models assume that conscious perception is the product of a series of processes that a stimulus must undergo. It is generally accepted that we do not process all available stimuli; they must be prioritized, accepted (which is determined by the level of "attention"), and stored into memory (165).

Memory is usually thought of as short-term (for fast processing), and long-term (for storage). The initial process of registration is referred to as iconic storage for visual input, and echoic storage for auditory data. These transient forms of information storage are susceptible to displacement if another stimulus follows within about 20 ms; the information can be dislodged for a longer time if the second stimulus is similar to that which was initially presented. The information eventually attains relative permanence, termed retention (165).

There are several variations on these basic assumptions, but laterality is generally not considered, although the right hemisphere has been shown to be faster than the left at this initial encoding (106). It is assumed that the intact brain assigns the most efficient processing sequence available.

A variety of information processing models have been proposed; each has supporting data. The Direct Access model, proposed by Kimura, assumes that stimuli will be processed mainly by the hemisphere receiving it (134). If that hemisphere is unable to complete processing, it passes the data to the other hemisphere. A task requiring verbal comprehension will, therefore, require eventual action by the left hemisphere. Zaidel proposed a Callosal Relay model, which differs from the Direct Access model only in that information arriving at the wrong hemisphere is passed, unprocessed, across the corpus callosum for action (277). Both of these models have supporting data, but do not have much practical application, since the intact human would not be expected to direct sensory information to either hemisphere exclusively. Kinsbourne has proposed an "attention-bias" model which holds that the hemispheric-processing strategy depends largely on the expected stimulus (136). If a person expected to process verbal input, for example, the left hemisphere would be primed and the right hemisphere inhibited. The reverse would be true for nonverbal information. As will be seen later, there may be application to aviation psychology in some of the proposed models.

One method of studying these information processing models is to use the principle of interference, which was discussed earlier in the research methods section. These strategies rely less on restriction of stimuli to one or the other hemisphere, but depend more on performance as an indirect measure of laterality. Results of this type of research are more easily applied to cockpit performance.

HANDEDNESS

Coren and Porac recently reviewed the history of hand preference (48). It has long been known that hand preference is closely linked to cerebral asymmetry. Since handedness is such a conspicuous manifestation of hemispheric laterality, it has been a frequent target for researchers seeking the answers to questions of cerebral neuropsychology.

Before examining hand preference, the term must be defined and measuring devices must be designed. Much of the difficulty encountered in reviewing the literature is due to a lack of consistency among investigators in measuring and labelling various subpopulations of lateralization. Many conclusions can, however, be safely drawn.

General

Even in utero, the size distribution of the left side of the brain is markedly skewed to the left (262), although the right hemisphere develops faster (80). This cerebral asymmetry probably influences the development of hand preference. Probably the first evidence of laterality in the newborn infant is head-turn preference; that is, the direction that the infant prefers to turn the head while prone (181).

Early evidence of neonatal laterality is also seen in the stepping reflex. Peters and Petrie found that this reflex leg movement began with the right leg in 18 out of 24 infants, who were an average of 17 days old (207).

Data gathered by observing the spontaneous manipulation of objects is useful in assessing differences in hand usage in infants (217). Clearly, the right hand is used more than the left to manipulate objects at least by the age of 15 months, although there is disagreement in the literature (14). Nonetheless, Chinese children were observed to show evidence of hand preference at approximately 2 years of age (153).

Apparently, complementary hemispheric specialization of function can be detected in the early years of life. It has not, however, been established how these affect later asymmetries in the adult. The research to date has largely been cross-sectional, a study design which introduces many potential biases.

Hand preference does appear to correlate with manual skill, but this has been shown to depend on the task under study. For example, different types of movement, such as peg-fitting and tapping, have produced disparate results (14). These conflicting results may be due to researchers ignoring such modifying effects as degree of hand preference, degree of practice, or the basic structure of the task under study. Dominant hand performance may be superior in tasks such as peg-fitting due to superior aiming, as the nonpreferred hand has been shown to require many more fine adjustments by the cortex in order to hit the target (4).

Some movements are accomplished better by the left hand, even in right-handers. Individual finger flexion, for example, has been found to be superior in the left hand (201). However, the control of the intricate, coordinated movements of hands and digits has not been well-studied. The literature is massively conflicting even considering only hand preference.

Measurement

Historically, the study of left-handedness has been fraught with problems. Researchers have established hand preference in several different ways. Early studies defined handedness simply by asking the subjects whether they were right- or left-handed. Unfortunately, subjects differ in their criteria for self-assessment; socioeconomic background may also influence responses. Self report has been shown to be poorly correlated with actual hand use, especially in left handers (112). Despite convincing data, this method of assessment continues to appear in the literature (58). Some researchers have taken the hand used for writing as the preferred hand (242). Often, social pressure causes individuals to abandon the use of their left hand, especially for writing. Inventory analysis has shown that the writing hand often does not accurately predict lateralization for other common tasks (228). The most meaningful method of assessment is direct observation by the investigators. This has been done with some success (182), but can become expensive and time consuming. The question of how many activities to observe then becomes an issue.

The last, and most common method used in modern laterality research, is the questionnaire. The nature and number of questions varies from inventory to inventory, but generally a laterality questionnaire asks subjects to state which hand they prefer to use for a set of common activities. Most questionnaires have not been validated against behavioral observations (14), although some have been subjected to various types of analysis (42, 228, 269).

A pitfall in the design of handedness inventories is the inclusion of items that do not correlate with hand usage, and may weaken the data. As just discussed, the preferred writing hand is relatively insensitive. Questions relating to eye dominance also have been shown to correlate poorly with actual hand use (80).

Chapman and Chapman have found that strongly right-handed subjects, and to a lesser extent left-handers, can be reliably separated from a larger group by asking them the following question (42):

Which description best applies to you?

1. Right-handed and strongly so.
2. Right-handed but only moderately so.
3. Left-handed and strongly so.
4. Left-handed but only moderately so.

Two inventories in common usage are the questionnaire by Annett (5), and the Edinburgh Handedness Inventory, by Oldfield (195). These inventories, or modifications thereof, appear in much contemporary laterality research, although it has been suggested that the most satisfactory measure of handedness would involve a short preference inventory and a performance test involving tapping speed (33).

Data analysis has been conducted in a number of ways. Most investigators divide subjects into handedness groups based on their laterality scores, but any such classification is arbitrary (111, 228). Tests that take advantage of the full distribution of handedness in the sample are the most powerful, and could detect more subtle shifts in laterality (80). Since handedness is not normally distributed, nonparametric tests such as those of Mann-Whitney and Kolgorov-Smirnov may be employed effectively (31). The often used chi-square test is appropriate, but is only as good as the categories of data.

<u>The Nature of Handedness</u>-- In describing handedness two distinct factors must be considered: the direction of handedness (i.e., right or left) and the degree of handedness (i.e., given that a person is right- or left-handed, how right- or left-handed is he, on a scale from totally ambidextrous to completely lateralized) (175). Most laterality inventories generate a number, commonly called a laterality quotient, which places the individual somewhere along a continuum of hand preference. Usually, the resulting distribution is bimodal, with a large peak toward the extreme dextral end of the spectrum, and a smaller, broader peak in the moderately sinistral range (195). It is now generally accepted that handedness is a continuously distributed

variable, although there is some concern that there may be additional axes of laterality that are not currently being measured (104).

Geschwind suggested that present measuring strategies ignore a different aspect of asymmetry. He speculated that there may be two types of motor learning that exhibit laterality, noting that there is often asymmetry in other types of movement that are not assessed by current laterality inventories (80). Among these movements are the preferred direction of turn by ice-skaters, or ballet dancers. Some people write with one hand on paper, which requires many fine hand movements, but use the other hand to write on a blackboard, which involves more central, truncal movements. The coarse, more truncal type of motor control is termed the "axial" system, while more commonly assessed fine movements are under the control of the "pyramidal" motor system. Geschwind proposed that an individual's relative talent in each system is independent, and that these two aspects of motor control are "wired" separately. A person with so-called "standard" dominance would have control of both types of motor control located in the left hemisphere, whereas one with "anomalous" dominance might have control divided between the two hemispheres. This pattern of lateralized control might explain much of the variance in the handedness literature, although Geschwind admits that supporting evidence is fragmentary. It is interesting to speculate that such lateralized control of these systems might facilitate complex bimanual movements; fine movements could be performed by one hand, while the other executed skilled supportive activities.

There is good evidence for a distinct truncal asymmetry of rotation in humans, which supports Geschwind's contention that current laterality inventories do not assess all aspects of motor asymmetry. Bracha et al. found that normal men and women rotate preferentially to the left or right during normal activities (27). Left-hemisphere dominant (judged by hand, foot, and eye preference) males rotated more to the right than to the left, whereas left-hemisphere dominant females rotated more frequently to the left than to the right. In males, eye preference was more clearly associated with rotational preference than hand or foot preference.

This concept of a separate truncal axis of laterality is not new. In 1928, Schaeffer noted that blindfolded persons tend to walk in "clock-spring spiral" paths when attempting to maintain a straight path (231). He also found that the direction of "spiral movements" was unrelated to hand preference, and speculated that it was controlled by a more deep-seated mechanism, and was "demonstrably present in more of the protoplasm of the body than is right-handedness or left-handedness."

Correlates With Other Asymmetries

A variety of structural and functional asymmetries have been linked with hand preference. Some are difficult to interpret; for example, blondes are significantly more sinistral than brunettes (80). Also, brachial artery pressures (taken from the arms) showed no correlation with handedness, although ipsilateral ophthalmic artery pressure did positively correlate with hand preference (35).

Clearly, left-handers do not simply show the reverse cerebral lateralization pattern of dextrals. In fact, since not even dextrals are uniformly lateralized, it is more proper to consider cerebral asymmetry as a continuum, rather than an all-or-none phenomenon.

A greater proportion of left-handers have weak hand preferences, finding it relatively easy to perform a given unimanual task with the nonpreferred hand, and a greater proportion of them show inconsistent lateral preference patterns, doing some tasks left-handed and some right-handed (76). With the notable exception of tongue clicking, which occurs to the ipsilateral side of the mouth more reliably in left-handers, studies of lateralized performance effects have demonstrated that right-handers are more lateralized than are left-handers (112).

Other organ systems, including the eye, ear, and foot have been shown to possess anatomic and functional asymmetry. Although the literature is once again conflicting, Beaton concluded that the correlations between preferred hand and foot were the strongest (14).

Theories of Genesis

Left-handers have been variously grouped into familial and nonfamilial, or normal and pathological. While there is evidence that heredity plays a large role in the development of laterality, other researchers believe that most sinistrality develops after brain damage in utero, or in early childhood. Contrary to earlier reports, there does not appear to be a relationship between birth order and lateral preferences (189).

Left-handedness has been associated with stuttering, autism, epilepsy, and subnormal intelligence (20). An increased incidence of left handedness in these various pathological groups can be explained by assuming that very early brain damage affects both hemispheres with equal frequency, and thereby causes a shift from the normal dominant side. Since there are more natural right-handers than left-handers, more of the brain-damaged people will shift from right-to-left than the reverse, resulting in a larger proportion of sinistrals in that clinical population (14).

It has been found useful in experimental verification of antecedent brain damage to test performance of the nonpreferred hand, relative to the preferred hand (19).

The weight of evidence, however, supports genetic control of most handedness. Several theories have therefore been proposed to account for such a hereditary factor. Older models generally assigned one gene for right handedness and another for left handedness. Newer theories have proposed single-gene control of hand preference.

A popular model is Annett's Right Shift Theory (7). She postulates the existence of a right shift factor, which biases the left hemisphere toward speech and dominant hand control. In the absence of the factor, hemispheric dominance and hand preference are random and independent of each other. Much evidence has accumulated supporting the Right Shift Theory. Especially compelling are good explanations for the raised incidence of left-handedness in twins, and the common finding that sinistral females are less lateralized than sinistral males (14).

Geschwind has more recently proposed a controversial theory that is, in effect, the mirror image of Annett's. He postulated that the basic pattern of the brain is one of anatomic asymmetry, so that language lateralization and handedness will depend largely on the size of the planum temporale and other regions of the hemisphere which are usually larger on the left (80). Influences that delay left hemisphere growth during pregnancy and early childhood thus tend to create brains in which the normal asymmetry of these regions is diminished, so that the corresponding areas on the two sides are more symmetrical. In some cases, the right hemisphere becomes more developed than the left. The group with symmetrical brains should then manifest random dominance (80).

While genetics play an important role in Geschwind's theory, the effect of other outside influences is strong. Among these influences are maternal dihydrotestosterone, progesterone, stress, or exposure to exogenous chemicals (90). This evidence does not imply that all left-handedness is pathological. The essential point is that there is a continuum between the cases of left-handedness with intrinsic and extrinsic etiologies.

There is convincing and surprising evidence that the position of the infant in the birth canal is somehow linked to subsequent development of handedness. Two studies have shown that infants born in the right occiput anterior position are much more likely to later develop left-handedness than infants born in the more common left occiput anterior position (44, 78, 92). Geschwind suggests that the head position at birth is not the cause of subsequent laterality, but is itself due to antecedent laterality of the brain.

Similarly, neonatal head-turn preference has been shown to predict hand-use preference in the first 74 weeks of life (181). These studies should not be interpreted as evidence for a purely environmental etiology of handedness (80).

Sociocultural Factors

It is clear that social factors affect the manifestation of handedness (243). The exact proportion of handedness due to these extrinsic factors is less clear.

The observation that an increase in age is associated with increasing dextral preference suggests that a cohort of people relatively intolerant of sinistrality is gradually aging, and being replaced with generations of people less conscious of the traditional dextral bias (16, 18).

Some researchers have attempted to compare ethnic trends in laterality, but Geschwind (80) concluded that, "The discussion of ethnic differences in handedness thus rests at present on mere fragments of information" (p.146).

Shanon studied American and Israeli subjects while they were drawing various characters. He noted that dextrals tended to execute lines in a left-to-right direction whereas sinistrals less consistently did so in a right-to-left direction, regardless of nationality. This finding meant that the Israeli dextrals were drawing opposite the direction of normal Hebrew writing. Shanon concluded that right-handers are more resistant to cultural pressure than left-handers (239).

The distribution of hand preference has been found to be different for Israeli, Taiwanese (254), and British populations. Marrion found that Kwatlutl Indians were significantly less dextral than a matched Caucasian control group (164).

A strong familial effect is apparent. It can be shown experimentally that right-handers with a left-hander in the family are less well lateralized for language than those without a familial sinistrality (173). This finding is probably true for nonverbal functions as well (14, 234).

Hand Posture

While writing, both right- and left-handers assume one of two hand postures: a "normal" posture (i.e., hand held below the line of writing, pencil pointed toward the top of the page), or an "inverted" posture (hand held above the line of writing, pencil pointed toward the bottom of the page). The more frequent inverted posture in left-handers is often ascribed to a simple practical avoidance of smeared ink, since English is written left-to-right. However, Shanon has shown that Israeli right-handers do not invert more often than American right-handers (238). Since Hebrew is written from right-to-left, this would suggest that inversion is not entirely a position of convenience, and may have a biological etiology. However, since many Israelis also speak and write English, it is possible that this may be a confounding factor.

Peters and McGrory evaluated the writing performance of right- and left-handers, and found that inverted writers wrote as quickly and accurately as noninverted writers when writing with the preferred hand (206). Right-handers did write more quickly than left-handers overall, however, possibly due to the advantage right-handers enjoy in pulling the pen across the page, rather than pushing it.

Levy and Reid have postulated that inverted writers control the language aspects of writing from the ipsilateral cerebral hemisphere, and that the reverse is true of normally positioned writers. Hemispheric laterality for language was correctly predicted in 45 out of 48 left-handers and in all right-handers (149). Their model predicted relative verbal and spatial abilities in various groups of people: First, among right-handers having the normal hand posture, verbal ability should exceed spatial ability in females, the reverse being the case in males. Among left-handers with the normal hand posture, females should display unusually good spatial abilities, compared to right-handed females, and males should have unusually good verbal abilities, when compared to right-handed males. In people using the inverted hand posture, females who are left-handed should be greatly superior on verbal as compared to spatial ability, whereas those who are right-handed should be greatly superior on spatial as compared to verbal ability. Precisely the reverse should be seen in males. When eye dominance is contralateral to the language hemisphere, the predicted associations ought to be most strongly manifested. When an ipsilateral relationship is seen, overall performance should be reduced, and the predicted effects attenuated (148). These predictions have accumulated both supporting and refuting data. Moscovitch and Smith found support for Levy's model only in the visual aspects of language. Auditory and tactile stimuli failed to produce the predicted patterns of dominance (188). Levy has conceded that her early findings may apply specifically to the visual aspects of language, such as reading or writing (147). In general, it can be said that hand posture has not proved to be as successful a predictor of cerebral laterality or performance as had been hoped.

Sex Differences

It is commonly accepted that females exhibit left-handedness less frequently than do males (42, 195), and that males, in general, tend to show stronger lateralization of function than do females (165). It has been speculated that this difference may result from a tendency among females to conform to sociocultural norms more readily than males, or simply from an excess of pathological left-handedness among males (14).

The basis of the sex difference may be due to the different maturation rates of the sexes (187). Males are more likely to mature later than females; therefore, they manifest more complete lateralization. This is an area of controversy.

Females have been shown to have no significant tachistoscopic hemifield asymmetry, whereas males have shown an RVF advantage (100). More women than men have difficulty at quickly identifying the directions right and left (162). This right-left confusion is associated with symmetry on tachistoscopic testing and supports the hypothesis that the female brain is less lateralized than the male brain.

The left temporal plane of the human brain has been noted to be slightly larger in males than in females. However, the normal patterns of anatomic asymmetry seem to exist for both sexes (262).

There is evidence that males are faster than females when tasks require the formation of a mental "picture," but females are faster when a purely verbal strategy can be used (179). In general, females seem to prefer verbal strategies, which may account for the hemifield differences that are seen.

Apparently, there are differences in handedness and cerebral organization of function between males and females. Experiments and theories purporting to explain these differences are conflicting and inconsistent. Different modes of information processing could account for much of the sex-related lateralization literature, but these differences are difficult to understand and apply to actual performance, at the present time (14). Some authors believe that intergender differences are too inconsistent and ill-defined to allow the formation of conclusions or theories (23).

Laterality and Dominance of Other Human Systems

Eye-- About 70% of right-handers are also right-eyed; but among left-handers, left-eyedness occurs only in about half (39, 178). These observations may have performance implications as discussed later. Strong right-handers who had suffered birth stress have an increased incidence of left eyedness (148).

Foot-- The foot preferred for kicking a ball has been shown to correlate the best with hand preference, compared with other lateral preferences (14, 215).

Ear-- The evidence for asymmetry within the auditory system was reviewed in the sections reviewing dichotic listening tasks, and the lateralization of language. Suffice it to say that right-handers recall significantly more verbal stimuli from the right ear than from the left ear, whereas left-handers as a group show smaller differences between the ears. This pattern has not proved reliable for determining the hemisphere specialized for speech in a patient (112).

Olfactory System-- Smell sensation is represented in the ipsilateral cerebral hemisphere (89). Lateral asymmetry has been found for a category judgment task, in that right-handed females are superior using the right nostril (203). This finding is consistent with other research which has found the right hemisphere superior in making categorical judgments.

CORRELATES OF HUMAN LATERALITY

Performance

It is difficult to distill the morass of laterality research into practical conclusions such as "better" or "worse," however, several authors have attempted to do so.

Geschwind has suggested that the lateralization of cerebral function is evolutionarily superior (80). He reasoned that an organism could successfully survive in a wider variety of situations if its brain was capable of performing more functions. A well-lateralized brain should be capable of a larger complement of talents. This theory has received considerable support.

Manual Tasks-- In right-handed persons, the left hand has been found to be about 10% weaker than the right hand. Similarly, the left leg is about 10% weaker than the right leg (52). In left-handers, the preferred left hand is usually stronger, although Reijs found that 30% of left-handers had a stronger grip in the right hand (220).

There is a correlation between hand preference and manual skill, but this depends on the task under study. The preferred hand does seem to be superior at aiming, while the nonpreferred hand requires many fine adjustments in order to hit the target (4). Simon found no difference in hand steadiness among hand preference groups (8). However, different types of movement, such as peg-fitting and tapping, have produced disparate results (14). The match-sorting task was discussed in the section on handedness. Hand preference does not seem to have a large effect on tracking tasks (244, 270).

Tasks requiring little skill are usually performed by the preferred hand, but as spatial complexity increases, right-handers tend to use the left hand more than the right hand (95). This preference may result from increasing right hemispheric input due to the spatial nature of the difficult task, or from a generalized cerebral activation due to the heightened task difficulty. Grote and Salmon found that those subjects with fastest performance on the most difficult task were those who demonstrated the strongest shift in hand use.

Left-handers seem more proficient than right-handers at some tasks. A 1959 study examining a complex perceptual-motor task found that left-handers scored higher and made fewer errors than right-handers (251). Left-handers have since been shown to be faster than right-handers on some peg-moving tasks, especially when considering the nonpreferred hand (131). This may reflect reduced lateralization of left-handers, or the effect of adjusting to a dextral society. Conversely, left-handedness is more common among children who perform poorly on a match-sorting task, using the nonpreferred hand (20). Left-handers also were significantly faster at visually judging two patterns as same or different (108).

Left-handers usually display smaller differences in performance and strength between the two hands than right-handers (131, 205). This observation would seem to support Annett's theory that left-handers arise from a random process, whereas more right-handers are genetically destined for the "standard" dominance pattern (80).

Increased attention to confounding factors may permit more stable conclusions in the future.

Spatial Performance-- Tests of visuospatial ability seem to measure two distinct spatial abilities: spatial visualization and spatial orientation. An example of the former ability is a cube rotation task, while the latter includes maze, map-reading, and embedded figures tasks. Mental rotation tasks rely heavily on the ability to reorient mental images in relation to left-right cues. Both types of spatial ability have been shown to correlate well with performance on the job, but it is not known why this is so (53).

Left-handers have indeed been found to perform poorly on some spatial tests, but this has by no means been a universal finding (249); left-handers of both sexes and those with learning disabilities often exhibit superior right hemisphere functions (84).

Thomas and Campos found the spatial performance of subjects who were said to be strongly left- or strongly right-handed was superior to those whose hand preference was less extreme (255). This finding would support the contention that it is the degree, rather than the direction, of handedness that is important.

Levy proposed that left-handers, who as a group are less well lateralized for language, would perform worse at a spatial task than dextrals. This hypothesis was based on the principle of task interference. As previously discussed, this "competition hypothesis" advocated by Levy and Reid (149), holds that verbal and spatial coding processes are basically unable to coexist in the same hemisphere, and that spatial skills suffer when such a conflict exists. Some studies have failed to confirm this concept (53), while Levy (145) and others (183) have provided strong support.

Left-handed divers have been shown to adapt less well to the underwater distortion of object size and position, although this spatial task improves markedly with practice (158).

Using dual-task methodology, Nagae found that left-handers were inferior to right-handers in recall of target positions (190). He concluded that, because left-handers are less lateralized for speech than right-handers, the right hemispheric component of language was interfering with spatial processing, causing a performance decrement in left-handers. Left-handed males may be the least hemispherically specialized, right-handed males the most specialized, with right- and left-handed females possessing an intermediate degree of lateralization.

Consistent with the view that left-handers and females are less lateralized than right-handers is the observation that right-left confusion is reported more frequently among female left-handers (103). This trait is more closely associated with sex than with hand preference (162). Wolf reported that 17.5% of women and 8.5% of men show a high degree of right-left confusability (273). An impaired appreciation of one's relation to the environment certainly could be detrimental in the flying environment.

There is evidence that familial non-right-handers may be more proficient than familial right-handers in using strategies of transformation of mental images in relation to left-right cues (40).

The effect of "androgyny" has been examined recently (171). In males, lesser masculinity, as measured by secondary sex characteristics and 17-ketosteroid excretion, was associated with higher spatial ability. Those females, conversely, with greater masculinity possessed greater spatial ability. This physiological index deserves further study.

Duhamel et al. recently assessed the auditory component of spatial performance by asking blindfolded subjects to manually localize auditory stimuli (59). This methodology is free from practice effects, since the subject receives no feedback on his performance accuracy. They found that (a) left-handers made significantly more errors than right-handers, (b) the right hand made more errors than the left hand, and (c) the right hemispace was associated with more errors than the left, especially when using the nondominant hand. These observations may have application in the design of cockpit threat or collision warning systems.

Verbal Performance-- Annett reported that subjects with mixed hand preference did worse on vocabulary tests than both consistent left- or right-handers. The well-lateralized dextrals and sinistrals did not differ (6). Conversely, McKeever (171) found support for Levy s contention that left-handers possess superior language ability (145).

Effect of Eye Dominance-- It has been reported that 20-30% of right-handers are left-eye sighting-dominant (178). The effect of this "crossed dextrality" on novice marksmanship performance was recently examined. Sheeran found that right-eye dominant dextrals had significantly higher scores than left-eye dominant dextrals (240). All subjects sighted with the right eye.

In 1952, Gilinsky and Brown investigated the effect of sighting dominance on a compensatory tracking task (82). They found that, while there was no effect seen in initial proficiency, practice on the task seemed to more greatly benefit the dominant eye. However, a beneficial effect of practice was seen for both eyes.

Monocular dominant and nondominant viewing during a tracking task was compared to binocular viewing by Madan (159). He found that binocular tracking was superior to monocular tracking, and that performance with the dominant eye was significantly better than that attained with the nondominant eye.

Effect of Family History-- As mentioned previously, a positive family history of left-handedness may exert an effect. It has also been reported that familial sinistrals do worse on the Wechsler Adult Intelligence Scale (WAIS) performance subscale (28), and the full-scale WAIS score (29).

It should be mentioned, in closing, that there is a weight of dissenting evidence that finds no difference between sinistrals and dextrals in these aspects of performance or intelligence. However, much of the research just cited that has provided evidence of handedness associations with proficiency was well-designed and valid. The exact nature of these differences remains elusive.

Occupation

The term "hemisphericity" refers to the tendency of people to rely on one hemisphere more than the other. This trait is closely related to the concept of "cerebral dominance," which usually expresses the preeminence of the left hemisphere, not only for language, but also for generally filling the "controller" role (165). Several researchers have examined various associations between occupational groups and hemispheric dominance, the underlying principle being that left-handers tend to rely on their right hemisphere more than the left.

Developmentally, if left hemisphere functions fail to "predominate," there may be a tendency to choose those occupations which benefit in some way from a visual mode of thought. The findings suggest that this tendency is sometimes associated with a hand preference that is other than fully dextral.

Several studies have shown an elevated rate of non-right-handedness in certain occupations, several of which require an increased use of spatial talents. Among these are professional athletes (174), artists (208), and architects and engineers (209). Left-handed architectural students entering college in 1970 were more likely to graduate, compared with right-handers (210). Engineering students have been shown to be significantly more dextral in hand preference than psychology students (123). Mathematically gifted children have a much elevated rate of left-handedness (139).

There is evidence that eye dominance may also act as a marker for occupational aptitude and choice. Among right-handed college students, those who were studying architecture or design were significantly more likely than law students to be left-eye dominant or ambiocular (66). Mixed dominance seems to be more common among students majoring in fields requiring visuospatial skill than those studying subjects requiring skill in reading and language.

Rossi and Zani found that athletes showed more hemispheric specialization than did nonathletes (224). Specifically, athletes were shown to be more accurate than nonathletes in perceiving rod orientation, especially with the left hand. This finding may be interpreted as evidence that athletes develop enhanced spatial abilities, which reside in the right hemisphere, or as evidence suggesting that athletes possess genetically based ability to process spatial information.

Other researchers have not been able to assign different spatial processing strategies to specific occupations (53). In general, there is little evidence to support the contention that an excess of sinistral tendencies among members of certain occupational groups necessarily means that such individuals are more likely to utilize right hemisphere processes than are members of other more left hemisphere "dominated" occupations. Beaton points out that both the trend towards sinistrality and the tendency to utilize right hemisphere skills might be a result of very early insult to the left half of the brain (14).

Management Skills and Laterality-- As the concepts of cerebral specialization have become more widely known, some professional and educational groups have attempted to utilize the differential abilities of the two hemispheres to improve learning and performance.

Gordon et al. recently critiqued the applied management psychology literature, and also reported three studies of occupational correlates that they conducted (87). The business and educational literature has seen a recent increase in articles describing various ways to improve performance and/or efficiency, by tapping one or the other cerebral hemisphere. Many workshops and seminars have sprung up, purporting to enhance specialized brain skills. Generally, business executives are urged to develop right brain skills (1), and educators are exhorted to format their teaching so as to appeal to students' right hemisphere (63). The right hemisphere is popularly regarded as the silent, untapped side, within which reside such processes as intuition, and holistic problem-solving. It should be noted, however, that most of the supporting research has not been conducted by neuropsychologists.

Gordon et al. note that the questionnaires and inventories that have been used in this research have not been neuropsychologically validated, and probably do not measure hemispheric function. Those people who are labelled "right-brained" or "left-brained" do not necessarily perform better on validated neuropsychological tests that do measure relative hemispheric function (87). In fact, these popular questionnaires often seem to be personality inventories rather than indicators of lateralized cognitive neuroprocessing. Although there is some evidence associating personality with cognitive strategies (43), the research that has been conducted using these suspect measures of laterality is of questionable validity. Personality characteristics may indeed be predictive of success in various occupations; however, conclusions regarding differential hemispheric function would be unwarranted.

Gordon et al. conducted three studies examining various occupations and their patterns of cognitive processing, using a previously validated collection of neuropsychological tests called the Cognitive Laterality Battery (CLB) (85). They did find some support for the contention that lateralized hemispheric function is correlated with workplace performance. However, some interesting patterns were found.

In the first study, bank employees in supervisory positions or with complex clerical duties performed better on tests of visucspatial skills. The second study showed that, in managers of a health care facility, job ratings correlated with visuospatial performance and job complexity. In the third study, managers in a major airline with higher verbosequential skills who were controlling greater numbers of people and services, received higher performance ratings from their supervisors. The investigators concluded that more "complex" jobs correlated better with visuospatial ability, whereas in jobs differing in magnitude, sucn as number of employees or service units, verbosequential ability seemed to correlate more with performance. Managers may indeed rely more on one mode of information processing than another, but it is clear that the optimum strategy may not be obvious to the casual observer.

Training managers in a standard "right-brain" approach is therefore inappropriate at the current level of knowledge. Gordon et al. also point out that there is no evidence that training programs enhance laterality, nor that any improved lateralization would enhance job performance. The cross-sectional study design does not support conclusions regarding cause-and-effect.

Educators have also begun to use "right-hemispheric" methods in teaching. There has been research supporting the concept that presenting information to students via music, cartoons, or methods that use mental imagery, enhances the learning process. As in the business psychology literature, the supportive research is often less than convincing.

In 1986, Evans and Payne reported an experiment in which they presented learning material to 31 subjects in a "right-brain" format (music and cartoons), a "left-brain" format (lecture-based), and a module which combined both approaches (63). They found that the combined and right hemisphere approaches were superior when they tested short-term recall, but long-term memory was superior after the bimodal approach only.

Caskey and Meier recently examined the effects of mental imagery on retention of learning material (41). They found that those subjects presented material through mental imagery had significantly better recall, and more positive attitudes toward the learning experience, than did controls, who learned the same material through a conventional lecture-based format.

These studies both suffer from the same problems of misclassification, in that the "right-hemisphere" modes of teaching may not actually be preferentially engaging the right hemisphere. For instance, either hemisphere may process music, depending on the experience of the listener (121, 128); and the process of mental imagery is not consistently lateralized in the reported literature (176). The experimental subjects may also be affected by the novelty of the "right-brain" stimuli, causing better learning and improved recall. These alternative strategies may well be better teaching methods, but it might not be due to asymmetrical hemispheric processing.

It is interesting to note the fervor with which the concepts of cerebral laterality are applied. In a highly speculative and unsubstantiated 1986 essay, E. Smith analyzed the educational plight of the modern black child (246). He contended that the public school system in the United States continues to foster an exclusively left-brain educational strategy, which does not address the needs and aptitudes of inner-city black children. This position is not unique, but Smith has prepared a unique hemispheric rationale. He opined that the African tribal heritage of blacks was rich, imaginative, oral, and agrarian, but lacking a written language. He states, "...the black experience in Africa, as well as in America, until recently has been a predominantly right brain experience." He believes that blacks have had a difficult time transitioning from the South, where "rural right hemisphere labor" is the norm, to "urban left hemisphere labor" in the North. He concludes that the black student would be better taught using educational methods that utilized their right hemispheric talents.

Emotions and Personality

There is some evidence that the two halves of the brain differ in their contribution to human emotions, and other evidence suggests interactions between handedness and personality.

Silberman and Weingartner recently reviewed the evidence suggesting that emotions are asymmetrically represented in the cerebral hemispheres (241). They found three hypotheses suggested in the literature: (1) emotions are better recognized and appreciated by the right hemisphere; (2) processing and control of emotional expression and behavior take place in the right hemisphere; and (3) the right hemisphere is specialized for dealing with negative emotions, while the left is involved with positive emotions. The evidence for these theories was mostly unreplicated and fragile; however, the authors concluded that the most likely model was based on interactive inhibition between a right negatively biased and left positively biased hemisphere.

It has long been noted that damage to the two hemispheres results in different patterns of emotional impairment. Right hemispheric damage often resulted in a pattern of "indifference," and the Wada test on the right was likely to result in euphoria. Left hemispheric damage, conversely, caused a "catastrophic" depressive response, as did the left-sided Wada test (225). Apparently, the more frontal region of each hemisphere is responsible for the strongest emotional response (184).

However, electrophysiological research has produced conflicting results regarding the hemispheric lateralization of emotion (45). Both negative and positive affective stimuli produce bilateral frontal activation of the EEG and symmetrical skin conductance response magnitudes (180).

There has been sporadic research aimed at determining the "seat of consciousness," which for years was assumed to be the left hemisphere. This research has been difficult to do in the intact brain, due to transcallosal communication. However, in an interesting tachistoscopic experiment with split-brain patients, Sperry et al. determined that the right hemisphere had its own consciousness, much like the left hemisphere. Although the corpus callosum was absent, evoking an emotional response in the right hemisphere resulted in transfer of the basic awareness of the emotion to the left hemisphere, but not any knowledge of the inciting stimulus (e.g., words, pictures, etc.) (248).

The right hemisphere has been linked with a variety of "unconscious" mental processes. Among these are hypnosis (172), hysterical symptoms (67), and phantom limb pain (14). In the intact brain, the right hemisphere seems to control attentional functions (165).

Some clinical psychologists and counselors have attempted to integrate these concepts of cerebral laterality into practical therapeutic strategies. Richardson et al. related the left-hemisphere/right-hemisphere dichotomy to the Eastern philosophy of yin/yang, and male/female strategies of thought (222). They suggested that clinical tools such as hypnosis, imagery, and psychodrama, which are predominantly mediated through the right hemisphere, represent "feminist" approaches to counselling. This conceptualization of left brain/right brain activities as male/female is interesting, but Richardson et al. seem to imply that males rely largely on left hemisphere strategies, and females prefer right hemispheric methods. In fact, some research indicates that males tend to prefer tasks requiring mental imagery, and females excel on tasks requiring purely verbal strategies. These psychological therapies have certainly proved their utility, but their characterization as masculine, or feminist, does not appear to be based on good neuropsychological data.

Some investigators have found that left-handers are significantly higher in socialization than right-handers (221). Personality inventories have shown that subjects who show strong manual lateralization, either dextral or sinistral, feel that they are more "externally controlled" than those with mixed hand preference, who tend to be more "internally controlled." Externally controlled individuals see themselves as being more controlled by their environment, whereas internally controlled subjects believe that they are responsible for their own fate

(113). However, Annett found no differences in Minnesota Multiphasic Personality Inventory (MMPI) and Edwards Personality Inventory (EPI) scores among handedness groups (8).

Geschwind and Galaburda speculated that left-handedness might be related to homosexuality (80). Recently, studies have been published which variously support (155) and contradict this theory (223).

Field Dependence/Independence-- Researchers have discovered that laterality, both cerebral and peripheral, interacts with the ability to characterize a stimulus in central vision, when the surrounding periphery is varied. In one of these tests, the Rod and Frame test, some subjects are more affected by the position of a central rod (termed "field independent" individuals) while the responses of others are more related to the position of the frame surrounding the rod ("field dependent" subjects) (14). In terms of "dominant" hemispheres, field dependent individuals have been characterized as left hemisphere dominant, and those displaying field independence as right hemisphere dominant (70).

Available data also suggest that field independent subjects tend to have strong lateral preferences for hand, ear, and eye movements. They also show clear visual field asymmetry in response to tachistoscopic tasks, intimating that field-independent persons have more differentiated cerebral lateralization than field-dependent subjects, who show the opposite tendencies (14).

Carretta recently reported that the Embedded Figures test did not significantly predict performance in U.S. Air Force Undergraduate Flight Training (37). However, the author pointed out that this test may not be a good measure of field dependence/independence; further, it is possible that this population is already screened for field dependence/independence, since a Hidden Figures test is included in the current selection test battery.

Human Disease and Laterality

A higher than expected incidence of left-handedness has been reported for a wide variety of different clinical populations, including stutterers, autistics, epileptics, and the mentally retarded (14). Many disorders seem to affect one side preferentially. These manifest abnormalities probably contributed to the historical idea that left handedness per se is abnormal. Some of these associations will be presented.

Cleft lip has been noted to occur on the left side in two-thirds of cases, and significantly more patients with cleft lip are left-handed than controls (257).

Undescended testes are located more frequently on the right side. Breast cancers, cysts, hypertrophy, and difficulties in lactation are located on the right side in most cases (116).

There is a left-sided predisposition for meningiomas of the lateral ventricle and papillomas of the choroid plexus (80) Tic douleureux is more often caused by pressure on the right trigeminal nerve by an anomalous cerebellar artery, therefore causing symptoms on the right side more often (119).

A variety of associations with psychiatric impairment have been made (220). Some investigators feel that schizophrenia is associated with disturbance of left hemisphere functions, and the affective psychoses with impaired right hemisphere function (65). Dextrals have been reported to be less neurotic than either left or mixed handers (169).

Alcoholism has been linked to cerebral laterality. London found that in men admitted to an inpatient alcohol rehabilitation facility, a history of paternal alcoholism was significantly associated with left-handedness in the patient or a first-degree relative of the patient (156).

Personality research has produced conflicting results in the area of anxiety and handedness; Beaton believes that methodological bias may account for positive results obtained in the past (14). Recently, the association of dyslexia with laterality has also been challenged (230).

Geschwind has speculated that left-handedness, disease, and immune disorders are strongly linked (69, 79). In his series, Geschwind found that 27 of 253 strong sinistrals reported a personal history of immune disorder, whereas only 10 of 253 strong dextrals gave such a history ($p<.01$). He suggested that the same factors influencing laterality also affect immune development. Aberrations such as anomalous dominance should therefore be associated with a variety of immune-related disorders. His data also showed an increased rate of left-handedness among those with atopic disorders such as asthma, eczema, and hay fever (80). This association has received support from some (233, 247, 268) but not all investigators (21).

Further, left-handedness was associated with the presenile form of Alzheimer's disease (235). Geschwind suggested that anomalous dominance, based on a common immunological link, predisposes individuals to the presenile form, in which aphasia is more common than in the late-onset disease (80).

These myriad associations are by no means universally accepted. Recently, Satz and Fletcher found no association of dyslexia with handedness, cognitive function, birth history, or parental achievement (230).

Research Applications

Research into cerebral laterality has provided concrete benefits, in addition to general advancement of knowledge and the call for further research. For example, the functional assessment of a patient recuperating from a cerebrovascular accident (CVA) is aided by knowledge of the specialized function of the injured area of brain. A rehabilitation program could take advantage of the functions of the remaining intact neural tissue (2, 14).

Evolution would seem to have favored asymmetry, and although the literature is conflicting, there is evidence that the degree and nature of functional cerebral specialization may be related to certain performance measures. The remainder of this paper will attempt to apply this psychological research to the field of aviation.

AIRCREW SELECTION AND PERIPHERAL LATERALITY

Since the early days of flying, aviators have enjoyed a certain amount of prestige associated with their ability to "slip the surly bonds of earth, and dance the skies..." (160). Flight surgeons owe their professional existence to the historical acknowledgment that successfully negotiating the flying environment demands a man (or woman) possessing particular qualifications, both physical and mental. This requirement became apparent early in aviation history: In the early part of World War I, Great Britain found that of every 100 of her flyers killed in action, only two died at the hands of the enemy, while 90 perished because of some individual deficiency (54). This unfortunate statistic was largely due to the British policy at that time of transferring "washouts" from other branches of the service to the Air Force (47).

As a result of similar experience in the United States, Major Theodore Lyster, an ophthalmologist, was directed in 1914 to develop meaningful physical standards for pilots. He implemented the first realistic selection standards for aviators, recognizing that many minor physical and psychological defects, which pass unnoticed in conventional occupations, were best excluded from the cockpit. Lyster's initial selection standards were based on consensus opinions of the small community of early flight surgeons, and obviously were not based on much experimental data. Nonetheless, the physical fitness-for-flight of the aviator population was dramatically improved.

Over the ensuing years, selection standards were continually refined and validated, based on principles of safety, physiology, and occasionally, supply and demand. Despite this evolution, most aircraft accidents continued to be caused by some judgment or performance shortcoming on the part of the pilot. Much energy was therefore devoted in the 1930s and 1940s to the development of preselection screening tests which could identify those candidates who possessed the necessary psychomotor aptitude to become a successful aviator.

A number of large studies were conducted (211), which were unfortunately plagued by methodological difficulties. A cross-sectional approach was often employed, with many variables simultaneously examined for possible predictive value in selecting pilot cadets. Statistically, in a study such as this, a certain percentage of variables will appear as significant predictors solely on the basis of chance. As a result, these studies initially produced some unlikely predictors of flight aptitude, such as reaction time, effect of startle, and, strangely, the presence of dermatographia (11). Subsequent verification of these "predictive" variables was frequently unsuccessful.

It should be no surprise that such an obvious variation as left-handedness has been suggested as a marker for aspects of flying aptitude. A few authors over the past 75 years have speculated about the effect of left-handedness on flying aptitude and/or flight safety. However, these scattered reports are mostly anecdotal, cross-sectional, and often obscure. Curiously, handedness does not appear in any of the aforementioned large analyses of pilot attributes conducted in the 1940s and 1950s. There has never been a study of handedness as a possible predictor of success in flight school, although such a study would be relatively easy to conduct. Apparently, hand preference was regarded as an easily manipulated demographic characteristic which had no effect on performance. More recently, there has been a modest increase in interest in hand preference; later in this section, all available references to handedness in the aviation literature will be reviewed.

Early cognitive psychologists directed their attention toward describing the skills that good pilots must possess. It was intuitively obvious that pilots worked in the three-dimensional environment more than most ground-based personnel. Accordingly, a variety of visuospatial/manual coordination tests were developed. In the immediate post-World War II era, several of these psychomotor tests were convincingly shown to significantly add to the accuracy of the pilot selection methods of the day (11). However, these tests were abandoned in 1955 because the testing had been decentralized (to reduce transportation costs) rendering the old electromechanical devices more difficult to calibrate and maintain. Since that time, selection in both the U.S. Army (USA) and U.S. Air Force (USAF) has been based on paper and pencil tests of flight experience and knowledge, general verbal and spatial performance, a review of the past service record, and a personal interview (219).

Two factors have contributed to a resurgence in interest in these psychomotor performance tests. First, the development of computers will now permit the reliable placement of testing modules in geographically dispersed locations, without fear for maintenance or calibration. Second, the emerging awareness of the functional specialization of the brain has provoked speculation as to the potential utility of hemispheric dominance patterns as predictors of performance or aptitude in aviation, as well as other occupational fields.

Are there patterns of functional cerebral asymmetry (or handedness), which can be identified, that are associated with better (or worse) aviator performance? This discussion will review the rationale for hypothesizing an ideal aviator brain, the relevant historical literature, and the most current experimental evidence.

Basis for the Hypothesis

From the previous review of the cerebral laterality literature, it should be obvious that the human thought process cannot be reduced to a simple series of consecutive steps, which predictably result in decisions and purposeful actions. Even in the split-brain patient, the hemisphere performing a task cannot be predicted with certainty (165). It is therefore extremely difficult to understand information processing in the intact brain, especially when considering such a complex action as flying. Nonetheless, the general theory of functional lateralization does appear to hold up under experimental scrutiny. As reviewed earlier, the left hemisphere tends to become involved in verbosequential processing, whereas the right hemisphere is usually involved in visuospatial processing.

The body of literature purporting to associate "hemisphericity" with occupation has been subject to much criticism, especially when handedness has been used as a marker for hemispheric predominance. It does appear, however, that some individuals consistently perform better when executing tasks that are attributed to one hemisphere, although most people do not display this lateral preference. It may be possible, therefore, that some occupations require such a degree of specialized processing that an individual possessing a corresponding "cognitive profile" would excel in that profession (88).

It can be stated with confidence that no profession requires an awareness of self-position in three dimensions more than that of an aircraft pilot. For this reason, researchers have long sought to isolate the skills required of pilots, although it was not until recently that this was done with functional cerebral laterality in mind.

The complex task of flying requires the smooth, continuous integration of many skills. Among these are: three-dimensional positional awareness, sustained vigilance, continuous and smooth limb coordination with closed-loop feedback monitoring, and integration of systems operations via the cockpit instrumentation. Naturally, there are many hundreds of tasks that are carried out during flying operations, and apparently many of these do involve the right hemisphere for processing. In the intact brain, it is likely that most tasks could be executed by either hemisphere, and lateralization depends on the concurrent task load, which is also probably distributed according to a lateralization pattern.

Although "seat of the pants" flying may be a fairly consistent set of cognitive skills, the requirements of each aircraft type vary; helicopter pilots have different concerns from transport pilots, who in turn have different concerns from fighter pilots. Different display systems and cockpit instrumentation demand different processing strategies, and different missions place varying levels of stress on the operator. Marsh summed up the right hemisphere's general role in flying as "manipulator of the environment," whereas the left hemisphere is crucial in processing the large amounts of information presented by modern sophisticated aircraft (165).

Early flight surgeons did not have the benefit of modern cognitive processing theories, and the only marker of cerebral laterality available was hand preference. Since current theory holds that optimum performance is attained by maximum functional hemispheric separation, left-handers, who as a group are less lateralized than right-handers (76, 112), may indeed function less well in the cockpit environment. However, left-handers are a much more heterogeneous group, and some show good hemispheric lateralization. These sinistrals would be expected to perform well on tests of lateralized cortical function, and to do well in flight training (165). The small body of aviation medicine literature examining handedness will be reviewed in the next section; research examining cerebral laterality and pilot performance will be presented later in the paper.

The Left-handed Pilot

Early History-- Hand preference and cerebral laterality issues have been virtually ignored throughout the history of aviation. Perhaps the fact that those pioneers of powered flight in America, the Wright brothers, were both right-handed was an omen (256). In any event, there has been a striking lack of aeromedical speculation regarding left-handedness. This absence is all the more surprising given the long quest for successful predictors of student pilot aptitude (202). The exhaustive testing of selection criteria for flight school admission included such esoteric factors as eye color, head circumference, startle reflexes, and types of dreams (26), but it was not until relatively recently that data on handedness were even collected. In 1920, handedness was not recorded on the U.S. Army Air Forces standard flight physical form (264). Handedness was also missing from the 1930 flight physical data sheet of the British (9) and the French (10) Air Forces.

To find reference to left-handedness, one must carefully peruse the early aviation medicine literature. In 1930, Bauer cited a study, by Longacre, of the reasons given by instructors why men fail to learn to fly (13). In his list of dozens of reasons for failure is buried the comment, "...had difficulty because left-handed..." Unfortunately, no further comment was made as to the nature of the student's difficulty.

A 1941 training manual published by the U.S. Army Medical Department, entitled "Notes on Psychology and Personality Studies in Aviation Medicine," contained a long list of qualities to look for in prospective aviators (265). In the section entitled "Morphology" are the only questions in the manual dealing with handedness or related issues: "Was cerebral dominance established early? Were definite efforts made to lateralize to right- or left-handedness and with what results? Stammering?" The 1943 edition of the U.S. Army Air Forces Flight Surgeon's Handbook asked the aviation candidate, "Did you ever stammer or stutter? Are you left-handed?" Unfortunately, these manuals contained no elaboration of the issues raised by many of the proposed questions. It is unclear, for example, how a unit-level flight surgeon would ascertain the cerebral dominance history of a prospective flyer.

In addition to concern about the safety of vocal communication, these questions were probably based on the popular observation that forcing left-handers to become right-handed resulted in a likelihood of stuttering and psychomotor ineptitude. This concept was embodied in a theory of mirror writing and reading by Samuel Orton, who called mirror reading "strephosymbolia," or "twisted symbols" (101). His theories were discussed previously. It was thought that one with strephosymbolia might have a lowered degree of manual or mental dexterity. An individual with severe difficulty would not be expected to pass through flight training successfully, but a pilot with mild difficulties might learn to compensate for his weakness. However, when tired or overloaded, he could become more liable to error, as his ability to compensate would be impaired (77). Although Orton's theories were popular, and seem to have had application to aviation safety, a discussion of these phenomena is not to be found in the aviation medicine references of the day (11, 17).

The only written evidence of the aeromedical thinking on this subject was found in the proceedings of a 1941 Postgraduate Course in Aviation Medicine (93). Dr. Ralph Greene, a past president of the Aerospace Medical Association, commented on his approach to anomalous dominance patterns:

> We take the sighting eye of every pilot examined. If he has a left dominant eye and is right-handed, we try to carry out special studies on him. If he is one who confesses to having been left-handed and having been changed over by his parents, we ask him questions about his progress in mathematics and foreign languages and get a very quick confirmation of the diagnosis of strephosymbolia. On the other hand, if he has a left dominant eye and is a right-handed individual, we ask

him: "Would you be good enough to walk over to the other side of the room, turn around and come back to me? We want to observe your method of walking." He will walk and will almost invariably turn to the left as he reverses direction. The person who has a dominant right eye and is right-handed will usually turn to the right.

It is interesting to note that Greene is referring to the concept of "truncal asymmetry" which would be described by Geschwind, 40 years later (104). Greene goes on:

> Awkwardness attributable to strephosymbolia is more widespread than many of us as physicians realize. Surely if one with strephosymbolia is placed at a serious disadvantage, it must reflect itself in a lowered degree of manual or mental dexterity by virtue of one having been made a right-handed person when he was born as a left-handed person. We know that the change-over inclines one to awkwardness. He may confess that he had great difficulty, by comparison, in making a right-hand turn or a left-hand turn in an open cockpit airplane while learning to fly.

Dr. Greene's position was that he would accept any left-handed applicant for training, but would reject a candidate who displayed evidence of strephosymbolia. If a fully trained pilot was discovered to have this condition, he would probably be retained, based on his prior performance. This is the only reference in the literature to disqualifying persons because of any correlate of left-handedness.

World War II to the Present-- The concept of strephosymbolia, as described by Orton, was abandoned as modern theories of cerebral specialization developed. Formal selection criteria never contained any reference to anomalous dominance, "twisted images," or left-handedness, although several authors wondered about an association between sinistrality and flying aptitude.

In 1959, Gerhardt, of the Institute of Military Psychology in Norway, noted an apparent excess of left-handedness among maladjusted pilots referred for psychological evaluation (77). He wondered why this excess should appear at that point in aviation history, and reasoned that the increased speed and performance of modern aircraft might have finally over-extended the left-handed pilot's cognitive reserves. Gerhardt recognized that there were left-handed pilots who did not experience any trouble when flying, and certainly there were right-handed pilots who had enormous difficulty learning to fly. He noted, however, that left-handedness was often accompanied by a generally reduced lateralization, resulting in a tendency toward letter and number reversals and right-left confusion. This might lead to difficulty interpreting and responding to directional information. He reported several cases of impaired pilots in which left-handedness and reduced laterality appeared to have been a contributing factor. As the reference is relatively obscure, four of the six cases are quoted below for illustrative purposes.

Case 1

A fighter pilot, second lieutenant, 24 years old, consulted the physician because he did not sleep and did not like his kind of service. He began to drink more liquor than usual and was frightened to observe that this made him feel relaxed. On interviewing him we found him very depressed. He said he always had been very careful while flying and did not like close formation flying. He began to be afraid, especially during gunnery missions, where he was most concerned with the flying and could not concentrate on the firing. Since he was often blamed by the other pilots, he felt more and more careful and this resulted in more criticisms and more isolation, which was in turn transferred to the family situation. We found this pilot to be ambivalent as regards hand preference. He had been left-handed as a child but had practiced many operations with the right hand as he grew older, writing for instance. In the plane the pilot had to look for his wedding ring in order to identify left and right when he got instructions over the radio to bank the aircraft. This delay of reactions seemed to explain why he did not like close formation and why he always had to be careful. He had a tendency to stutter and to mix letters in his writing, symptoms which often follow handedness problems.

This pilot was grounded for 2 months. During this period he recovered from his psychosomatic symptoms and felt happy. He was then transferred to a communication wing where he has adjusted himself successfully during these past 6 months.

Case 4

One fighter pilot, a second lieutenant, 22 years old, was grounded because of "dangerous tendencies" in the air. He was characterized as "peculiar" by most of his colleagues.

After one year of "rest" a flying board has recommended his transference to communication flying duty, and the pilot himself does not want to return to a fighter squadron. The pilot is left-handed, writing with his right hand but drawing with the left. He has obviously learned to use the right hand in a great many situations.

Case 5

A lieutenant, 25 years old, flying as a second pilot in a Dakota, was grounded because of a flying deficiency. One year before he had been transferred from a fighter to a transport squadron upon his own request.

About one month after being grounded he had a severe automobile crash. This happened in a Jeep on the taxi-ing strip and no other car was involved.

At present this pilot is planning his future in civil air transport. This pilot was dominantly left-handed as a child, but now he prefers the right hand in most situations.

Case 6

A 23 year old fighter pilot made a crash landing about 2000 ft from the runway because of "flame out." It was found that he had run out of fuel although he had been flying near the air base for a long time. At one time he had reported a fuel level of 900 lb and a few minutes afterwards he reported 1370 lb without perceiving the inconsistency.

It seems highly probable that the pilot read the usual "fuel level indicator" the first time and that he concentrated on the "fuel flow instrument" the second time. The last instrument does not as a rule give readings corresponding to the fuel level indicated by the first mentioned instrument. The pilot had observed the "fuel pressure warning light" and he checked the fuel level again but probably on the wrong instrument, and he did not react as in emergency because he thought that the red signal had appeared because of electrical "snags."

This pilot had been fairly well adjusted before this accident and was on the point of being selected as a "deputy flight commander." The pilot is left-handed, writing with his right hand.

All six cases cited by Gerhardt involved left-handers who probably would have met Greene's criteria for strephosymbolia, as they were left-handers who wrote with the right hand. Of course, his report has no statistical value, but it is a valuable record. Gerhardt also began to apply the concept of differential lateralization of various cognitive modes, naming four "functional fields": handedness, vision, form and space, and ideation.

In a subsequent report, Coucheron-Jarl, Gerhardt, and Riis provided data that indicated that a population of "problem case" pilots referred to their psychology unit for evaluation contained a significantly higher proportion of left-handers (49).

J. L. Gedye, of the Royal Air Force (RAF) Institute of Aviation Medicine, reported a study in 1964 that related pilot proficiency to degree of laterality, as measured by handedness (76). He measured the consistency and degree of lateral preference, using a paper and pencil inventory, in three groups of aviation personnel: 143 student aircrew, 95 fighter pilots, and 59 test pilots. The relative proportions of (a) consistent/inconsistent use of right or left hands for a series of tasks (a measure of preferred hand), and (b) the median difficulty of using the nonpreferred hand (a measure of the strength of lateral preference), were then compared across the three populations of differing flying skill.

He found that the proportion of "left" inconsistent subjects fell as the level of flying skill increased, which was interpreted as evidence that "left" inconsistent patterns were unfavorable. Seven fighter pilots, who were members of a demonstration aerobatic team, had significantly more consistent right laterality scores than the sample fighter pilot population, suggesting that consistency was associated with proficiency, even in right-handers. The combination of inconsistency and low non-preferred hand difficulty score emerged as unfavorable characteristics. The most skilled group, the test pilots, had significantly stronger lateral preferences than the student aircrew group. The author noted, however, that all three groups had several members with weak lateral preferences.

This study was of a cross-sectional design, and therefore does not allow inferences regarding cause and effect; that is, the differences in laterality patterns may or may not be reflected in pilot proficiency. There also is the possibility that flying training may somehow affect performance on the test used to evaluate laterality. The age distribution of each of the three groups also differed, and the data were not age adjusted. In the earlier discussion of handedness, it was pointed out that hand preference proportions have been changing over the past few decades (18); a cohort effect may have confounded this aspect of the data. Nonetheless, Gedye did present evidence suggestive of a gradient of laterality among levels of pilot skill/training. Since hand preference for writing was not reported, it is not possible to determine the likelihood of any of these subjects having been labelled as strephosymbolia cases by Greene. However, the theme of reduced laterality being a negative pilot attribute appears to be supported.

This exhausts the Western aviation medicine literature with respect to hand preference. The issue of cognitive performance as a predictor of flying performance will be considered in the final section of this paper. Before leaving this literature review of peripheral laterality and aviation, we should take note of four reports from the Union of Soviet Socialist Republics (USSR).

In 1975, Yegorov and Shirogorov reported a study of pre- and postflight laterality measures in an unspecified number of pilot subjects (274). They measured asymmetry of brachial artery blood pressure, skin temperature, skin resistance, electromyogram (EMG) of the bicipital muscle of the shoulder, proprioceptive thresholds, and the relative motor activity of the two index fingers. These measures were combined to generate an asymmetry index.

Yegorov and Shirogorov found that those subjects with preflight right- or left-sided asymmetry showed a postflight decrease in asymmetry. They cited other Soviet research which associated a decrease in asymmetry of a variety of physiological functions with concurrent vestibular stimulation, and an increase in asymmetry during intellectual activity (226). The authors point out that the motor asymmetry of the arms was reduced only in those with a preflight left arm predominance, since they were compelled to use their right arms to fly the aircraft, whereas the right-arm dominant pilots showed no change in motor asymmetry. Overall, while general asymmetry was reduced postflight, the direction of the asymmetry was maintained. The authors concluded that the inflight activity of a pilot leads to changes in asymmetry of physiological function, determined to a great extent by the number of flights per flying day, and suggested that changes in physiological asymmetry could serve as an indicator of workload. Unfortunately, details about flight hours, number of flights, and type of aircraft mission were not provided.

In a follow-up study, Yegorov and Shirogorov reported in 1976 on the effect of inflight activity on asymmetry of motor activity and reaction time (275). In this investigation, 37 fighter pilots and 50 ground crewmembers were tested for asymmetry and reaction time before flying. Motor asymmetry was measured by instructing the subject to press two buttons simultaneously, and recording which button was depressed first. The authors found that right-handers (classified by reaction time) showed a decrease in motor asymmetry after three flights; the results of the left-handers were inconclusive due to their small number.

Clearly, these two reports, while concerned with the general issue of functional asymmetry, are not looking at pilot performance or flight safety. However, it is interesting to note this application of laterality research. Unfortunately, this research is incompletely described, which may be an artifact of translation, and appears to be confounded to some extent by the cockpit requiring the preferential use of the right hand and arm. Several of the parameters measured are mediated to a large degree by the autonomic nervous system; it would be interesting to attempt to correlate these measures with pilot proficiency.

In 1980, Gyurdzhian and Fedoruk published a paper which examined possible correlations between pilot performance and functional hemispheric asymmetry (97). They studied three groups of rated aviators and student pilots, classified on the basis of physical health and flight performance. Flight performance was evaluated by examining flight records, and pilot's subjective report of flight difficulties or episodes of spatial illusions. The first group consisted of 37 pilots and 15 cadets who had no history of flight difficulties or mishaps. The second group contained 27 pilots who had had near-misses or mishaps, and 37 students who were doing poorly in flight training. The third group consisted of 24 pilots who had "functional diseases" of the cardiovascular or central nervous system (CNS). Laterality measures included a speech perception index, derived from a dichotic listening task, which specified the extent to which the left hemisphere was dominant for speech. A handedness index incorporated several tests of motor function, and provided a summary measure of manual preference.

Gyurdzhian and Fedoruk found that the speech perception index was much higher in the first group (44% in the pilots, 33% in the students) than in group 2 (12% in the pilots, 14% in the students). As discussed previously, many authors consider dichotic listening to be an unreliable method of determining the language hemisphere, especially in those showing a left ear advantage (229). However, these sample differences are impressive. If the speech perception index is taken as a measure of lateral function, and not necessarily a reliable indicator of the language hemisphere, these data seem to point out a processing difference between the two groups. The handedness index also was higher in group 1 (67%) than group 2 (31%), indicating a higher degree of right-handedness in the successful group of pilots and students. The pilots in the group 3 appeared very much the same as group 2.

The authors concluded that a poorly lateralized (to the left) language hemisphere was an unfavorable pilot attribute, and speculated that, since group 2 was very similar to group 3, inadequate lateralization might be related both to accident-proneness and the incidence of functional diseases of the cardiovascular system and CNS. However, the authors mentioned that it was often difficult to separate groups 2 and 3, because many of the "accident-prone" pilots also had functional diseases, and pilots with these diagnoses often reported near-misses more frequently. It seems that the more stable findings relate to the differences between groups 1 and 2. The conclusion, that a well-lateralized speech hemisphere is desirable for pilots, is in basic agreement with the previous research cited, although lateralization of speech has not been previously examined in relation to aviation. It would be interesting to study a sample of left-handers with well-lateralized right hemispheric control of speech, although such a sample would be nearly impossible to assemble. One might expect a pilot with speech strongly lateralized to the right hemisphere to fly as well as any strongly dextral pilot. Strongly lateralized left-handers might still be expected to show a performance decrement under simultaneous spatial and manual loading, however. Unfortunately, by expressing the handedness index as a group mean, the authors have obscured the bimodal distribution of handedness; arranging handedness into multiple categories, or even presenting the entire distribution, would have allowed much more powerful statistical analysis.

Flying personnel (pilots and students) were compared to healthy male adults in a 1985 report by Bodrov and Fedoruk (25). They measured laterality of manual preference (by several manual tasks, strength, and physical indicators such as the width of thumbnail bed), language hemisphere (by a dichotic listening task), and eye sighting dominance. In the first part of the analysis, they found no differences between groups for laterality of hands, legs, or eye dominance. However, more flying personnel displayed a left hemispheric dominance for receptive language than did the controls. Among the flying personnel, there were no differences between students and pilots; however, "first class flyers" were found to be more right-handed, more right-eye dominant, and more right-ear dominant than either regular pilots or students. Each group of flying personnel had individuals with different patterns of laterality. The authors concluded that the right-dominant profile of functional asymmetry was characteristic of their highly trained pilots.

In the second part of the article, Bodrov and Fedoruk categorized the flight personnel into 2 groups based on quality of flying. Group 1 consisted of flyers who seldom made mistakes in flying technique, and Group 2 contained those who frequently erred while flying. The authors found Group 1 pilots to be predominantly right-handed, with "asymmetry of hearing and eye dominance." Group 2 contained significantly more people with left-handed laterality and functional symmetry (i.e., poor lateralization). The findings in this analysis are not elaborated further, although it is clear that Group 1 was predominantly composed of consistently right-sided asymmetrical pilots.

Bodrov and Fedoruk felt that their results strongly supported the theory that pilot skill is correlated with a high degree of cortical development and specialization. They speculated that individual profiles of functional asymmetry could be used for selection of flying personnel, and in the study of reasons for flying errors. This paper is a fascinating cross-sectional study of pilot laterality attributes. However, like the previously reviewed report, by Gyurdzhian and Fedoruk, it is incompletely described. We are not told how many subjects were involved, nor is there even a rudimentary description of methods for subject selection. Further, it is unclear what distinguishes a first-class pilot from other aviators. The authors recommend these methods for selection of aviators, but the only difference from the general public that they noted was the lateralization of receptive language. As previously mentioned, the method used in this study for determining the lateralization of language, a dichotic listening task, may be unreliable, especially in those showing non-right-ear preferences. Nonetheless, the general historical theme of strong asymmetry being linked to flying skill is supported in this report.

We will now return to the general psychology literature, reviewed previously in this paper, in an attempt to substantiate and expand these observations by the aeromedical community.

<u>Extrapolations From The Psychology Literature</u>-- Earlier, it was noted in passing that Zimmerberg et al. reported that rats that do not show strong turning tendencies to either side perform poorly in mazes (280). The application of this experimental observation should now be obvious; pilots may be similar to rats in this respect, if we are to believe the previously reviewed aeromedical literature concerned with laterality and pilot proficiency.

It is difficult to extrapolate from the results of basic psychology research to predictions of cockpit performance. The reader should therefore note that the following suggested applications represent conjecture, and have not been experimentally validated in the aviator population. Of course, prior to instituting any selection parameter, extensive testing and validation must be completed.

The psychological literature is replete with associations between left-handedness and psychophysical impairment, such as stuttering, epilepsy, mental retardation, and brain tumors. Clearly, most of these patients would not be accepted as pilots, and represent the "pathological left-handedness" category of sinistrality (90). As Geschwind pointed out, however, not all left-handedness is pathological, and certainly the majority of left-handers would pass the neurological and psychological parts of a standard Class I flight physical. The topic of the present discussion is this population of apparently normal left-handed flight applicants. Is there evidence of potential subtle performance deficiencies that might affect flight performance?

We have noted several references in the aeromedical literature suggesting that incomplete lateralization is associated with impaired pilot performance. A number of pilots with poorly developed functional asymmetry would meet Geschwind's criteria for "anomalous dominance," and therefore be suspected of less than optimal cognitive ability (80). The psychological concept of anomalous dominance thus seems to find support in the clinical aerospace medicine literature.

Since left-handers are, in general, less well-lateralized than right-handers, it would follow that the performance of sinistrals should be inferior. While this is sometimes true (183, 190, 196), many authors have concluded that in some tasks the performance of left-handers is at least equal to that of right-handers (108, 251). Annett concluded that the only significant motor difference that emerged from the literature was a superiority of left-handers in control of the nonpreferred hand (8). The specific task involved in each experiment is critical in this research. This complication is one of the many reasons that it is difficult to make generalizations regarding flight aptitude based on hand preference. Despite Levy's evidence that left-handers perform worse at spatial tasks (145), the amount of literature to the contrary caused Annett to comment, "This great weight of negative evidence should surely be sufficient to counter the left-handers' spatial disability hypothesis" (8). Most of this research treated handedness as a dichotomous variable, however, which may have obscured the effect of any less lateralized subjects. More research is needed with greater attention to subjects possessing lesser laterality.

Although hand posture while writing has not proved to be a reliable predictor of spatial processing in all studies (149), it would be interesting to attempt to correlate flying performance with these different writing modalities.

The concept of truncal laterality, as proposed by Geschwind, may contribute to an individual's overall laterality pattern (80). The observation that rotational preference varies with gender supports the widespread contention that females as a group are less lateralized than males (27). Rotational preference should be investigated further; perhaps this truncal asymmetry influences flight control inputs. For instance, preference in direction of aircraft roll might be associated with rotational preference.

Left-handers' impaired ability to localize auditory stimuli (59) probably has no consequences in the present generation of aircraft cockpits, since aural warnings and communications emanate from monaural speakers. However, future cockpit concepts may include directional aural threat warnings, for example, to enable the pilot to more quickly determine the location of an approaching missile. Other similar cockpit systems can be envisioned in which the ability to localize sound would be important. It is unlikely that the left-hander's impairment will be operationally significant, but this is an interesting area for further study.

Eye dominance is an aspect of laterality that is easily measured and could be used as a selection criterion for pilot applicants. The observation that right-eye sighting dominant subjects are more accurate on a verbal task, while left-eye sighting dominant subjects are superior on a spatial task, would suggest that left-eye dominant flight students might be preferable (130). However, Bodrov and Fedoruk found no difference between pilots and nonpilots in terms of sighting dominarce, but did note that their best pilots were right-eye dominant (25). The basic experimental literature obviously is in conflict with these clinical observations.

A more direct application of eye dominance may be in monocular sighting systems, which are currently used on several modern military aircraft. Sheeran's observation that right-eye dominant dextrals were better marksmen than left-eye dominant dextrals, when sighting with the right eye (240), raises questions regarding the effectiveness of left-eye dominant aircrew who are compelled to sight with the right eye. Most systems currently in use do not allow the pilot to select the eye used for sighting. Aircrew being trained in these systems possibly should be restricted to those with compatible eye dominance, if this effect was experimentally verified.

Research into personality correlates of handedness does not seem to apply readily to aviation psychology. Hicks and Pellegrini found that subjects who showed strong lateralization, either dextral or sinistral, tend to see themselves as being more controlled by their environment, whereas those with mixed hand preference believe they are responsible for their own fate. One would expect the reverse, based on observations of the typical pilot personality (122). Aviators are generally characterized as manipulators of the environment, and very independent. The reason for this conflict between the basic and applied psychology literature is unclear.

Apparently, a family history of left-handedness in dextrals is associated with decreased lateralization of language (173). Performance data correlated with handedness and family history would be interesting, to determine the performance effects of this easily measured historical item.

Many authors have noted gender-specific differences in laterality patterns. In general, right-handed males consistently show more developed functional asymmetry. Nagae suggested that females possess a level of specialization less than dextral males, but more than sinistral males (190). He also presented experimental data which supported the contention that left-handed males might have difficulty processing verbal and spatial information simultaneously. A particularly interesting finding was that of Manga and Ballesteros, who noted that right-left confusion was more common among females, especially left-handers (103, 162).

Contrasted with these experimental findings are the empirical observations that females do not, in fact, make poorer pilots than males (219). However, fewer females than males seek to become pilots, so it may be that those females who enter flight training are a self-selected population with an exceptional degree of lateralization and cognitive capacity. There are no reports in the literature concerning the lateralization characteristics of female flyers. This is another area for future research.

Handedness as a Selection Criterion

Although there do appear to be subtle interactions between handedness and aviator performance, the future of handedness and other correlates of laterality as selection criteria is uncertain. It is clear that much interesting research remains to be done in this area. Whereas conflicts between the psychology and aviation literature exist in some areas (such as aviator personality and laterality), other facets of functional asymmetry in aviation simply have not been examined at all.

It bears repeating, at this point, that a statistical association between demographic variables and performance does not imply a cause-and-effect relationship, and that individual members of the study population may not exhibit the performance characteristics of the sample as a whole. The laterality literature is full of contradictions and weak associations, which probably will be difficult to resolve in future research.

It is possible that laterality of central cognitive processing may be more amenable to such application. The body of aeromedical literature dealing with these issues will be reviewed in the next section.

AIRCREW SELECTION AND COGNITIVE LATERALITY

Although handedness has been associated with flying aptitude, it readily becomes apparent to the student of human laterality that hand preference is only a manifestation of some cortical asymmetry. As described in the preceding section, it is those with poor lateralization of motor and sensory functions who may be at a disadvantage in the cockpit, compared to subjects who manifest strong functional asymmetry. This handedness research supports the theory that optimum cognitive efficiency is achieved by maintaining functional separation of the cerebral hemispheres (14), and suggests that left-handedness may serve as a marker for this less-lateralized population. However, it is the cortical processing of information that ultimately should be well lateralized.

Aviation psychologists have long sought to define a set of readily tested cognitive abilities, a cognitive profile, which characterizes the skills and aptitude required of an aviator. These efforts have produced several pencil and paper tests, as well as actual performance tests requiring hardware and software support, which have been shown to help predict student pilot performance in flight school. However, this research has not been concerned with the hemispheric location of a given task's processing. The general approach has been to employ a multiple regression modelling technique to determine which of many tests under study add significance to the regression equation. This approach is certainly of some value in the selection process, but does not provide insight into the structural workings of the "aviator brain."

By using tests for which the hemisphere required for processing has been determined, investigators have begun to characterize the hemispheric processing ability of aviators. This knowledge can then be applied to the selection process. Researchers who are familiar with the concepts of cerebral laterality can also use dual-task research to assess the effect of multiple task loading on performance, which has important application to the real-time cockpit environment (165).

In a fascinating essay, Tipton and Mohler compared the fathers of powered flight, Orville and Wilbur Wright, in terms of personality and cognitive talents (256). They carefully examined several biographical accounts, and found that the two brothers apparently possessed dramatically different cognitive profiles. For example, Orville was extroverted, creative, and mechanically inclined, whereas Wilbur was analytical, organized, and mathematically adept at the new science of aerodynamics. Although Orville is credited with the first successful powered flight, Wilbur actually attempted the feat 3 days earlier, having won the coin toss. His flight ended quickly, however, due to improper horizontal stabilizer control input. Tipton and Mohler concluded from this analysis that Wilbur possessed cognitive and personality traits characteristic of superior left brain function, and Orville, the better aviator, was probably gifted with exceptional right hemispheric ability. It is of additional interest that both brothers were right-handed. Of course, these conclusions cannot be verified experimentally, but the Wright brothers' abilities seem well-documented, and there is evidence that extroversion/introversion correlates with relative hemispheric ability (43). Perhaps, as suggested by Tipton and Mohler, it was the fortuitous combination of these two minds, with their complementary cognitive abilities, that was finally able to solve the problems of powered flight.

In this section, the evidence for an "ideal aviator brain" will be reviewed, and possible applications outlined.

Desirable Cognitive Abilities in Aviators

Aviators are required to work in a rapidly changing three-dimensional world to a greater extent than any other profession, and it seems likely that talent for this continuous spatial processing would reside in the right hemisphere (88). However, modern cockpits present a large amount of numerical, sequential, and trend information to the pilot, which may engage the left hemisphere. The best laterality pattern for a prospective aviator may therefore not be intuitively obvious.

Different types of flying may require different cognitive profiles; it is important to characterize these subpopulations of aviators. Fighter pilots rely heavily on pattern recognition and spatial orientation, and must be able to react quickly to a perceived directional threat. Tanker, transport, and bomber pilots may require more monitoring and vigilance skills. While all flyers must maintain good three-dimensional position awareness, there are obvious qualitative differences between a precise instrument approach by an airline pilot, and the aggressive air combat maneuvering of a fighter pilot.

Helicopters require another set of pilot skills. Successful helicopter control requires the constant integration of all four extremities, in response to sensory input regarding helicopter pitch, roll, and yaw. Several authors have considered piloting a helicopter to be a more complex task than piloting a fixed wing aircraft (170, 279). Helicopter pilots may require a more omnidirectional position awareness, especially while at a hover. Although the apparent movement of the environment is relatively slow, the helicopter can move in any direction, including backward. Zavala et al. showed that both fixed- and rotary-wing flying could be described by independent component abilities, or "maneuver dimensions," which may superficially appear to describe similar flight maneuvers. For example, takeoffs and landings are common to all types of flying, but require radically different cognitive strategies in fixed-wing versus helicopter flight. Other maneuver dimensions, such as autorotations or hovering turns, are more obviously unique to rotary-wing operations (279). The requirements of rotary-wing and fixed-wing flying are so different that it is often very difficult for a fixed-wing pilot to learn to fly rotary-wing aircraft, and vice-versa (170). Researchers have attempted to define different cognitive profiles for these different varieties of aviator; this work will be presented later.

Undesirable Cognitive Profiles in Aviators

In a previous section, the effect of handedness and other peripheral manifestations of human laterality on aviation were reviewed. Several cases were presented, and the few experiments relevant to the topic were discussed, with the general conclusion being that poorly lateralized aviators might be at a disadvantage compared to their well-lateralized colleagues. In this section, the more central aspects of laterality will be discussed. Gerhardt suggested that some components of anomalous dominance are frequently present in persons without any peripheral manifestation of reduced laterality (77).

Effects of Anomalous Dominance Patterns-- The basic utility of peripheral laterality as an experimental variable, or as a selection criterion, is to serve as a marker for cerebral function. The previously discussed concepts of anomalous dominance and strephosymbolia, which are diagnosed by peripheral signs, connote disturbed cognitive processing.

Since the ideal aviator brain is well-lateralized, permitting separation of function and reduced task interference, any process which reduces this laterality could be expected to impair performance. For example, the reduced language laterality present in many left-handers has been shown to interfere with right hemisphere spatial tasks (145, 190). This small degree of impairment is unlikely to be a factor during normal flight operations, but under conditions of fatigue or task overloading, might affect cockpit performance (76). This could mean a decrement in spatial awareness for a poorly lateralized pilot trying to understand complicated, garbled, Air Traffic Control clearances over the radio. More research in this area is needed: it is possible that improved methods of information display or control layout would reduce the effects of hemispheric competition.

Safety Implications-- One application of laterality to the arena of aviation safety is derived from the principle of task interference. As just restated, those aviators who are less completely lateralized mignt experience more hemispheric competition during multiple task loading, and suffer a performance decrement.

Another application might be found in aircraft accidents which result from directional confusion. Beaty reviewed several civil aviation accidents in which laterality might have been a factor (15). Four accidents were cited in which the pilot had correctly diagnosed engine trouble, correctly specified the affected engine, and then unwittingly shut down the good engine, on the opposite side, resulting in aircraft loss of power, and subsequent loss of life.

Beaty also cites two accident cases which resulted from simply turning the wrong way. These cases are reproduced here in their entirety:

> Just after midnight on 9th August, 1954, a Constellation was diverted from Santa Maria and landed at Terceira--both islands in the Azores. Lagens aerodrome in Terceira is built in a valley on the extreme northeast end of the island, and the only really long runway possible lies northwest/southeast. Facing northwest, to the right is a ridge. To the left is Monte de Pico, rising 2,321m (7615 ft) above sea-level. As a result, normal procedure after takeoff on the northwest runway is a right turn out over the sea.
>
> When I was in Lagens during the war, in spite of briefing to the contrary, a transport aircraft took off in a northwest direction, turned left and crashed into the mountain, killing all on board. There was ever afterwards particular care taken in briefing pilots for takeoff.
>
> When the captain and the navigator of the Constellation called at the Navigation Briefing Office, requesting information for preparation for a flight plan to Bermuda, the briefing officer went to considerable pains to explain that on the runway in use it was necessary to make a right turn out, and proceed to a checkpoint over the sea called Ponto Sul, in order to avoid the mountain. The exact words were: "Following takeoff, turn right, climb until 2500 (762m) on heading 160 degrees and proceed to Ponto Sul." This procedure was included in the first stage of the flight plan.

After completing the flight plan, the two crewmembers went to the Meteorological Office, before proceeding to the aircraft. The Tower cleared the Constellation to taxi to the south taxiway to engine run up. The clearance was acknowledged and repeated. After run up, the captain took up position on the runway, and asked for takeoff clearance. The Tower replied: "After takeoff, turn right and climb till 2500 feet on heading 160 degrees, then proceed to Ponto Sul." The captain opened up the engines to full power. The Constellation took off normally to the northwest. The Tower reported time off as 02.37 and instructed the aircraft to "turn right."

"Shortly afterwards," says the report, "the aircraft not having turned to the right, the Controller asked the pilot to report his position. The pilot replied that he was northeast of the aerodrome."

The pilot could only have been northeast of the aerodrome if he had turned right. He was, in fact, northwest.

The Controller looked towards the northeast, and saw no aircraft. He asked the captain whether he was flying on an approach heading or was still outbound. He received no answer. The aircraft had already collided with the mountain about 5 miles (8 km) west-south-west of Lagens at a height of about 2000 feet (610m), killing all nine crew and twenty-one passengers.

No mechanical failure was found. The probable cause of the accident was given as "the failure of the pilot to carry out the normal climbout procedure following takeoff from runway 34 on a flight to Bermuda, and his having made a turn to the left instead of to the right, thus flying into the mountains instead of turning out to sea."

The other case involves a takeoff from Shannon airport in Ireland:

In September, 1961, a DC6 taking off from Shannon turned left instead of right as it had been cleared to do on takeoff. During the whole operation, the weather was very bad--in fact below limits. The report stated that there was a "strong possibility that the captain, copilot, and flight engineer were suffering from fatigue due to a long duty period, a short rest prior to the flight and their amount of flying during the previous 90 days." A malfunction was possible.

Although we are not provided information regarding the hand preferences of the crew on these ill-fated flights, the pilots obviously suffered from right-left confusion, at least at the time of the mishaps. Earlier in this paper, other cases of right-left confusion in aviators were noted. Greene mentioned pilots with strephosymbolia who had difficulty making a right-hand turn, or a left-hand turn, in an open cockpit airplane while learning to fly (93). Similarly, Gerhardt cited a pilot who "had to look for his wedding ring in order to identify left and right when he got instructions over the radio to bank the aircraft" (77). Recently, in a case reported to the author, a helicopter pilot routinely placed pieces of tape on the instrument panel, with the words "right" and "left" written on them, to help him speedily respond to the instructor's commands (personal communication, K. Mason MD, 1988).

There is some evidence to suggest that the mental representation of "right" is less complex than that of "left," in right-handers. Olson and Laxar investigated the speed and accuracy of comprehending submarine fire control displays, and found asymmetries in reaction times which favored the direction "right" (196). They concluded that, for right-handers, right is the natural reference direction in the sagittal plane, just as aboveness and forwardness seem to be reference directions in the other two planes. Left-handers recognized the direction "left" better than the right-handers, but made more errors overall.

Another type of error which might be related to laterality is number or letter reversals, which would be expected in dyslexics and, according to Geschwind, mild cases of anomalous dominance. Beaty cites such an airplane mishap:

> The first officer, flying the aircraft from the right-hand seat, asked for the setting to put on his altimeter for aerodrome height at Nairobi (QFE). Control told him 839 millibars. The first officer set it reversed on his altimeter--that is 938.
>
> Nairobi is 5500 feet (1676m) above sea-level. By setting up a level almost 100 millibars higher than the true one, the pilot raised his height indication by 3000 feet (914m). Being 3000 feet lower than he thought he was, he hit the ground 9 miles (5.4 km) from the threshold of the runway.

Beaty notes that in the eight accidents in which he felt that laterality might have been a factor, six occurred outside normal daytime working hours, and five occurred under conditions of increased stress on the cockpit crew. These additional loads may have been enough to uncover a latent tendency toward left-right confusion.

Research with Aircrew

Most research in aircrew selection has been concerned with group trends. To employ cognitive laterality as a selection tool, it will be important to characterize subjects in more depth, to evaluate how abilities cluster within individuals (165). Some recent research with aircrew has begun to examine these detailed individual differences.

Selecting Parameters to Evaluate-- When devising selection tools, investigators usually first perform a job analysis, attempting to isolate the individual tasks that are required to execute a given job. Then, aptitudes that would be necessary to perform these tasks are specified, and finally, tests are devised to identify applicants that possess these talents (219). As we have seen, the talents necessary to make a good pilot are not always clear, much less the skills that would distinguish between the various subtypes of aviator, such as fighter pilots and helicopter pilots.

Because the cognitive skills required of pilots are resistant to investigators' intuition, the trend in aviator selection has been to gather data on many tests and demographic variables that might correlate with flying skill, and see how each variable fares in a multiple regression analysis (38). This approach has also been applied in the cognitive laterality field, but more attention is necessarily paid to the nature of the measurement instrument. Obviously, cognitive tests for which the responsible hemisphere has been determined are of much value. Also, tests which measure dimensions of performance or personality which have been associated with laterality are of interest. Examples of these dimensions would include an applicant's field dependence/independence orientation, or tendencies toward introversion or extroversion. In addition, the effect of dual-task testing can be evaluated, to simulate the high workload environment encountered in the cockpit.

It is reasonable to expect that individuals should vary in their ability to perform multiple tasks simultaneously. As we have seen, a subject's degree of cognitive asymmetry would probably influence this ability. Wickens et al. searched for a general time-sharing factor, that might be used to select aviators, but were unsuccessful (267). They did conclude, however, that hemispheric-task integrity was a neglected field, which appeared to have much promise in aircrew selection and aircraft design.

This job analysis approach to aviator selection is somewhat more intellectually pleasing than the simple multivariate analysis. It demands a more complete understanding of the abilities being tested, and the neuropsychological processes required of the successful pilot.

Review of Cognitive Laterality Research in Aircrew

Visual Evoked Potentials-- The first report in the literature to describe the hemispheric asymmetry of aircrew appears to be that of Lewis and Rimland, in 1979 (152). These investigators, from the Naval Personnel Research and Development Center, attempted to differentiate between pilots and radar intercept officers (RIOs) on the basis of visual evoked potentials (VEPs). The initial hypothesis was that pilots would display higher amplitude VEPs over the right hemisphere, and RIOs would generate larger potentials over the left hemisphere. They based this supposition on an intuitive job analysis; pilots deal with problems in three-dimensional space, at a high rate of speed, and often with incomplete information. The RIOs, on the other hand, work with explicit information, largely numerical, in a sequential and logical fashion.

The subjects were 28 pilots and 30 RIOs assigned to an F-4 base. VEPs were recorded with the subject at rest, without any secondary task. They found that those pilots with the highest flight performance ratings tended to have the largest R-L parietal VEP amplitude differences. Within the RIO group, those with the highest performance ratings tended to be evenly split between RIOs with larger amplitudes on the right and those with larger amplitudes on the left. Considered as a simple dichotomy, the pilots could be discriminated at a significant level from the RIOs on the basis of the electrical potential at one of the frontal electrodes. Thus, proficient pilots and RIOs showed different patterns of hemispheric activity, as predicted by the hypothesis.

Marsh has criticized this study, however, on two main points (166). First, the subjects' minds were allowed to wander, since no secondary task was required. This wandering could dramatically shift an individual's mode of cognitive processing. Second, 8/58 subjects were left-handed; these were included in much of the analysis, which may have biased the results. Nonetheless, significant preliminary differences were noted between and within these aircrew occupations, providing encouragement to other cognitive psychologists.

In 1981, a similar study was reported by Schlichting and Kindness, in which 32 right-handed sonar operators were tested using a similar VEP methodology (234). They found that in sonar operators as a group, the right hemisphere displayed greater VEP amplitude than the left, in response to complex visual stimuli. Also, there were significant interhemispheric asymmetries in VEP amplitude which correlated with supervisor ratings of job performance. Interestingly, only those subjects with no left-handed relatives in the immediate family displayed significant asymmetry. Although this experiment excluded left-handers, these subjects also were not given a secondary task to control their cognitive processing mode during the VEP recording. Echoing Lewis and Rimland (152), VEP amplitude was suggested by Schlichting and Kindness (234) as a future tool in initial selection of personnel requiring spatial proficiency.

It is difficult to understand why such a crude electrical measure of brain activity during the viewing of various random patterns should be correlated with sonar operation, or a complex act like flying. However, it is likely that the observed utility of the amplitude difference between hemispheres reflects the degree of cerebral lateralization. Although these studies do take advantage of some principles of hemispheric laterality, cognitive function is not assessed in a readily interpretable fashion.

Cognitive Performance Testing-- In 1982, Gordon et al. administered a set of more clearly performance-oriented cognitive tests to three groups of Israeli student and fully trained aircrew, to evaluate relative information processing modes (88). The test battery (dubbed the Cognitive Laterality Battery) consisted of six subtests, three measuring left hemispheric functions, and three measuring right hemispheric functions. The left hemispheric tests were Serial Sounds, Serial Numbers, and Word Production (Fluency), and the right hemispheric tests were Orientation, Localization, and Form Completion. Gordon et al. hypothesized that those individuals excelling in right hemispheric functions such as pattern perception and orientation would be more likely to succeed as fighter pilots, and that helicopter pilots would be less skilled in these dimensions. Navigators were also predicted to possess less right hemisphere skills than fighter pilots, as their jobs require calculation and analytical abilities as well as positional and spatial awareness. Although the exact number was classified, and therefore not reported, approximately 50 navigators, 50 helicopter pilots, and 100 bomber and fighter pilots were tested with the CLB. In addition, a group of high school students were tested to provide a control group for the second part of the analysis.

Two outcome measures were calculated: (a) a Cognitive Laterality Quotient (CLQ), which was obtained by subtracting the average left hemisphere score from the average right hemisphere score, and (b) a Cognitive Performance Quotient (CPQ), which was obtained by adding the two mean hemisphere scores.

Gordon et al. found significant differences among the different study groups ($p<0.05$). Specifically, they found that fighter pilots favored functions attributed to the right hemisphere (CLQ=0.11), helicopter pilots performed better at left hemispheric functions (CLQ=-0.3), and navigators showed no strong hemispheric advantage (CLQ=0.02). The right hemisphere group of tests was the discriminating factor among groups, while the left hemisphere scores were statistically similar. Helicopter pilots were not statistically different from the high school student control group, whereas navigators and pilots showed better right hemispheric function. The fighter pilots had slightly higher CPQ scores than the other groups, but this was not a significant difference. All three groups had higher CPQ scores than the controls, indicating an overall performance superiority for the aircrew personnel.

A separate analysis compared instructor ratings of the six aviators with the most positive CLQ scores, with the six pilots with the most negative CLQ scores. They found that those subjects who were considered "natural" pilots tended to have higher CLQ scores; that is, they performed better on the tests of right hemisphere function than on tests of left hemisphere function.

The CLB appears to be a useful tool, however these data must be interpreted with caution. Gordon et al. combined students and rated aircrew in their sample, and did not specify the numbers or relative proportions of each. If, for example, qualified fighter pilots composed a large proportion of that subgroup, their cognitive skills might dominate the group's profile. A related problem involves the subject air force's selection process. As described by Gordon et al., all students begin in a common class, and only the superior students are selected to continue as fighter pilots, while the next best become helicopter pilots, and the rest enter navigator training. This procedure prompts two caveats: First, it is not specified how far along in the training cycle the subjects were at the time of testing. The possibility might exist that the members of this group could still drop out into one of the other two groups, which would mean that the performance scores of the fighter/bomber pilot group would be diluted by these future dropouts. This would appear to be a minor criticism, since significantly better scores were consistently obtained for the pilot group. If, however, the testing occurred relatively early in the training cycle, the navigator and helicopter pilot groups might contain those who had been weeded out earliest and, therefore, had the most obvious difficulty flying. The second concern relates to conclusions about the non-fixed-wing pilot cognitive profiles. In a training system such as that described by Gordon et al., conclusions about ideal rotary-wing or navigator profiles are unwarranted. It seems a foregone conclusion that these subjects will have different cognitive profiles, just as dropouts from any pilot program will perform differently than the successful trainees. Conclusions regarding helicopter pilot attributes would be better gauged by examining a program which places students in rotary-wing training based on ambition, or random selection.

Nonetheless, the conclusion that successful fighter and bomber pilots differ from those who are removed from training is an important one. This might suggest that such a battery of tests could be used to help predict success in flight training.

In 1988, Gordon and Leighty reported a prospective study of naval student aviators (86), extending the findings of the Israeli Air Force study just discussed. They tested 600 students in ground school or early in flight training, using a slightly expanded version of the CLB. The subjects included students destined to fly jet, helicopter, or propeller-driven aircraft. It is important to note that the U.S. Navy assigns aircraft-type early in the training process, and bases this determination on a variety of factors, unlike the Israeli Air Force, in which fighter pilot dropouts are enrolled in helicopter or navigator training. Gordon and Leighty noted that 11% of their subjects were left-handed, by self report. The flight school performance of each subject was tracked, and recorded as success or failure. Of their 600 subjects, 130 (22%) did not complete training; specific reasons for failure are not reported. The successful group had significantly higher mean visuospatial scores than the failure group ($p<0.0001$), but the mean verbosequential score did not differentiate between the two groups. There were no differences among the successful students, regardless of aircraft type.

Gordon and Leighty subjected their data to a logistic regression analysis, and developed two model equations to describe the likelihood of success in flight training. In the study sample, variables that were not found to contribute significantly to the model included previous flight experience and hand preference. The CPQ was found to be significant in one model, indicating that overall performance predicted the chances of success, but the CLQ did not add to any of the models tested. As expected, visuospatial scores did significantly predict flight school performance. Verbosequential ability, as measured by the CLB, did not by itself add significance to the model, although there was an interesting interaction effect with visuospatial ability. Verbosequential scores had little effect on the odds of being graduated, except in individuals with high scores, in which case coincident high visuospatial scores seemed to lower the odds of success. The authors conceded that this result was difficult to explain, but speculated that highly verbal, analytical traits might interfere with superior spatial intuition, or "seat of the pants" talent.

Gordon and Leighty described how these data could be used to develop selection criteria for pilot training. By using the mean visuospatial score of the dropouts as a cut-off score, 52% of the dropouts could have been eliminated, while 28% of the future successes would have been removed from training in error. Alternatively, a more conservative approach would involve setting the cutoff at the normative mean, which would have eliminated 22% of the failures, and 7% of the eventual successes. Factors which would affect the choice of the cut-off level include training cost, applicant ability, and other administrative considerations.

The main problem in this study is common to virtually all aircrew selection research. All flight cadets are heavily screened prior to entering flight training, which probably means that the results of this study do not apply to an untested aviator applicant population. In fact, it is somewhat surprising that visuospatial skills were so predictive of flight school success, since the preadmission visuospatial testing would be expected to produce a student population with fairly homogeneous performance in this area. Most tests used in conventional selection batteries probably measure left hemisphere functions (165), which may account for the poor predictive value obtained for the verbosequential battery. However, the model may be valid as a secondary selection tool. Research must be conducted on applicants prior to selection, although this is difficult to accomplish.

There are other methodologic criticisms of this study. Self report is generally acknowledged as an unreliable method of determining hand preference. Perhaps more meaningful methods of peripheral laterality assessment would produce more significant results. Also, by not verifying the specific reasons for dropping out of flight training, the authors cannot be sure that all failures were due to flight deficiencies. Some students withdraw for family or medical reasons; if these individuals are not removed from the analysis, the cognitive profile of the dropout subgroup could be diluted.

Gordon and Leighty did demonstrate that regardless of aircraft type, the cognitive profiles of successful pilot graduates are fairly uniform, contradicting the 1982 report of Gordon et al. They also provided a valuable example of the use of cognitive laterality as a secondary selection tool.

Future Trends

As the cognitive abilities that characterize the ideal aviator become more apparent, flight school admission screening will no doubt include cognitive performance testing. Such testing is already the practice in many aviation training programs.

The concept of hemispheric interference appears to be well accepted by modern psychologists. The early aeromedical literature, suggesting that those pilots with marked functional asymmetry were better and safer, might eventually be proved more correct than not. Selection testing could attempt to find those individuals who possess the most cognitive laterality, and the least hemispheric interference under heavy task loading.

Marsh has speculated that laterality might be enhanced by training (165), by teaching the pilot to employ the most efficient cognitive strategy possible at that particular time. By practicing spatial or vigilance tasks while simultaneously performing left hemisphere problems, skills in using the two hemispheres simultaneously might be trained. Biofeedback sessions could be used to practice selectively engaging one or the other hemisphere. Marsh suggests that pilots may benefit from training in orientation and spatial perception, using cognitive psychology tools such as block rotation and random dot stereograms. If aviators can enhance their spatial awareness by simple tasks which exercise the mind, actual flight performance might be improved significantly. While this capability would probably be most useful for fighter-type pilots, many helicopter and transport pilots are also reaching the point of task saturation in their respective cockpits. All aircrew, especially those engaged in rapid maneuvering in three dimensions such as in air-to-air combat, could benefit from enhanced visuospatial skills.

New knowledge of the principles of cognitive laterality should aid in the intelligent design and selection of these tools, and help aeromedical specialists better understand the workings of the aviator mind.

References

1. Agor, W. H. Brain skills development in management training. Training Devel J. 37:78-83; 1983.
2. Albert, M. L.; Helm-Estabrooks, N. Diagnosis and treatment of aphasia. Pt II. JAMA. 259:1205-1210; 1988.
3. Allen, D. Are lefties left out? Family Safety. :18-19; 1978.
4. Annett, J.; Annett, M.; Hudson, P. T.; Turner, A. The control of movement in the preferred and non-preferred hands. Quarterly J Exper Psychol. 31:641-652; 1979.
5. Annett, M. A classification of hand preference by association analysis. Br J Psychol. 61:303-321; 1970.
6. Annett, M. Hand preference and the laterality of cerebral speech. Cortex. 11:305-328; 1975.
7. Annett, M. Family handedness in three generations predicted by the right shift theory. Ann Human Genet. 42:479-491; 1979.
8. Annett, M. Left, right, hand and brain: the right shift theory. Hillsdale, NJ: LEA Publishers; 1985.
9. Anonymous. British examination form for civilian flyers. J Av Med. 2:92-96; 1931a.
10. Anonymous. French physical examination forms: civilian airplane pilot. J Av Med. 2:97-106; 1931b.
11. Armstrong, H. G. Principles and practice of aviation medicine. 3d ed. Baltimore: Williams & Wilkins Company; 1952.
12. Bakan, P. Hypnotizability, laterality of eye movements and functional brain asymmetry. Perceptual and Motor Skills. 28:927-932; 1969.
13. Bauer, L. H.; Christian, H. A., editors. Aviation medicine. New York: Oxford University Press; 1930.
14. Beaton, A. Left side, right side: a review of laterality research. New Haven: Yale University Press; 1985.
15. Beaty, D. The human factor in aircraft accidents. New York: Stein and Day; 1969.
16. Berg, P. Being left-handed losing its stigma. Washington Post. :26; 1987 Aug. 6.
17. Bergin, K. G. Aviation medicine: its theory and application. Bristol: John Wright & Sons, Ltd; 1949.
18. Beukelaar, L. J.; Kroonenberg, P. M. Changes over time in the relationship between hand preference and writing hand among left-handers. Neuropsychologia. 24:301-303; 1986.
19. Bishop, D. V. Handedness, clumsiness and cognitive ability. Dev Med Child Neurol. 22:569-579; 1980.
20. Bishop, D. V. Using non-preferred hand skill to investigate pathological left-handedness in an unselected population. Dev Med Child Neurol. 26:214-226; 1984.
21. Bishop, D. V. Is there a link between handedness and hypersensitivity? Cortex. 22:289-96; 1986.
22. Blau, A. The master hand. American Orthopsychiatric Asso.; 1946.
23. Bleir, R.; Houston, L.; Byne, W. Can the corpus callosum predict gender, age, handedness, or cognitive differences? Trends in Neurosciences. 9:391-394; 1986.

24. Bodo, D.; Baranova, V. P.; Matsnev, E. I.; Yakovleva, M. Y. On the nature of caloric nystagmus in healthy persons (in response to caloric stimuli). In: National Aeronautics & Space Administration, The function of the body and factors of space flight. NASA-TT-E-15971. Moscow: Meditsina Press; 1974:74-79. Translation from Russian.
25. Bodrov, V. A.; Fedoruk, A. G. A study of functional asymmetry of paired organs in aircraft personnel. Voenno-Meditsinskii Zhurnal. :50-52; 1985. Translation from Russian. A86-10750.
26. Boyer, J. Psycho-physiological examination of aviators. Milit Surg. 39:440-445; 1916.
27. Bracha, H. S.; Seitz, D. J.; Otemaa, J.; Glick, S. D. Rotational movement (circling) in normal humans: sex difference and relationship to hand, foot and eye dominance. Brain Res. 411:231-235; 1987.
28. Bradshaw, J. L.; Nettleton, N. C.; Taylor, M. J. Right hemisphere language and cognitive deficit in sinistrals. Neuropsychologia. 19:113-132; 1981.
29. Briggs, G. G.; Nebes, R. D.; Kinsbourne, M. Intellectual differences in relation to personal and famil andedness. Quart J Exper Psychol. 28:591-601; 1976.
30. Broca, P. Remarques sur le siege de la faculte du langage articule, suivies d'une observation d'aphemie. Bull Soc Anat Paris, 2nd series. 6:398-407; 1861. cited in: Geschwind, N.; Galaburda, A. M. Cerebral lateralization. Cambridge, Massachusetts: The MIT Press; 1987.
31. Brown, G. W.; Hayden, G. F. Nonparametric methods: clinical applications. Clin Pediat. 24:490-498; 1985.
32. Bryden, M. P. An evaluation of some models of laterality effects in dichotic listening. Acta Oto-laryngologica. 63:595-604; 1967.
33. Bryden, M. P. Handedness and its relation to cerebral function. In: Bryden, M. P., editor. Laterality--functional asymmetry in the intact brain. New York: Academic Press; 1982.
34. Cain, D. P.; Wada, J. A. An anatomical asymmetry in the baboon brain. Brain Behav Evol. 16:222-226; 1979.
35. Carmon, A.; Gombos, G. M. A physiological vascular correlate of hand preference: possible implications with respect to hemispheric cerebral dominance. Neuropsychologia. 8:119-128; 1970.
36. Carpenter, M. B. Human neuroanatomy. 7th ed. Baltimore: Williams & Wilkins Company; 1976.
37. Carretta, T. R. Field dependence-independence and its relationship to flight training performance. Brooks Air Force Base, Texas: USAF Human Resources Laboratory; 1987a. AFHRL-TP-87-36.
38. Carretta, T. R. Basic attributes tests (bat) system: development of an automated test battery for pilot selection. Brooks Air Force Base, Texas: USAF Human Resources Laboratory; 1987b. AFHRL-TR-87-9.
39. Carroll, H. E. Eye-hand preference in military officers. [Master's Thesis]. Monterey, Calif: Naval Postgraduate School; 1971. AD-722560.

40. Casey, M. B.; Brabeck, M. M.; Ludlow, L. H. Familial handedness and its relation to spatial ability following strategy instructions. Intelligence. 10:389-406; 1986.
41. Caskey, O.; Meier, D. The effect of guided imagery and internal visualization on learning. AD-A179854 (ARI). Lake Geneva, WI: Center for Accelerated Learning; 1987. Contract No. MDA903-83-C-0134.
42. Chapman, L. J.; Chapman, J. P. The measurement of handedness. Brain and Cognition. 6:175-183; 1987.
43. Charman, D. K. Do different personalities have different hemispheric asymmetries? a brief communique of an initial experiment. Cortex. 15:655-657; 1979.
44. Churchill, J. A.; Igna, E.; Seirf, R. The association of position at birth and handedness. Pediatrics. 29:307-309; 1962.
45. Collet, L.; Duclaux, R. Hemispheric lateralization of emotions: absence of electrophysiological arguments. Physiol Behav. 40:215-220; 1987.
46. Collins, R. L. On the inheritance of handedness. 2. selection for sinistrality in mice. J Hered. 60:117-119; 1969.
47. Cooper, H. J. The relation between physical deficiencies and decreased performance. J Aviat Med. 1:4-24; 1930.
48. Coren, S.; Porac, C. Fifty centuries of right-handedness: the historical record. Science. 198:631-632; 1977.
49. Coucheron-Jarl, V.; Gerhardt, R.; Riis, E. Approaches to the problem of flying safety. In: Geldard, F. A.; Lee, M. C., editors. First international symposium on military psychology. Washington DC: National Academy of Sciences; 1961. National Research Council Publication 894.
50. Cremer, M.; Ashton, R. Motor performance and concurrent cognitive tasks. J Motor Behav. 13:187-196; 1981.
51. Damasio, A.; Bellugi, U.; Damasio, H.; Polzner, H.; Van Gilder, J. Sign language aphasia during left-hemisphere Amytal injection. Nature. 322:363-365; 1986.
52. Damon, A.; Stoudt, H. W.; McFarland, R. A. The human body in equipment design. Cambridge, Massachusetts: Harvard University Press; 1966.
53. De Renzi, E. Disorders of space exploration and cognition. New York: John Wiley & Sons; 1982.
54. DeHart, R. L. The historical perspective. In: Dehart, R. L., editor. Fundamentals of aerospace medicine. Philadelphia: Lea & Febiger; 1985:3-25.
55. DeMyer, W. Technique of the neurologic examination. New York: McGraw-Hill Book Company; 1980.
56. Denel, N. R.; Lawrence, L. M. Laterality in the gallop gait of horses. J Biomechanics. 20:645-649; 1987.
57. Denenberg, V. H. Hemispheric laterality in animals and the effects of early experience. Behav Brain Sci. 4:1-49; 1981.
58. Drake, R. A. Lateral asymmetry of impression formation. Intern J Neuroscience. 30:121-126; 1986.
59. Duhamel, J. R.; Pinek, B.; Brouchon, M. Manual pointing to auditory targets: performances of right versus left handed subjects. Cortex. 22:633-638; 1986.

60. Durnford, M.; Kimura, D. Right hemisphere specialization for depth perception reflected in visual field differences. Nature. 231:394-395; 1971.
61. Dwyer, J.; Rinn, W. E. The role of the right hemisphere in contextual inference. Neuropsychologia. 19:479-482; 1981.
62. Ehrlichman, H.; Weinberger, A. Lateral eye movements and hemispheric asymmetry: a critical review. Psych Bull. 85:1080-1101; 1978.
63. Evans, K. A.; Payne, D. A. An experimental study of the relationship between hemispheric dominance and the effectiveness of instructional processes. Occup Ther J Res. 6:251-252; 1986.
64. Fincher, J. Lefties: the origins and consequences of being left-handed. New York: Perigee Books; 1977.
65. Flor-Henry, P. On certain aspects of the localization of the cerebral systems regulating and determining emotion. Biol Psych. 14:677-698; 1979.
66. Fry, C. J. Eye-hand dominance and college major. Percept Motor Skills. 62:918; 1986.
67. Galin, D.; Diamond, R.; Braff, D. Lateralization of conversion symptoms: more frequent on the left. Am J Psychiatry. 134:578-583; 1977.
68. Galin, D.; Ornstein, R. Lateral specialization of cognitive mode. Psychophysiology. 9:412-418; 1972.
69. Garmon, L. Of hemispheres, handedness and more. Psychol Today. Nov(11):40-48; 1985.
70. Garrick, C. Field dependence and hemispheric specialization. Perceptual and Motor Skills. 47:631-639; 1978.
71. Gazzaniga, M. S. The bisected brain. New York: Appleton-Century-Crofts; 1970. cited in: Beaton, A. Left side, right side: a review of laterality research. New Haven: Yale University Press; 1985.
72. Gazzaniga, M. S.; Bogen, J. E.; Sperry, R. W. Laterality effects in somesthesis following cerebral commissurotomy in man. Neuropsychologia. 1:209-215; 1962.
73. Gazzaniga, M. S.; Bogen, J. E.; Sperry, R. W. Observations on visual perception after disconnexion of the cerebral hemispheres in man. Brain. 88:221-236; 1965.
74. Gazzaniga, M. S.; Bogen, J. E.; Sperry, R. W. Dyspraxia following division of the cerebral commissures. Arch Neurol. 16:606-612; 1967.
75. Gazzaniga, M. S. Right hemisphere language following brain bisection: a 20-year perspective. Am Psychologist. 38:525-537; 1983.
76. Gedye, J. L. Hand preference in aircrew. Aerospace Med. 35:757-63; 1964.
77. Gerhardt, R. Left-handedness and laterality in pilots. In: Evrard, E.; Bergeret, P.; Van Wulfften Palthe, P. M., editors. Medical aspects of flight safety. (The unexplained aircraft accident). New York: Pergamon Press; 1959:262-272. AGARD NATO.

78. Geschwind, N. Cerebral dominance in biological perspective. Neuropsychologia. 22:675-683; 1984.
79. Geschwind, N.; Behan, P. Left-handedness: association with immune disease, migraine, and developmental learning disorder. Proc Natl Acad Sci USA. 79:5097-5100; 1982.
80. Geschwind, N.; Galaburda, A. M. Cerebral lateralization: biological mechanisms, associations, and pathology. Cambridge, Massachusetts: The MIT Press; 1987.
81. Geschwind, N.; Levitsky, W. Human brain: left-right asymmetries in temporal speech region. Science. 161:186-187; 1968.
82. Gilinsky, A. S.; Brown, J. L. Eye dominance and tracking performance. Aero Medical Laboratory Contract No. AF 33 (038) 22616. Wright-Patterson AFB, Ohio: Wright Air Development Center; 1952. WADC Tech Report 52-15.
83. Gillingham, K. K.; Wolfe, J. W. Spatial orientation in flight. USAFSAM-TR-85-31. Brooks Air Force Base, Texas: USAF School of Aerospace Medicine, Aerospace Medical Division; 1986.
84. Gordon, H. W. Cognitive asymmetry in dyslexic families. Neuropsychologia. 18:645-656; 1980.
85. Gordon, H. W. The cognitive laterality battery: tests of specialized cognitive function. Int J Neurosci. 29:223-244; 1986.
86. Gordon, H. W.; Leighty, R. Importance of specialized cognitive function in the selection of military pilots. J Appl Psychol. 73:38-45; 1988.
87. Gordon, H. W.; Sherman, E.; Charns, M. P. Management success as a function of performance on specialized cognitive tests. Human Relations. 40; [1987]. In Press.
88. Gordon, H. W.; Silverberg-Shalev, R.; Czernilas, J. Hemispheric asymmetry in fighter and helicopter pilots. Acta Psychol. 52:33-40; 1982.
89. Gordon, H. W.; Sperry, R. W. Lateralization of olfactory perception in the surgically separated hemispheres of man. Neuropsychologia. 7:111-120; 1969.
90. Gordon, N. Left-handedness and learning. Dev Med Child Neurol. 28:649-661; 1986.
91. Govind, C. K.; Kent, K. S. Transformation of fast fibres to slow prevented by lack of activity in developing lobster muscle. Nature. 298:755-757; 1982.
92. Grapin, P.; Perpere, C. Symetrie et lateralisation du nourrisson. In: Kourilsky, R.; Grapin, P., editors. Main droite et main gauche cited in:. Paris: Presses Universitaires de France; 1968:83-100. Cited in: Geschwind, N.; Galaburda, A.M. Cerebral lateralization. Cambridge, Massachusetts: The MIT Press; 1987, p.226.
93. Greene, R. Interpretations of neurological signs in aviation medical examinations. In: Proceedings from 2nd Annual Postgraduate Course in Aviation Medicine. Wash DC: The George Washington University; 1941.
94. Greiner, J. R.; Fitzgerald, H. E.; Cooke, P. A. Bimanual hand writing in right-handed and left-handed stutterers and non-stutterers. Neuropsychologia. 24:441-447; 1986.

95. Grote, C.; Salmon, P. Spatial complexity and hand usage on the block design test. Percept Motor Skills. 62:59-67; 1986.
96. Gur, R. E.; Gur, R. C. Sex differences in the relations among handedness. Neuropsychologia. 15:585-590; 1977.
97. Gyurdzhian, A. A.; Fedoruk, A. G. The role of functional asymmetry of the central nervous system in pilot performance. Kosmicheskaya Biologiya I Aviakosmicheskaya Meditsina. :41-45; 1980. Translated from Russian.
98. Hahn, W. K. Cerebral lateralization of function: from infancy through childhood. Psychol Bull. 101:376-392; 1987.
99. Hamburger, V.; Oppenheim, R. W. Naturally occurring neuronal death in vertebrates. Neurosci Commentaries. 1:39-55; 1982.
100. Hannay, H. J. Real or imagined incomplete lateralization of function in females? Perception and Psychophysics. 19:349-352; 1976.
101. Harris, J. H. Left-handedness: early theories, facts, and fancies. In: Herron, J., editor. Neuropsychology of left-handedness. New York: Academic Press; 1980.
102. Harris, L. J. Which hand is the "eye" of the blind? In: Herron, J., editor. Neuropsychology of left-handedness. New York: Academic Press; 1980:322-326.
103. Harris, L. J.; Gitterman, S. J. University professors' self descriptions of left-right confusability: sex and handedness differences. Perceptual and Motor Skills. 47:819-823; 1978.
104. Healey, J. M.; Liederman, J.; Geschwind, N. Handedness is not a unidimensional trait. Cortex. 22:33-53; 1986.
105. Hecaen, H.; Ajuriaguerra, J. de. Left handedness: manual superiority and cerebral dominance. New York: Grune & Stratton; 1964.
106. Hellige, J. B.; Webster, R. Right hemisphere superiority for initial stages of letter processing. Neuropsychologia. 17:129-134; 1979.
107. Helm-Estabrooks, N.; Yeo, R.; Geschwind, N.; Freedman, M. Stuttering: disappearance and reappearance with acquired brain lesions. Neurology. 36:1109-1112; 1986.
108. Hermann, D. J.; Van Dyke, K. A. Handedness and the mental rotation of perceived patterns. Cortex. 14:521-529; 1978.
109. Hermelin, B.; O'Connor, N. Functional asymmetry in the reading of Braille. Neuropsychologia. 9:431-436; 1971.
110. Herron, J. Neuropsychology of left-handedness. Preface. New York: Academic Press; 1980.
111. Hicks, R. A.; Dusek, C.; Larsen, F.; Williams, S.; Pellegrini, R. J. Birth complications and the distribution of handedness. Cortex. 16:483-486; 1980.
112. Hicks, R. E.; Kinsbourne, M. Human handedness. In: Kinsbourne, M., editor. Asymmetrical function of the brain. London: Cambridge University Press; 1978:523-41.
113. Hicks, R. E.; Pellegrini, R. J. Handedness and locus of control. Perceptual and Motor Skills. 46:369-370; 1978.
114. Hier, D. B.; Le May, M.; Rosenberger, P. B.; Perlo, V. P. Developmental dyslexia: evidence for a sub group with a reversal of cerebral asymmetry. Arch Neurol. 35:90-92; 1978.

115. Holmes, G.; Horrax, G. Disturbances of spatial orientation and visual attention with loss of stereoscopic vision. Arch Neurol Psychiatr. 1:385-407; 1919.
116. Howard, J.; Petrakis, N. L.; Bross, I. D. Handedness and breast cancer laterality: testing a hypothesis. Human Biol. 54:365-371; 1982.
117. International Occupational Safety Health Information Centre. Human factors and safety. Information Sheet 15. Geneva: IOSHIC; 1965.
118. Jackson, J. H. case of large cerebral tumour without optic neuritis and with left hemiplegia and imperception. R Lond Ophthal Hosp Rep. In: Taylor, J., editor. Selected writings of John Hughlings Jackson. London: Hodder and Stoughton; 1876:146-152. Vol II.
119. Janetta, P. J. Microsurgical approach to the trigeminal nerve for tic douleureux. Prog Neurol Surg. 7:180-200; 1975.
120. Jennings, H. S. Behavior of the lower organisms. New York: Publisher unknown.; 1906. Cited in: Schaeffer, A. A. Spiral movement in man. J Morph. 45:293-398; 1928.
121. Johnson, P. R. Dichotically-stimulated ear differences in musicians and non-musicians. Cortex. 13:385-389; 1977.
122. Jones, D. R. Flying and danger, joy and fear. Aviat Space Environ Med. 57:131-136; 1986.
123. Jones, G. H.; Bell, J. Handedness in engineering and psychology students. Cortex. 16:521-525; 1980.
124. Jonsson, J. E.; Hellige, J. B. Lateralized effects of blurring: a test of the visual spatial frequency model of cerebral hemisphere asymmetry.. Neuropsychologia. 24:351-362; 1986.
125. Julesz, B. Foundations of cyclopean perception. Chicago: University of Chicago Press; 1971. Cited in: De Renzi, E. Disorders of space exploration and cognition. New York: J Wiley & Sons; 1982.
126. Junque, C.; Litvan, I.; Vendrell, P. Does reversed laterality really exist in dextrals? Neuropsychologia. 24:241-254; 1986.
127. Kee, D. W.; Morris, K.; Bathurst, K. Lateralized interference in finger tapping: comparisons of rate and variability measures under speed and consistency tapping instructions. Brain and Cognition. 5:268-279; 1986.
128. Kellar, L. A.; Bever, T. G. Hemispheric asymmetries in the perception of music as a function of musical experience and family handedness background. Brain and Language. 10:24-38; 1980.
129. Kempler, D.; Van Lancker, D. The right turn of phrase. Psychol Today. 21(4):20-22; 1987.
130. Kershner, J. R.; Jeng, A. G. Dual functional hemispheric asymmetry in visual perception: effects of ocular dominance and postexposural processes. Neuropsychologia. 10:437-445; 1972.
131. Kilshaw, D.; Annett, M. Right and left hand skill--I. effects of age, sex and hand preference showing superior skill in left handers. Br J Psychol. 74:253-268; 1983.

132. Kimura, D. Some effects of temporal lobe damage on auditory perception. Canadian J Psychol. 15:156-165; 1961a.
133. Kimura, D. Cerebral dominance and the perception of verbal stimuli. Canadian J Psychol. 15:166-171; 1961b.
134. Kimura, D. Dual functional asymmetry of the brain in visual perception. Neuropsychologia. 4:274-285; 1966.
135. Kimura, D.; Davidson, W.; McCormick, C. W. No impairment in sign language after right-hemisphere stroke. Brain and Language. 17:359; 1982.
136. Kinsbourne, M. Asymmetrical function of the brain. Cambridge, England: Cambridge University Press; 1978.
137. Kinsbourne, M.; Bruce, R. Shift in visual laterality within blocks of trials. Acta Psychologica. 66:139-155; 1987.
138. Kinsbourne, M.; Cook, J. Generalized and lateralized effects of concurrent verbalization on a unimanual skill. Quarterly J Exper Psych. 23:341-345; 1971.
139. Kolata, G. Math genius may have hormonal basis. Science. 222:1312; 1983.
140. Larrabee, A. P. The optic chiasm of teleosts: a study of inheritance. Proc Amer Acad Arts & Sciences. 12:217-231; 1906.
141. Lehman, D.; Julesz, B. Lateralized cortical potentials evoked in humans by dynamic random-dot stereograms. Vision Research. 18:1265-1271; 1978.
142. LeMay, M. Asymmetries of the skull and handedness. J Neurol Sci. 32:243-253; 1977.
143. LeMay, M.; Culebras, A. Human brain: morphologic differences in the hemispheres demonstrable by carotid arteriography. NEJM. 287:168-170; 1972.
144. LeMay, M.; Geschwind, N. Hemispheric differences in the brains of great apes. Brain Behav Evol. 11:48-52; 1975.
145. Levy, J. Possible basis for the evolution of lateral specialization of the human brain. Nature. 224:614-615; 1969.
146. Levy, J. Psychobiological implications of bilateral asymmetry. In: Dimond, S.; Beaumont, J. G., editors. Hemisphere function in the human brain. London: Paul Elek, Ltd.; 1974.
147. Levy, J. Handwriting posture and cerebral organization: how are they related? Psychol Bull. 91:589-608; 1982.
148. Levy, J.; Gur, R. C. Individual differences in psychoneurological organization. In: Herron, J., editor. Neuropsychology of left-handedness. New York: Academic Press; 1980.
149. Levy, J.; Reid, M. Variations in writing posture and cerebral localization. Science. 194:337-339; 1976.
150. Levy, J.; Trevarthan, C. Metacontrol of hemispheric function in human split-brain patients. J Exper Psychol: Human Perception and Performance. 2:299-312; 1976.
151. Levy-Agresti, J.; Sperry, R. Differential perceptual capacities in major and minor hemispheres. Proc Nat Acad Sci. 61:1151; 1968.
152. Lewis, G. W.; Rimland, B. Hemispheric asymmetry as related to pilot and radar intercept officer performance. San Diego, Calif: Navy Personnel Research and Development Center; 1979. NPRDC TR 79-13.

153. Li, X.; Li, X.; Go, H.; Wei, X. A study of hand preference in children. Info Psychol Sci. :1-7; 1984. [English abstract].
154. Liebowitz, H. W.; Dichgans, J. The ambient visual system and spatial orientation. In: AGARD-CP-287, Spatial disorientation in flight: current problems. Neuilly-sur-Seine, France: NATO/AGARD; 1980.
155. Lindesay, J. Laterality shift in homosexual men. Neuropsychologia. 25:965-969; 1987.
156. London, W. P. Handedness and alcoholism: a family history of left-handedness. Alcoholism: Clin Exper Res. 10:357; 1986.
157. Luria, A. R. On quasi-aphasic speech disturbances in lesions of the deep structures of the brain. Brain Lang. 4:432-459; 1977.
158. Luria, S. M.; McKay, C. L.; Ferris, S. H. Handedness and adaptation to distortions of size and distance underwater. Report #724. Groton, Conn: Naval Submarine Medical Research Laboratory; 1972. RWU M4306.03-2050.
159. Madan, M. L. Comparison of performance on a tracking task utilizing binocular, dominant and non-dominant viewing. [Master's Thesis]. Monterey, CA: Naval Postgraduate School; 1980. AD-A084 905.
160. Magee, J. G. Jr. High Flight. [poem].
161. Manelis, N. G.; Grebennikova, N. V. Laterality differences in visual perception. [translation]. Human Physiology. 10:347-351; 1984.
162. Manga, D.; Ballesteros, S. Visual hemispheric asymmetry and right-left confusion, Percept Motor Skills. 64:915-921; 1987.
163. Marchant, L. F.; Stekhs, H. D. Hand preference in a captive island group of chimpanzees (Pan troglodytes). Am J Primatology. 10:301-313; 1986.
164. Marrion, L. V. Writing hand differences in Kwakiutls and Caucasians. Percept Motor Skills. 62:760-762; 1986.
165. Marsh, G. R. Individual differences in brain laterality. (USAFSAM Research in Biotechnology Contract F33615-82-D-0627). Brooks AFB TX: Southeastern Center for Electrical Engineering Education; 1984.
166. Marsh, G. R. Lateralization of verbal, spatial and orientation abilities and their measurement with event-related potentials. Brooks Air Force Base, Texas: USAF School of Aerospace Medicine; 1986. Research in Biotechnology Contract F33615-83-D-0601-0008.
167. Marshall, J. C. Signs of language in the brain. Nature. 322:307-308; 1986.
168. Martin, M. Hemispheric specialization for local and global processing. Neuropsychologia. 17:33-40; 1979.
169. Mascie-Taylor, C. G. Hand preference and personality traits. Cortex. 17:319-322; 1981.
170. McClellan, J. M. Pilot, superpilot. Flying. March:50-53; 1988.
171. McKeever, W. F. The influences of handedness, sex, familial sinistrality and androgyny on language laterality, verbal ability, and spatial ability. Cortex. 22:521-537; 1986.

172. McKeever, W. F.; Larrabee, G. J.; Sullivan, K. F.; Johnson, H. J. Unimanual tactile anomia consequent to corpus callosotomy: reduction of anomic deficit under hypnosis. Neuropsychologia. 19:179-190; 1981.
173. McKeever, W. F.; Van Deventer, A. D.; Suberi, M. Avowed assessed and familial handedness and differential hemispheric processing of brief sequential and non-sequential visual stimuli. Neuropsychologia. 11:235-238; 1973.
174. McLean, J. M.; Ciurczak, F. M. Bimanual dexterity in major league baseball players: a statistical study. NEJM. 2:1278-1279; 1982.
175. McManus, I. C. Handedness, language dominance and aphasia: a genetic model. Psychological Medicine. ; 1985. Monograph Supplement 8.
176. McMullen, P. A.; Bryden, M. P. The effects of word imageability and frequency on hemispheric asymmetry in lexical decisions. Brain and Language. 31:11-25; 1987.
177. Mehta, Z.; Newcombe, F.; Damasio, H. A left hemisphere contribution to visuospatial processing. Cortex. 23:447-461; 1987.
178. Merrell, D. J. Dominance of eye and hand. Human Biol. 23:314-328; 1957.
179. Metzger, R. L.; Antes, J. R. Sex and coding strategy effects on reaction time to hemispheric probes. Memory and Cognition. 4:167-171; 1976.
180. Meyers, M.; Smith, B. D. Hemispheric asymmetry and emotion: effects of nonverbal affective stimuli. Biol Psychol. 22:11-22; 1986.
181. Michel, G. F.; Harkins, D. A. Postural and lateral asymmetry in ontogeny of handedness during infancy. Develop Psychobiol. 19:247-258; 1986.
182. Millar, S. The perceptual "window" in two-handed braille: do the left and right hands process text simultaneously? Cortex. 23:111-122; 1987.
183. Miller, E. Handedness and the pattern of human ability. Br J Psychol. 62:111-112; 1971.
184. Miller, L. The emotional brain. Psychol Today. Feb(2):34-42; 1988.
185. Miller, N. R. Walsh and Hoyt's clinical neuro-ophthalmology. 4th ed. Baltimore: Williams & Wilkins; 1982.
186. Miller, R. W. Western horse behavior and training. Garden City, NJ: Doubleday & Company, Inc.; 1975.
187. Moscovitch, M. Information processing and the cerebral hemispheres. In: Gazzaniga, M. S., editor. Handbook of behavioral neurobiology. Vol. 2. New York: Plenum Press; 1979:379-446. Cited in: Marsh G. Individual differences in brain laterality. USAFSAM Contract F33615-82-D-0627. 1984. SE Center for Electrical Engineering Education.
188. Moscovitch, M.; Smith, L. C. Differences in neural organization between individuals with inverted and non-inverted handwriting postures. Science. 205:710-712; 1979.
189. Nachson, I.; Denno, D. Birth order and lateral preferences. Cortex. 22:567-578; 1986.

190. Nagae, S. Handedness and sex differences in the processing manner of verbal and spatial information. Am J Psychol. 98:409-420; 1985.
191. Narang, H. K. Right-left asymmetry in myelin development in epiretinal portion of the rabbit optic nerve. Nature. 266:28-29; 1977.
192. Nebes, R. D. Hemispheric specialization in commissurotomized man. Psychol Bull. 81:1-14; 1974.
193. Nottebohm, F. Brain pathways for vocal learning in birds: a review of the first 10 years. Prog Psychobiol Physiol Psychol. 9:85-124; 1980.
194. O'Neil, C.; Stratton, H. T.; Ingersoll, R. H.; Fouts, R. S. Conjugate lateral eye movements in Pan Troglodytes. Neuropsychologia. 11:343-350; 1978.
195. Oldfield, R. C. The assessment and analysis of handedness: the Edinburgh inventory. Neuropsychologia. 9:97-113; 1971.
196. Olson, G. M.; Laxar, K. Speed of comprehending submarine fire control displays: III processing information about "right" and "left"-- a note on left-handers. Groton, CN: Naval Submarine Medical Research Laboratory; 1973. AD-775-685.
197. Ornstein. R. E. The psychology of consciousness. 2d ed. New York: Harcourt Brace Jovanovich; 1977. Cited in: Marsh, G. R. Individual differences in brain laterality. USAFSAM Research Contract F33615-82-D-0627. 1984. SE Center for E. E. Education.
198. Orton, S. T. "Word-blindness" in school children. Arch Neurol Psychiat. 14:581-615; 1925.
199. Oscar-Berman, M.; Rehbein, L.; Porfert, A.; Goodglass, H. Dichaptic hand-order effects with verbal and non-verbal tactile stimulation. Brain and Language. 6:323-333; 1978.
200. Papcun, G.; Krashen, S.; Terbeek, D.; Remington, R.; Harshman, R. Is the left hemisphere specialized for speech, language and/or something else? J Acoust Soc Am. 55:319-328; 1974.
201. Parlow, S. Differential finger movements and hand preference. Cortex. 14:608-611; 1978.
202. Passey, G. E.; McLaurin, W. A. Perceptual-psychomotor tests in aircrew selection: historical review and advanced concepts. Lackland Air Force Base, Texas: Personnel Research Laboratory, USAF Systems Command; 1966. PRL-TR-66-4.
203. Pendse, S. G. Hemispheric asymmetry in olfaction on a category judgement task. Percept Motor Skills. 64:494-498; 1987.
204. Penfield, W.; Jasper, H. Epilepsy and the functional anatomy of the human brain. Boston: Little, Brown and Co; 1954.
205. Peters, M. A nontrivial motor difference between right-handers and left-handers: attention as intervening variable in the expression of handedness. Canad J Psychol. 41:91-99; 1987.
206. Peters, M.; McGrory, J. The writing performance of inverted and noninverted right- and left-handers. Canad J Psychol. 41:20-32; 1987.
207. Peters, M.; Petrie, B. F. Functional asymmetries in the stepping reflex of the human neonate. Canad J Psychol. 33:198-200; 1979.

208. Peterson, J. M. Left-handedness: differences between student artists and scientists. Percept Mot Skills. 48:961-962; 1979.
209. Peterson, J. M.; Lansky, L. M. Left-handedness among architects: some facts and speculation. Percept Mot Skills. 50:547-550; 1974.
210. Peterson, J. M.; Lansky, L. M. Left handedness among architects: partial replication and some new data. Percept Mot Skills. 45:1216-1218; 1977.
211. Peyton, G. Fifty years of aerospace medicine. AFSC Historical Publications. Series No. 67-180. Washington DC: Government Printing Office; 1967.
212. Phillips, R. E.; Youngren, O. M. Unilateral kainic acid lesions reveal dominance of right archistriatum in avian fear behavior. Brain Res. 377:216-220; 1986.
213. Pitblado, C. Visual field differences in perception of the vertical with and without a visible frame of reference. Neuropsychologia. 17:381-392; 1979.
214. Pizzamiglio, L.; De Pascalis, C.; Vignati, A. Stability of dichotic listening test. Cortex. 10:203-205; 1974.
215. Plato, C. C.; Fox, F. M.; Garruto, R. M. Measures of lateral functional dominance: foot preference, eye preference, digital interlocking, arm falling, and foot overlapping. Human Biol. 57:327-334; 1985.
216. Porac, C.; Coren, S.; Searleman, A. Environmental factors in hand preference formation: evidence from attempts to switch the preferred hand. Behav Genet. 16:251-261; 1986.
217. Provins, D. A.; Dalziel, F. R.; Higginbottom, G. Asymmetrical hand usage in infancy: an ethological approach. Infant Behav Dev. 10:165-172; 1987.
218. Rasmussen, T.; Milner, B. Clinical and surgical studies of the cerebral speech areas in man. In: Zulch, K. J.; Creutzfield, O.; Galbraith, G. C., editors. Cerebral Location. New York: Springer Verlag; 1975:238-235.
219. Rayman, R. B. Aircrew health care maintenance. In: Dehart, R. L., editor. Fundamentals of aerospace medicine. Philadelphia: Lea & Febiger; 1985:403-420.
220. Reijs, J. H. On the variation of strength with movement. [translation]. Archiv fur die Gesamte Physiologie. 191:234-257; 1921. NASA TT F-9339.
221. Reiter, H. H. Personality correlates of left-handedness. Mankind Quarterly. 26:271-275; 1986.
222. Richardson, S. A.; Donald, K. M.; O'Malley, K. M. Right brain approaches to counseling: tapping your "feminine" side. Women Ther. 4(4):9-21; 1985-86.
223. Rosenstein, L. D.; Bigler, E. D. No relationship between handedness and sexual preference. Psychol Rep. 60:704-706; 1987.
224. Rossi, B.; Zuni, A. Differences in hemispheric functional asymmetry between athletes and nonathletes: evidence from a uni-lateral tactile matching task. Percept Motor Skills. 62:295-300; 1986.

225. Rossi, G. F.; Rosadini, G. Experimental analysis of cerebral dominance in man. In: Millikan, C. H.; Darley, F. L., editors. Brain mechanisms underlying speech and language. New York: Grune & Stratton; 1967:167-184.
226. Roze, N. A. Psychomotor activity of the adult man. [in Russian]. Leningrad: USSR; 1970.
227. Sacks, O. The man who mistook his wife for a hat and other clinical tales. New York: Harper & Row; 1987.
228. Salmaso, D.; Longoni, A. M. Problems in the assessment of hand preference. Cortex. 21:533-549; 1985.
229. Satz, P. Laterality tests: an inferential problem. Cortex. 13:208-212; 1977.
230. Satz, P.; Fletcher, J. M. Left-handedness and dyslexia: an old myth revisited. J Ped Psychol. 12:291-298; 1987.
231. Schaeffer, A. A. Spiral movement in man. J Morphol and Physiol. 45:293-398; 1928.
232. Schaller, G. B. The mountain gorilla. Chicago: Chicago University Press; 1963. Cited in: Beaton, A. Left side, right side: a review of laterality research. New Haven: Yale University Press; 1985.
233. Schleifer, S. J.; Shapiro, R. M. "Brain neocortex lateralized control of immune recognition": commentary. Integ Psych: 4:36-38; 1986.
234. Schlichting, C. L.; Kindness, S. W. The relationship of visual evoked potential asymmetries to the performance of sonar operators. Report #957. Groton, Conn: Naval Submarine Medical Research Laboratory; 1981. AD A104116.
235. Seltzer, B.; Sherwin, I. A comparison of clinical features in early- and late-onset primary degenerative dementia. Arch Neurol. 40:143-46; 1983.
236. Sergent, J. Role of the input in visual hemisphere asymmetries. Psychol Bull. 93:481-512; 1983.
237. Sergent, J. A new look at the human split brain. Brain. 110:1375-1392; 1987.
238. Shanon, B. Writing positions in Americans and Israelis. Neuropsychologia. 16:587-591; 1978.
239. Shanon, B. Graphological patterns as a function of handedness and culture. Neuropsychologia. 16:587-591; 1979.
240. Sheeran, T. J. Effect of pure and crossed dextrality on marksmanship skill. Percept Motor Skills. 61:1171-1174; 1985.
241. Silberman, E. K.; Weingartner, H. Hemispheric lateralization of functions related to emotion. Brain and Cognition. 5:322-353; 1986.
242. Silva, D. A.; Satz, P. Pathological left-handedness: evaluation of a model. Brain and Language. 7:8-16; 1979.
243. Silverberg, R.; Obler, L. K.; Gordon, H. W. Handedness in Israel. Neuropsychologia. 17:83-88; 1979.
244. Simon, J. R.; DeCrow, T. W.; Lincoln, R. S.; Smith, K. U. Effects of handedness on tracking accuracy. Percept Motor Skills Res Exchange. 4:53-57; 1952.
245. Smith, A.; Sugar, O. Development of above normal language and intelligence 21 years after left hemispherectomy. Neurology. 25:813-818; 1975.

246. Smith, E. C. Cultural differences and academic achievement. Pointer. 30:28-31; 1986.
247. Smith, J. Left-handedness: its association with allergic disease. Neuropsychologia. 25:665-674; 1987.
248. Sperry, R. W.; Zaidel, E.; Zaidel, D. Self recognition and awareness in the deconnected minor hemisphere. Neuropsychologia. 17:153-166; 1979.
249. Strauss, E.; Goldsmith, S. M. Lateral preferences and performance on non-verbal laterality tests in a normal population. Cortex. 23:495-503; 1987.
250. Strub, R. L.; Black, F. W.; Naeser, M. A. Anomalous dominance in sibling stutterers: evidence from CT scan asymmetries, dichotic listening, neuropsychological testing, and handedness. Brain and Language. 30:338-350; 1987.
251. Suddon, F. H.; Link, J. D. Handedness, body orientation, and performance on a complex perceptual-motor task. Percept Motor Skills. 9:165-166; 1959.
252. Sussman, H. M. The laterality effect in lingual-auditory tracking. J Acoust Soc Am. 49:1874-1880; 1971.
253. Tan, U. Paw preference in dogs. Intern J Neuroscience. 32:825-829; 1987.
254. Teng, E. L.; Lee, P. H.; Yang, K. S. Handedness in a Chinese population. Science. 193:1148-1150; 1976.
255. Thomas, D. G.; Campos, J. J. The relationship of handedness to a lateralized task. Neuropsychologia. 16:511-517; 1978.
256. Tipton, D. A.; Mohler, S. R. The Wright brothers: a personality profile. Aviat Space Environ Med. 54:560-62; 1983.
257. Tisserand, M. Dominance laterale et bec-de-lievre. Arch francaises Pediatrie. II:166-167; 1944. Cited in: Geschwind,N.; Galaburda,A.M. Cerebral lateralization: biological mechanisms, associations, and pathology. Cambridge, Mass: MIT Press.
258. Trevarthen, C.; Sperry, R. W. Perceptual unity of the ambient visual field in human commussurotomy patients. Brain. 96:547-570; 1973.
259. Trevarthen, C. B. Analysis of cerebral activities that generate and regulate consciousness in commissurotomy patients. In: Dimond, S. J.; Beaumond, J. G., editors. Hemisphere function in the human brain. New York: Wiley; 1974.
260. Van den Hooff, A. Reflections of Pascal's two types of esprit in the light of certain current insights into brain physiology. Perspect Biol Med. 29:164-167; 1985.
261. Van Wagenen, W. P.; Herren, R. Y. Surgical division of commissural pathways in the corpus callosum: relation to spread of an epileptic attack. Arch Neur Psych. 44:740; 1940.
262. Wada, J. A.; Clarke, R.; Hamm, A. Cerebral hemispheric asymmetry in humans. Arch Neurol. 32:239-246; 1975.
263. Wapner, W.; Hamby, S.; Gardner, H. The role of the right hemisphere in the apprehension of complex linguistic materials. Brain and Language. 14:15-33; 1981.
264. War Department. Physical examination for flying. In: Aviation medicine in the AEF. Washington DC: Government Printing Office; 1920:312-14.

265. War Department. Notes on psychology and personality studies in aviation medicine. Washington DC: US Army Medical Department; 1941. TM 8-320. p272-273.
266. Webster, W. G.; Poulos, M. Handedness distributions among adults who stutter. Cortex. 23:705-708; 1987.
267. Wickens, C. D.; Mountford, S. J.; Schreiner, W. Multiple resources, task-hemispheric integrity, and individual differences in time-sharing. Human Factors. 23:211-229; 1981.
268. William, J.; Phyllis, A. Left-handedness and immune disorders in familial dyslexia. Arch Neurol. 44:634-639; 1987.
269. Williams, S. M. Factor analysis of the Edinburgh handedness inventory. Cortex. 22:325-326; 1986.
270. Wilson, R. V. The effect of handedness on a tracking task. [Tech. rept.]. Farnborough, England: Royal Aircraft Establishment; 1972. AD- 753 785 RN RAE-TR-72117.
271. Witelson, S. F. Hemispheric specialization for linguistic and non-linguistic tactual perception using a dichotomous stimulation technique. Cortex. 10:3-17; 1974.
272. Witelson, S. F. Neuroanatomical asymmetry in left-handers: a review. In: Herron, J., editor. Neuropsychology of left-handedness. New York: Academic Press; 1980:80-81.
273. Wolf, S. M. Difficulties in right-left discrimination in a normal population. Arch Neurol. 29:128-129; 1973.
274. Yegorov, V. A.; Shirogorov, V. K. Change in asymmetry of some paired functions in airmen under the influence of flight factors. Kosmicheskaya Biologiya I Aviakosmicheskaya Meditsina. 9(3):60-64; 1975. Translated from Russian.
275. Yegorov, V. A.; Shirogorov, V. K. Changes in motor symmetry in air pilots as a function of in-flight activity. [Abstract]. Voprosy Psikhologii. :129-132; 1976. Translated from Russian.
276. Zaidel, E. A response to Gazzaniga: language in the right hemisphere, convergent perspectives. Am Psychologist. 38:542-546; 1983a.
277. Zaidel, E. Disconnection syndrome as a model for laterality effects in the normal brain. In: Hellige, J. B., editor. Cerebral hemisphere asymmetry: method, theory, and application. New York: Praeger Publishers; 1983b:95-151. Cited in: Marsh, G. Individual differences in brain laterality. USAFSAM Contract F33615-82-D-0627. 1984. SE Center for Electrical Engineering Education.
278. Zangwill, O. L. Cerebral dominance and its relation to psychological function. Edinburgh: Oliver and Boyd; 1960.
279. Zavala, A.; Locke, E. A.; Van Cott, H. P.; Fleishman, E. A. The analysis of helicopter flight performance. OSC Contract No. DA-49-193-MD 2632. Washington DC: American Institutes for Research; 1965. AIR-E-29-6/65-TR.
280. Zimmerberg, B.; Strumpf. A. J.; Glick, S. J. Cerebral asymmetry and left-right discrimination. Brain Res. 140:194-196; 1978.