Left-Handedness

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The phenomenon of left-handedness is reviewed from prehistoric man through contemporary studies of lateralization of cerebral function. The following conclusions seem warranted: Handedness is most appropriately regarded as a continuum ranging from strong right-handedness across mixed-handedness to strong left-handedness. Left-handedness, ranging from moderate through strongly left-handed, is found in approximately 10% of the population. Evidence for a genetic basis of handedness remains positive, but with no direct link established. There is remarkably little evidence for any association of left-handedness with deficit, as has often been suggested. The familial left-handed show greater recovery of functioning following unilateral cerebral insult than do nonfamilial right-handed and nonfamilial left-handed. Both behavioral and clinical lesion studies indicate systematic differences in lateralization of cerebral function between the right- and left-handed and the familial and nonfamilial left-handed. A classification of handedness and lateralization of cerebral function is suggested, with the right-handed with no family history of left-handedness being the most strongly lateralized and the left-handed with a positive family history of left-handedness showing bilateral localization of functions. The left-handed with no family history of left-handedness are classified as identical in cerebral lateralization with the right-handed with no family history of left-handedness. The possibilities exist that bilaterality of cerebral functioning is either stable in the human race or is changing at an extremely slow rate.

In the Old Testament, in the Book of Psalms (Joint Committee on the New Translation of the Bible, 1970), the statement is made that the Lord’s “right hand is full of righteousness” (48:10); in the Book of Isaiah, that his “right hand shall spread out the heavens” (48:13); and again in Psalms, that his “right hand shall hold me” (139:10).

The Old Testament provides no specific information as to what is contained in the Lord’s left hand, what part, if any, it played in the creation of the heavens, and who is held in the left hand. However, in the New Testament, the Book of Matthew (Joint Committee, 1970) provides some fairly specific information on the fate of those individuals at the left hand:

When the Son of Man comes in his glory and all the angels with him, he will sit in state on his throne, with all the nations gathered before him. He will separate men into two groups, as a shepherd separates the sheep from the goats and he will place the sheep on his right hand and the goats on his left. Then the king will say to those on his right hand, “You have my father’s blessing; come enter and possess the kingdom that has been ready for you since the world was made.” . . . Then he will say to those on his left hand, “The curse is upon you; go from my sight.
to the eternal fire that is ready for the devil and his angels." (Matthew, 25)

The above quotations, selected from the 80 Biblical references to the right hand, are not atypical; honors, virtues, and powers are all ascribed to the right hand. By contrast, as Wile (1934, p. 340) notes, "there is not one honorable reference to the left hand."

Even if the picturesque language is ignored, evidence seems convincing that in Biblical times, negative qualities were attributed to the left hand. By implication, those individuals who carry out a variety of actions using the left hand are different and probably suspect. However, the outlook is not limited to antiquity. Among the contemporary ideological descendants of the Biblical scribe who, along with their ancestor, would be eager to consign the left-handed to burn in hell forever, would be found a good many neurologists, neurosurgeons, and neuropsychologists, sharing among themselves the frustrations of seeing their theories of cerebral function unable to account for the bilateral cerebral organization found in many of the left-handed. Their frustrations have been aptly characterized by Subirana (1969):

If the difference between the left and right hemispheres were to stick to an exact pattern in human beings, it would have been relatively easy for the investigators who from the second half of the last century have worked unceasingly on the matter to find out the relative functions of each hemisphere; but not all people have a right hand preference and a dominant left hemisphere for language function, since left-handers are not included in this pattern and seem to have been created on purpose to upset all the different conceptions which have prevailed during the last century in connection with the pathology and physiology of the two hemispheres. (p. 248)

Reaction to the problems of explanation posed by the left-handed has followed two courses. Perhaps the most common approach has been to assume that left-handedness is a signal that something is wrong—that the left-handed represent an aberrancy or abnormality and can thus be excluded from consideration in theories of normal cerebral functioning. Certainly the search for deficit associated with left-handedness has been both extensive and unceasing. Attempts have been made to link left-handedness with mental deficiency, dyslexia, speech disturbances, birth defects, emotional instability, motor awkwardness, and alcoholism, to provide only a partial list. A variant of this position has been the suggestion that the left-handed represent an evolutionary retrogression (Levy, 1969; Miller, 1971; Nebes, 1971)—a phylogenetic step backward.

A second approach has been to disregard the left-handed, usually by ignoring the observed differences in cerebral organization or by assuming that they are the simple mirror images of the right-handed. Broca, in 1861, seems to have been the first to suggest the mirror image hypothesis, only to have case reports appear almost immediately that prevented his formulation from being considered absolute. However, belief that the left-handed are mirror images of the right-handed survived in the clinical neurological literature until at least 1936 and still has adherents today (Sperry, 1973).

Those who disregard the left-handed usually describe the characteristic form of cerebral organization for the right-handed, noting briefly in the process that there are some exceptions, such as the left-handed. A contemporary example has been given in Ornstein's (1972, 1973) writings on the psychology of consciousness. In two volumes on the subject of consciousness, including a discussion of the nature of functions performed by the right and left cerebral hemispheres, the delineation of function is represented as being straightforward, with the left hemisphere specialized for "analysis" and the right hemisphere specialized for "holistic mentation." In the course of this discussion is the following footnote: "This right–left specialization is based on righthanders. Left-handers, who are about 5 percent of the population, are less consistent; some have reversed specialization of the hemispheres, but some have mixed specialization—e.g., language in both sides" (p. 53). This "5 percent" is not mentioned again in the discussion of consciousness and cerebral specialization—a procedure that is not as extreme as consigning the left-handed to hell, but does seem to leave them, at least, in purgatory.

Formulations on the relation of handedness to magic, religion, and cultural symbolism can be found in the collection edited by
Needham (1973). In general, scientific outlooks on left-handedness are consistent with philosophical formulations.

Faced with what is essentially a harmonious outlook in scientific thought and in philosophical speculation, some justification should be offered for considering the left-handed, whatever percentage of the population they may be, as a problem worthy of detailed study.

1. The evidence for the association of left-handedness and deficit is based largely on accumulated clinical impressions rather than on systematic study. It seems appropriate to review this evidence and the conclusions that have been drawn from it.

2. The left-handed of high ability are usually conveniently forgotten in discussions of handedness and deficit. Among notable examples of left-handed individuals of high ability are Michelangelo, Leonardo da Vinci, Benjamin Franklin, and Pablo Picasso. A recent evaluation of characteristics common to left-handed children (T. H. Blau, Note 1) reported that left-handed children may be more creative than their right-handed counterparts, although the evidence is only suggestive.

3. Much has been made of the deficit of the left-handed in certain types of cognitive tasks, such as spatial ability (Levy, 1969; Miller, 1971; Nebes, 1971), where the evidence is based on small and highly selected samples. Attempts to replicate these findings (Fagan-Dubin, 1974; Hardyck, in press-a; Hardyck, Petrinovich, & Goldman, 1976; Kutas, McCarthy, & Donchin, 1975; Newcombe & Ratcliff, 1973) have not been successful.

4. The strengths specific to the left-handed have not, in general, been included in any overall evaluation. Extensive analyses of patterns of recovery from the effects of cerebral lesions indicate that the left-handed recover functions more quickly and show fewer long-term effects of brain lesions than do the right-handed. Such effects are not limited to the phenotypically left-handed. As Subirana (1969) has pointed out, "The cases seen in last years authorize me to write that the aphasics with a left-handed sibling are nearly always the champions of the language rehabilitation division" (p. 268).

5. The left-handed have frequently been categorized as a group requiring special education or presenting special educational problems, these opinions again being based primarily on accumulated clinical impressions.

These considerations persuaded us, following an examination of handedness and its relationship to intellectual functioning in 7,686 school children (Hardyck, Petrinovich, & Goldman, 1976), to review in detail the problem of handedness and its relationship to intellectual functioning and cerebral dominance.

The Ontogeny of Handedness

Theories of the causation of handedness are plentiful, although the majority of early suggestions can be dismissed on the basis of known anatomical evidence. The evidence favors a genetic basis, but existing genetic models are all limited by the fact that data on the incidence of handedness are extremely variable.

Psychological-Social (Nongenetic) Theories

Explanations for the preference habits of man are so extensive that any detailed account is impractical. Extensive reviews of social and psychological theories of handedness were given by Jackson (1905), Wile (1934), and A. Blau (1946). Jackson's approach is illustrative of the purely social outlook. He argued that handedness was entirely a matter of habit and that all children should be taught to use either hand interchangeably. A. Blau (1946), using a psychoanalytic framework, argued that left-handedness is a result of emotional negativism and has no biological basis whatever, a point of view also advocated by Domhoff (1969–1970) and Thass-Thienemann (1955), who focused on the negative qualities associated with the term left.

A variety of social evolution explanations have been suggested, perhaps the most common one being the "sword and shield" theory. This explanation, attributed to Thomas Carlyle, among others, has had numerous advocates (Gould, 1908; Harman, 1905; Pye-Smith, 1871; Woodruff, 1909). The basic argument is that the soldier who held his shield in his left hand offered his heart better
protection and thus had a better chance of survival. By the same process, the right hand grew more skilled in manipulative movement and eventually came to be used for all skilled manipulative activities.\(^1\)

**Anatomical Theories**

Organ asymmetry has often been suggested as an explanation for handedness. Aristotle (1941) believed that the organs for the right side of the body were more powerful than those for the left. Sir Francis Bacon (1875) was more specific in his formulations, offering the opinion that the liver being located predominantly on the right side was the basis for handedness.

It is difficult to identify origins of the idea that the two sides of the brain might differ and be related to handedness. The idea that one side of the brain had a direct relationship to the opposite side of the body seems to have originated at least during the first century A.D., according to Gianntrapani (1969). In 1871, Ogle gave an account of his investigations, including detailed descriptions of an independent investigator's assessment of the differences present in the brains of two left-handed women as compared with the brains of right-handed individuals, stating that many features appeared to be reversed. Heschl, in 1878, provided a detailed description of organic asymmetry.

Contemporary opinion on the topic is divided. Von Bonin's (1962) detailed review of anatomical differences led him to conclude that any observable differences are so insignificant as to be totally inadequate to account for any differences in specialization of function. Geschwind and Levitsky (1968), in an analysis of 100 brains, reported that the area behind Heschl's gyrus was larger on the left in 65% of the brains examined and larger on the right in 11%. Unfortunately, neither von Bonin nor Geschwind and Levitsky had handedness data to accompany their investigations.

A variant on the idea of brain differences is the proposal that the left side of the brain is better vascularized. Gratiolet (1839–1857) suggested that the left side of the brain had a more rapid flow of blood, based on the claim that the left carotid artery, arising directly from the aorta, had a faster blood flow than did the right carotid artery, being separated from the aorta by the innominate artery. This position was developed and elaborated by Hyrtl (1871). In general, these positions were discredited by advances in anatomical knowledge, particularly when it was shown that the circle of Willis provides for the equalization of blood supply to both hemispheres.

In this context, a more recent study by Di Chiro (1962) is of interest. He took angiograms of predominant venous drainage on 46 patients, noting reported handedness and determining localization of speech by means of Wada and Rasmussen's (1960) technique of injecting sodium amytal into the carotid arteries. Our recalculation of his data, removing ambiguous cases of handedness, indicates that the relationship between handedness and predominant venous drainage is within the limits expected by chance.

**Genetic Theories**

There have been many attempts to develop genetic models for handedness (Annett, 1964, 1967, 1972, 1973a, 1973b, 1974, 1975; Bradbury, 1912; Chamberlain, 1928; Falek, 1959; Hudson, 1975; Jordan, 1911, 1914; Levy & Nagylaki, 1972; Newman, 1931; Ramaley, 1912, 1913; Rife, 1940, 1950; Schott, 1931; Trankell, 1950, 1955), but not a great deal

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\(^1\) The problem common to all social evolutionary explanations is that disproof is impossible. The "sword and shield" theory should, to be comprehensive, offer some explanation as to why women, who did not usually carry swords and shields, have an even lower incidence of left-handedness than do men. To illustrate the ease with which such explanations can be constructed, we may take the data of Salk (1966), showing that women tend to hold neonates with the left arm, whether right- or left-handed. Salk suggests that this places the neonate in closer contact with the mother's heartbeat and results in a greater feeling of security for the infant. As a social evolution explanation for handedness, it will work just as well as the sword and shield theory. In fact, since it seems safe to postulate that more women have held more infants than men have held shields and swords, it is even possible to "explain" the lower incidence of left-handedness in women.
of success. The majority of views argue that left-handedness is carried as a Mendelian recessive, but the data base for these arguments is far from adequate. Trankell (1950) collected data on all seventh-grade children and their parents in the city schools of Stockholm, allowing him to standardize his measures on 800 children and to test over 800 more. However, his incidence data from parents were collected by questionnaire, and the unreliability of such data collection for handedness has been shown in several studies (Benton, Meyers, & Polder, 1962; Satz, Achenbach, & Fennell, 1967). Falek's (1959) study, which used interviews and behavioral testing to determine incidence and preference, produced an inconclusive result, possibly by discarding those individuals who had no strong hand preference. Findings from both lesion (Hécaen & Saquet, 1971) and behavioral studies (Dee, 1971) suggest that those individuals who have a family history of left-handedness are also less likely to be strongly left-handed. Falek, by attempting to select clearly defined groups, may have discarded the genetically meaningful portion of his data. The ambiguity of many data in this area has been pointed out by Fuller (1960), who noted that the same data have been used to support and to disprove genetic theories.

The most recent attempts to develop genetic models of handedness have been those of Annett (1964, 1967, 1972, 1973a, 1973b, 1974, 1975) and Levy and Nagylaki (1972). The Annett model argues that handedness is distributed binomially as left, mixed, and right, in the proportions .04, .30, and .66, respectively, and is due to the presence or absence of a Right Shift factor. In Annett's model, the presence of this factor will produce both a localization of speech in the left cerebral hemisphere and a bias toward right-handedness. Annett has reported a series of studies in support of this model. However, her model is dependent on the acceptance of the conditions she has developed. The model does not seem to fit the data of Hécaen and Saquet (1971) on either strength of handedness or on bilateral speech representation in many left-handed. In her most recent account (1975) Annett reviewed a number of lesion studies with respect to her model, arguing that three of the studies (Bingley, 1958; Newcombe & Ratchiff, 1973; Penfield & Roberts, 1959) were in accord with the results of her genetic model. Unfortunately, the studies of Conrad (cited in Zangwill, 1967) and Hécaen and de Aju-riguerra (1964) show significant discrepancies. Annett also failed to include in her analysis the extensive study done by Hécaen and Saquet (1971). Since Hécaen and Saquet took great care to evaluate both preferred handedness and family history of handedness, this omission is not easily dismissed. Also, Annett's model requires a lateralization of speech to either the left or the right hemisphere, which requires dismissing the considerable body of both lesion (Branch, Milner, & Rasmussen, 1964; Hécaen & Saquet, 1971; Wada & Rasmussen, 1960) and behavioral (Lomas & Kimura, 1976) evidence for bilateral speech representation in many left-handed.

The two-gene, four-allele model presented by Levy and Nagylaki (1972) is undoubtedly the most detailed and comprehensive of the genetic models. However, it has recently been critically evaluated by Hudson (1975) who argued that the model is unable to account for observed distributions of handedness in three sets of data.

The Levy-Nagylaki model does attempt to account for bilateralization of function, but argues that only half the population of familial left-handed should show bilaterality. In view of the large number of studies reporting that interhemispheric differences are less pronounced in the left-handed than in the right-handed (see Handedness and Cerebral Dominance, this review), this aspect of the model seems suspect.

Perhaps the principal proponent of a non-genetic explanation is Collins (1968, 1969, 1970, 1975), who has argued that handedness can be accounted for without any recourse to genetic considerations, a position strongly contested by proponents of genetic models (Nagylaki & Levy, 1973).

In summarizing this area, the most appropriate conclusion seems to be that a genetic model is a more probable explanation. Such a conclusion has to be based more on the cumulative body of data on the left-handed than on the strictly genetic evidence. The most compelling evidence is the systematic
behavioral differences in hemispheric specialization that have been reported on the left-handed. A final comment on the evidence for a genetic base is reserved until behavioral and lesion studies are reviewed.

Developmental Status

Evidence on developmental patterns of hand preferences has largely been accumulated through the study of individual children (Baldwin, 1895; G. V. N. Dearborn, 1913; Fenton, 1925; Gesell & Ames, 1947; Giesecke, 1936; Halverson, 1931; Heinlein, 1930; Lippman, 1927; Major, 1906; Seth, 1973; Shin, 1914; Updegraff, 1932; Voelkel, 1913; Wooley, 1910). Giesecke's (1936) study of infants ranging in age from 5 days to 17 months can serve as an illustration of this class of studies. She observed the manipulative activities of her subjects, combining this with the presentation to the infant of brightly colored objects, such as blocks, in a medial plane and alternatively to the right and left sides. In four subjects, ranging in age from 7 to 14 months, she found three subjects to carry out a predominance of activities with the right hand and one with the left.

Some interesting neurophysiological relationships are suggested by the work of Cernacek and Podivinsky (1971), who studied evoked cortical potentials in response to mild electrical shock administered to right and left hands in infants and children. They found evoked cortical potential in the left hemisphere to be significantly larger for right-hand stimulation in dextrals. There were no differences found for children classified as ambidextrous, and there was considerable variability in the size of the evoked response for those children classified as left-handed. The researchers speculated that for the right-handed, cortical representation of the right hand is much more focally concentrated within the somatosensory regions of the left hemisphere, whereas the left hand may project more diffusely to the right hemisphere, or even to both hemispheres. A similar finding has been reported by Kutas and Donchin (1974). This work is also supported by the findings of Wyke (1969), who, in lesion studies, found tapping and manipulative skills to be impaired in both arms in subjects with left-side lesions, but only contralateral impairment with right-side lesions. The model of hemispheric functioning proposed by Semmes (1968) is also compatible with these ideas. A survey of results of these studies indicates that knowledge of the ontogeny of handedness and of its pattern of development is still ambiguous and incomplete, particularly for the left-handed.

The problem is further complicated by the fact that societies have had, at different times, quite different degrees of tolerance for the phenomenon of left-handedness. The extent to which this affects the tendency toward left-handedness is difficult to assess; but the data of Dawson (Note 2) on societies with varying degrees of permissiveness toward left-handedness provide average percentages of 10.4% for societies that Dawson characterized as "extremely permissive," 5.9% for "permissive," and 1.8% for "harsh, restrictive" societies.

The Incidence of Handedness

Handedness in Early Man—Archeological and Anthropological Evidence

Although the amount of evidence is limited, existing data suggest that the incidence of handedness in early man was not essentially different from the ratios found today. Dart (1949), in an analysis of 47 fossil baboon skulls found under circumstances indicating they had been killed as food by Australopithecus, found 7 skulls clearly identifiable as fractured on the left side by a blow from the front, indicating that the implement used to strike the blow had been held in the assailant's right hand. Only 2 skulls were found with similar fractures on the right side. Although such data are hardly sufficient for any stable determination of incidence, the evidence suggests a predominance of right-handedness. Black, Young, Pei, and de Chardin (1933) suggested that the stone implements used by Peking man fit the right hand better than the left. By contrast, both Sarasin (1882) and de Mortillet (1882) reported the incidence of stone scraping tools to be about equal for both hands, concluding that early
Table 1
Incidence of Handedness

<table>
<thead>
<tr>
<th>Type of data</th>
<th>Range of incidence (%)</th>
<th>Mean (%)</th>
<th>Median (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incidence figures unsupported by data</td>
<td>2-8</td>
<td>4.8</td>
<td>5.0</td>
</tr>
<tr>
<td>Indirect measures of handedness</td>
<td>3.9-29.3</td>
<td>12.2</td>
<td>18.0</td>
</tr>
<tr>
<td>Self-report and questionnaire studies</td>
<td>5.5-15.8</td>
<td>8.64</td>
<td>8.0</td>
</tr>
<tr>
<td>Performance tests and behavioral measures</td>
<td>3.3-11.4</td>
<td>8.58</td>
<td>8.7</td>
</tr>
</tbody>
</table>

man was equally skilled with both hands, a conclusion also reached by D. Wilson (1904). Magoun (1966) has noted that in Cro-Magnon paintings, silhouettes of the human hand are common, with the left hand occurring about 80% of the time. If it can be assumed that the preferred hand was used to trace the silhouette, then it seems safe to assume that Cro-Magnon man was predominantly right-handed. Similar evidence for the predominance of right-handedness was provided by Brinton (1896) in a commentary on North American aboriginal art and by Mason (1896) in an examination of throwing sticks.

An unusual measure of incidence was developed by Dennis (1958), who examined the frequencies of handedness as depicted in paintings in the tombs of Beni Hasan and Thebes, spanning the eras from about 2500 B.C. to 1500 B.C. Dennis noted the frequency with which the right or left hand was used for activities requiring skill, excluding unskilled activities such as carrying or instances of bimanual acts. His results are not drastically different from many contemporary incidence figures.

The first written record of the incidence of left-handedness, as von Bonin (1962), Brain (1945), and Burt (1937), among others, have noted, is in the Book of Judges (Joint Committee, 1970) and describes the Benjamite army of 26,700 men. Within this army was a battalion of 700 men described as “seven hundred picked men from Gibeah, left-handed men, who could sling a stone and not miss by a hair’s breadth” (20:15). If this information is used to calculate an incidence ratio, the figure of 2.6% is obtained—a rather low ratio of left-handed, until the rather demanding selection factors are considered, entirely apart from the consideration that there is no evidence that the other 26,000 soldiers were all right-handed.
Contemporary Estimates of the Incidence of Left-Handedness

When contemporary estimates of the incidence of left-handedness such as those presented by Wile (1934) and Hécaen and de Ajuriaiguerra (1964) are examined, an astonishing range of values appears. Estimates of left-handedness in the population at large range from a low of 1% to a high of 30%. However, examination of the methods used to arrive at incidence figures reveals that (a) many incidence estimates are actually opinions unsupported by any data, and (b) incidence of handedness is closely related to methods of determination.

In Table 1, a classification of incidence figures is given, categorized by the methods used to determine them. Examination of this table indicates that estimates that are either extremely high or extremely low tend to be those based either on opinion unsupported by data or on indirect determinations of handedness, such as eyedness or strength of grip—measures that have a positive but far from perfect correlation with preferred handedness.

When performance measures have been taken, results have been much more stable, with the incidence of left-handedness centering around 9%-10%. Within this group of studies, there is only one striking deviation: Newcombe and Ratcliff (1973) reported an incidence of only 3%. This low figure seems to have been produced by an extremely stringent criterion, which required that all seven performance tasks be done with the same hand. On the basis of the accumulated performance studies, a population estimate of 8%-10% seems most appropriate. However, it should be kept in mind that this figure represents a range of preference rather than an absolute, with preferred handedness ranging from those few individuals who are totally left-lateralized to the individuals who use either hand with almost equal skill.

The Measurement of Handedness

Viewed phenomenologically, the measurement of handedness would seem to be simplicity itself. However, in a technological society, most devices are designed for the right-handed. Simple use of devices such as can openers made to be turned with the right hand, scissors angled so that the cutting edge is appropriate for right-hand usage, and other such devices undoubtedly has some effect on the incidence of certain types of hand activities.

Self-report is certainly the most common method used to assess handedness, whether by simple self-categorization or by means of detailed questionnaires. Next to self-report, the next most common determination is made on the basis of writing hand. As a measure of handedness this particular measure has several drawbacks, being subject to cultural pressure, both by parents and by the educational system. The beginning left-handed writer is frequently reported to be a source of annoyance and frustration to the primary school teacher and probably continues to be pressured to learn to write with the right hand, even in today’s era of more permissive school systems.

There has also been a tendency to equate strength with handedness. Woo and Pearson (1927) analyzed Sir Francis Galton’s dynamometer grip data to arrive at an estimate of left-handedness. Woo and Pearson apparently assumed that strength of grip could be equated with handedness, an assumption that was brought into serious question by the study of Koch (1933), who showed that dexterity and strength of grip were not closely related and that for her left-handed subjects, about 28% had stronger grips with their right hands.

Handedness has also been equated with sensitivity of discrimination, although the techniques used at times are difficult to fathom. Van Biervliet (1897) suspended equal weights from his subjects’ right and left index fingers and had them make repeated judgments as to which weight was heavier. Subjects who consistently reported the right side weight as heavier were judged as left-handed. A variant on this approach was the brachimeter test of E. Jones (1911), in which a variety of bone measurements were taken on both arms.

Parsons (1924) was firmly committed to the belief that handedness was completely determined by dominant eyedness and developed
a device called the Manuscope to use in determining the preferred hand. (Later studies have indicated that handedness and eyedness are correlated only about .53, based on the average relationships found among several studies.)

A variety of questionnaires have been constructed at various times to assess handedness (Annett, 1970; Benton, Meyers, & Polder, 1962; Crovitz & Zener, 1962; Hildreth, 1949a, 1949b, 1950; Oldfield, 1971; Satz, Achenbach, Pattishall, & Fennell, 1965). The majority of these questionnaires cover the same items and differ primarily in the type of answer option given to the respondent. A variation on handedness questionnaires have been the so-called tests of laterality (Belmont & Birch, 1965; Berman, 1971; Crinella, Beck, & Robinson, 1971; Harris, 1955; Sabatino & Becker, 1971), which differ from handedness measures primarily in that determinations of eye and foot dominance are also measured and an overall indicator of "lateral dominance" is derived. Performance measures of handedness have in general been behavioral demonstrations of the activities listed in questionnaires. Formal routines have been devised by a number of investigators (Roudinesco & Thyss, 1948; Subirana, 1961; Zazzo, 1960).

Only a few comparisons of questionnaires and behavioral measures exist. One of the most comprehensive comparisons was done by Koch (1933), who compared observations of performance on 105 tasks with responses to a questionnaire asking for preferred hand usage on the same tasks. Her set of tasks included both frequently occurring items, such as writing hand or hand used to deal cards, and less frequent activities, such as hand used to manipulate the clasp on an umbrella or hand used to pull the string when using a bow and arrow. The subjects were observed on each of these activities and then given a questionnaire. After a 1-week interval, the questionnaire was given again, resulting in a test–retest reliability of .81 overall.

Similar comparisons, though not as detailed in scope, have been done by other investigators (Benton et al., 1962; Raczkowski, Kalat, & Nebes, 1974; Satz et al., 1967). The results have been, in general, consistent; the conclusion is that handedness is not reliably determined by questionnaire measures alone and that behavioral measures are necessary to insure accurate classification. In this context, the studies of Benton et al. (1962) and Satz et al. (1967) are of particular interest, since they tested subjects self-classified as left-handed on behavioral measures of manual dexterity. Benton et al. gave subjects the Crawford and Crawford (1956) Small Parts Dexterity Test and two paper-cutting tasks, deriving a composite score of skill with each hand. A similar procedure was used by Satz et al., who also used the Crawford measure and the Reitan (1959) finger oscillation (tapping) test. In these two studies, those subjects who classified themselves as left-handed were classified by the performance measures as follows:

Benton, Meyers, and Polder (1962)
- Predominantly left-handed: 44% (22)
- Ambilateral: 35% (14)
- Predominantly right-handed: 10% (4)

Satz, Achenbach, and Fennell (1967)
- Predominantly left-handed: 61% (33)
- Ambilateral: 22% (12)
- Predominantly right-handed: 17% (9)

By contrast, of the 69 self-classified right-handed in the Satz et al. study, 3% (2) were left-handed and 4% (3) were ambilateral. For Benton et al., of the 66 self-classified right-handed, 3% (2) were left-handed and 30% (20) were ambilateral.

This evidence suggests that the probability of misclassification in self-reports of handedness is much higher for the left-handed than for the right-handed. Such a possible misclassification may aid in explaining some of the inconsistent results found in studies of handedness as related to intellectual or cognitive deficiency, and in studies of cerebral dominance.

Handedness and Deficit

Left-handedness has been linked with a variety of deficits. In reviewing what has come to be an enormous literature, the teasingly suggestive nature of this relationship is rather striking in its persistence.
through generations of research workers. There is usually just enough of a relationship to suggest a possible link and never enough of one to establish firmly a solid correlation. To evaluate this material, it is necessary to assess the validity of methods of classification of handedness. As mentioned earlier, the possibility of misclassifying the left-handed on the basis of self-report is considerably higher than that for the right-handed.

A second distinction that must be kept in mind is the population from which the groups being examined are drawn. Studies postulating relationships between handedness and deficit have been largely based on samples drawn from clinics where children have been referred because of speech, language, or other kinds of problems.

Still another type of problem exists. The emphasis placed on the testing of hypotheses by the approach of determining statistically "significant differences" may well have led to an overcapitalization of chance relations. In the studies reviewed for this paper, we found relatively little emphasis on the extent to which handedness as a variable is associated with variance in other variables under question. When reviewed as a problem in accounting for variance in performance on a variety of test measures, handedness turns out to account for remarkably little variance—far less, in fact, than the emphasis placed on small but statistically significant differences would warrant.

A detailed review of studies comparing the performance of the left- and the right-handed is precluded by space limitations. A summary does, however, indicate the overall trend of results. Of 14 studies of reading ability, 13 reported no differences (Allison, 1966; Balow, 1963; Balow & Balow, 1964; Coleman & Deutsch, 1964; W. F. Dearborn, 1931; Gilkey & Parr, 1944; Hildreth, 1934; Koos, 1964; Sabatino & Becker, 1971; Wittenborn, 1946; Witty & Kopel, 1936; Wolfe, 1941a, 1941b; Woody & Phillips, 1934), and 1 found the left-handed to be superior (M. M. W. Jones, 1944). In two studies of academic achievement, one found no difference (Sabatino & Becker, 1971), and the other (Gilbert, 1973) found the strongly left-handed to do less well on a college entrance examination. Of 8 studies of measured intelligence, 7 found no difference (Fagan-Dubin, 1974; Hardyck et al., 1976; Keller, Croake, & Riesenman, 1973; Miller, 1971; Newcombe et al., 1973; Orme, 1970; M. O. Wilson & Dolan, 1931) and 1 (Levy, 1969) found left-handed to do less well on Wechsler Adult Intelligence Scale performance items. Since the comparison in Levy's study was between two groups of graduate students in scientific and engineering fields, "less well" cannot be interpreted in relation to usual test norms. A questionnaire study reported left-handed girls in a juvenile detention home to be more unstable than right-handed ones (Orme, 1970), and another questionnaire study (Bakan, Dibb, & Reid, 1973) found that left-handed college students reported more parental accounts of stressful births. Three studies (Flick, 1966; Nebes, 1971; Silverman, Adevai, & McGough, 1966) reported poorer performance for the left-handed on perceptual tasks. The studies by Flick and by Silverman et al. have not been replicated, to our knowledge; however, four replications of the Nebes study (Hardyck, in press-a; Kutas, McCarthy, & Donchin, 1975) found no differences between right- and left-handed subjects. Three studies reported a larger percentage of left-handed among mentally defective children than among normal children (Burt, 1937; Gordon, 1920; M. O. Wilson & Dolan, 1931) and one study (Wile, 1934) found no difference. Finally, one study reported a high incidence of left-handedness among patients in an alcoholic ward (Bakan, 1973). It appears that the data indicating that left-handedness is associated with deficits of various kinds is far from compelling.

Handedness and Cerebral Dominance

Speculations about the relation of handedness to cerebral dominance are at least as old as the initial speculation that the two hemispheres of the brain perform different functions. Credit for the idea of cerebral specialization is usually given to Dax (1865) and to Broca (1861), who seem to have presented the first specific set of statements concerning localization of function in relation to handedness. The concept of cerebral dominance seems to have begun with Jackson (1958) and to have been given added credence by the work of Bastian (1868).
The study of specialization of functions within the hemispheres has, in recent years, been stimulated by the studies of Sperry, Gazzaniga, and Bogen (Sperry, 1968a, 1968b; Sperry; Gazzaniga, & Bogen, 1969) on patients who have undergone cerebral commissurotomy. Studies on these patients led to the conclusions that "... the disconnected left hemisphere processing information from the right hand and the right half visual field is the hemisphere that does essentially all the talking, reading, writing, and mathematical concepts in the right hand subjects ..." (Sperry, 1973, p. 212). The right hemisphere is superior at form relations and perceptual organizations, but, in Sperry's terms, "the disconnected right hemisphere on the other hand remains essentially mute, alexic, agraphic, and unable to carry out calculations beyond simple additions to sums under 20 ..." (1973, p. 212).

The results of these studies have stimulated a flood of investigations into the nature and function of cerebral dominance and localization. In particular, the discovery of specialized nonverbal processing centers has sparked a variety of speculations, ranging from questions on current educational practices to the somewhat metaphysical speculations of consciousness and brain function typified by the work of Ornstein (1972, 1973).

The value of the commissurotomy studies can scarcely be overestimated. At the same time, it is quite possible that generalizations made from nine patients suffering from severe epileptic disorders of unknown etiology may not be completely applicable to the population at large. In this context, the studies of visual-field differences in normal subjects stimulated by the Sperry et al. studies of visual half-field differences in the commissurotomy patients and the dichotic listening studies stemming from Kimura's applications of Broadbent's techniques (Broadbent, 1954, 1956; Kimura, 1963, 1964, 1967; Kimura & Folb, 1968) are of particular interest, especially in relation to handedness. In these studies, handedness was usually considered to be an indicator of cerebral dominance. Differences in efficiency of visual-field localization and in accuracy of report in dichotic listening were measured in relation to handedness.

The number of studies currently reported is too extensive to review in any detail. A summary reveals the following trends:

- Of studies of visual-field preference that report no data on family history, six found the right-handed to show a right visual-field preference (Bryden, 1973; Dimond, 1971; Dimond & Beaumont, 1974; McKeever & Gill, 1972; Orbach, 1967; Zurif & Bryden, 1969), and four reported no visual-field differences (Beaumont & Dimond, 1973; Groberg, Dustman, & Beck, 1969; Hines & Satz, 1974; McKinney, 1967). One study (Orbach, 1967) reported that the left-handed recognize Hebrew words better in the left visual field, and English words better in the right visual field. Another study (Lomas & Kimura, 1976) found that concurrent manual activity (rhythmic tapping) with the right hand interfered with speech in right-handed subjects but that left-hand activity had no effect on speech. Left-handed subjects showed equal interference with speech activity when tapping with either hand.

When family history is taken into consideration, the right-handed with both a positive and a negative family history of left-handedness have higher accuracy scores and show faster reaction times in the right visual field (Cohen, 1972; Dimond & Beaumont, 1974; Hines & Satz, 1971; McKeever, Gill, & Van Deventer, 1975; McKeever, Van Deventer, & Suberi, 1973). The left-handed with a family history of left-handedness have better word recognition in the left visual field than do the left-handed with no family history of left-handedness (Bryden, 1965; Zurif & Bryden, 1969). When differences between visual fields were examined, several studies (Beaumont & Dimond, 1975; Buffery, 1974; Cohen, 1972; Daviddoff, 1975; Dimond & Beaumont, 1972, 1974; Efron, 1962; McKeever, Gill, & Van Deventer, 1975; Moscovitch & Catlin, 1970; Provins and Jeeves, 1975) reported inter- and intra-visual-field differences in reaction time to be less for the left-handed.

Studies of dichotic listening have revealed a similar pattern. Of those studies that reported no family history, three found a smaller difference between the left and right ear for the left-handed, as compared with the right-handed (Curry, 1967; Curry & Rutherford, 1967; Satz et al., 1965), and three found
that the right ear was dominant for the right-handed (Curry, 1967; Knox & Boone, 1970; Zurif & Bryden, 1969). One investigator found the latter results only for those with a strong hand dominance (Dec, 1971), one reported left-ear dominance for the left-handed (Knox & Boone, 1970), and another found this only for those individuals who had a moderate degree of left-handedness; for individuals who were strongly left-handed, the right ear was dominant (Dec, 1971). Three studies found no differences (Cyr, Daniloff, & Berry, 1971; Hines & Satz, 1971; Satz et al., 1965). One complicating factor was suggested by Bryden (1965), who reported that right-ear dominance increased with age for the right-handed and decreased with age for the left-handed. Thus, developmental age may be a confounding factor in some of these studies.

Finally, when family history was recorded, it was found that the left-handed with a positive history of left-handedness showed a left-ear dominance (Dec, 1971; Zurif & Bryden, 1969), whereas those with a negative family history of left-handedness showed a right-ear dominance (Zurif & Bryden, 1969). When these studies are examined for common trends, the variability shown by the left-handed is again striking. The right-handed groups display a clear-cut pattern of function in most cases. The left-handed are sometimes identical in performance with the right-handed, but more often than not, usually show smaller interhemisphere differences.

The results of these studies lead to the following conclusions: First of all, the systematic differences found in visual field and dichotic listening experiments for familial left-handed raise serious questions about non-genetic explanations of handedness, such as that put forth by Collins (1970). If, as Collins argued, an unspecified environmental mechanism is adequate to explain the fact that offspring resemble their parents in handedness, such a mechanism would have to work in a rather strange manner, since it would be in effect for the familial left-handed, but not for the nonfamilial left-handed.

The evidence from the few studies in which familial handedness has been carefully evaluated suggests that bilaterality of cerebral organization is not a characteristic of the nonfamilial left-handed and that as a group, they are organized for cerebral specialization exactly as are the right-handed. Such individuals may be left-handed owing to some early brain insult, as hypothesized by Bakan et al. (1973), or perhaps some unspecified environmental effect, as Collins (1970) suggested, or perhaps even a basis such as the extreme negativism proposed by A. Blau (1946).

Bilaterality of cerebral function seems to be present in the left-handed only when there is a family history of left-handedness; measures of dichotic listening and visual-field differences in these individuals show a consistent lack of difference in both visual field and ear preferences. In the 15 studies reviewed in which familial handedness was used as a classificatory variable, 10 reported smaller between-hemisphere differences for the familial left-handed and 5 found no difference when compared with the right-handed. No studies reported larger between-hemisphere differences for the left-handed.

Lesion Studies

Concern with localization of function and the characteristics of cerebral dominance began with studies of patients who had suffered various types of cortical lesions. Broca (1861) provided a dramatic demonstration of the localization of speech in an aphasic patient and originated the notion that left-handedness is related to localization of language in the right hemisphere. However, for some time after Broca, case reports continued to appear citing instances of aphasia for left-hemisphere lesions in left-handed patients and, very rarely, aphasia following a right-side lesion in a right-handed patient. It was quite some time before these cases were considered as other than simple exceptions to Broca's formulations.

Since the clinical literature on this topic is huge and has been adequately summarized by a number of investigators, we limit the present review to those contemporary reports based on reasonable numbers of cases (Branch, Milner, & Rasmussen, 1964; Gloning, Gloning, Haub, & Quatember, 1969; Goodglass & Quaddas, 1954; Hécaen & Piercy, 1956; Hécaen & Sauget, 1971; Luria, 1970; Penfield & Roberts, 1959; Subirana, 1958). The results
can be summarized rather succinctly. About 24% of right-handed individuals with left-side cortical lesions develop language disorders, as compared with 6.7% of right-handed with right-side lesions (data taken as a median percentage over all studies in which data are roughly comparable, and summing over all categories of verbal disorders—oral language, reading, writing, etc.). The left-handed with left-side cortical lesions show language disorders in 22.4%, and for right-side lesions, 13.7%.

These between-hemisphere differences are not as extreme for visual measures: For the right-handed, the percentage of visual disorders for left-side lesions is 7.1%, and for right-side lesions, 10.8%. For the left-handed, the percentage of disorders for left-side lesions is 7.8%, and for right-side lesions, 10.1%.

Another way of examining these differences is by comparison of the frequency of statistically significant differences in occurrence of deficits in performance, as related to lesion sites in the right- and left-handed. For the right-handed, disorders in relation to lesion site are almost always statistically significant—for example, language disorders occur frequently with left-side lesions and rarely with right-side lesions. For the left-handed, the lack of significance in relation to lesion site is the most usual finding—disorders associated with one hemisphere seem to occur at no more than chance levels of significance. Hécaen and Sauget (1971) assessed 50 types of symptoms in relation to lesion site—right or left hemisphere—on right- and left-handed patients. For the right-handed, they reported 47 out of 50 between-hemisphere differences as statistically significant at a probability of .05 or less. The corresponding number of significant differences for the left-handed patients was 4 out of 50.

The evidence again supports the view that the left-handed have a more bilateral functional organization, both verbally and visually, than do the great majority of the right-handed. However, as the study of Hécaen and Sauget (1971) indicated, both the family history of left-handedness and the behavioral tendency of left-handedness must be carefully assessed, since there are some rather striking differences between the familial left-handed and the nonfamilial left-handed. There are no differences in the verbal performances of the familial left-handed who have suffered either right or left cortical lesions—the frequency of language difficulties of all types is virtually identical for right- and left-side lesions. For the nonfamilial left-handed, the frequency of language difficulties of all types is always greater with left-side lesions. To further complicate the analysis, the pattern of deficit as a function of lesion site for the weakly left-handed—those subjects who do not show extremely strong left-handed preferences in the behavioral measures—is almost identical with that shown for the familial left-handed, no matter what the degree of left-handedness. For the strongly left-handed—those subjects who perform almost all activities with the left hand—the pattern of deficit is almost identical with that of the nonfamilial left-handed, with the majority of disturbances of language associated with a left-side lesion. When the frequency of familial to nonfamilial handedness is assessed in relation to the degree of handedness, the familial cases are more often associated with moderate than with extreme left-handedness. Although Hécaen and Sauget cautioned that these findings should be replicated, the data are nonetheless striking, especially in view of the differences found by Zurif and Bryden (1969) between familial and nonfamilial handedness in visual field and dichotic listening performance.

In reviewing these studies of handedness, it is easy to understand Subirana's (1969) lament that the left-handed seem to have been put on earth to plague and to complicate straightforward interpretations of human cortical functioning. They are both a fascination and an annoyance, and although our review of handedness leads us to wonder why the left-handed have been viewed so darkly throughout history, it is possible to understand the researcher who, having his neat theoretical formulations concerning cortical functioning reduced to absurdity by the left-handed, argues that left-handedness is the simple reverse of right-handedness, or else pretends that the left-handed do not really exist.

Discussion
Several conclusions seem evident:
1. One conclusion has been reached by
every researcher who has studied the problem of handedness. Though obvious, it still needs emphasis: Handedness is not a simple phenomenon that is easily determined phenomenologically or by self-report. The development of preferred handedness can be markedly affected by such factors as family and cultural preferences, educational practices, the prevalence of certain types of devices more suitable for one hand than the other, genetic factors, and specific brain damage, to mention only the immediately obvious items.

2. Left-handedness, even when behaviorally established, is not a unitary trait. As several studies (Bryden, 1973; Hécaen & Sauget, 1971; Hines & Satz, 1971; McKeever et al., 1973; Zurif & Bryden, 1969) suggest, the left-handed with a positive family history of left-handedness are different in many ways from the left-handed who are solitary within a family of right-handed. These left-handed with no family history are, paradoxically, the most strongly left-handed and most often show a pattern of cerebral localization that is characteristic of the right-handed.

The left-handed with a family history of left-handedness range from those with strong (but not absolute) left-hand preferences to those who are approximately equally skilled with either hand. These individuals most frequently show the bilateralized cerebral organization that was characteristic of the patients of Hécaen and Sauget (1971), in whom the incidence of dysphasias and spatial disturbances was approximately equal, regardless of lesion site. However, as Luria (1970) has shown, individuals with this bilateral organization also recover function following brain damage much more quickly and show fewer lasting after-effects from lesions than do the more lateralized right-handed.

3. The tendency of the left-handed to be less strongly handed than their right-handed counterparts is, in view of the other evidence, not surprising. This could be the result either of having to cope with a world organized for the right-handed or of an intrinsic bilateral organization. Given the patterns of bilateralization shown by many left-handed, an ability to use either hand would be a natural corollary of such organization. A few studies (Bryden, 1970; Curry & Gregory, 1969; McFie, 1952; Witelson & Rabinovitch, 1972; Zurif & Carson, 1970) have suggested that certain types of verbal deficit, such as dyslexia, are linked to incomplete cerebral lateralization, but these relationships are far from firmly established. It is possible that the left-handed, as a group, do differ in maturational rate of lateralization. Thus, if cognitive functions are bilaterally located, then the time period taken to establish predominant usage might require a longer period of development.

4. The relationship between handedness and cerebral organization seems definite, though far from precise. Those reports that have included handedness as a selection variable in studies of dichotic listening or visual half-field differences indicate that the relationship is systematic, though not straightforward. The few studies that have assessed family history of handedness have, in general, increased the precision of the relationships under study.

Given these obtained relationships and the systematic nature of the differences found in both the behavioral and clinical lesion studies, a tentative classification of individual differences in handedness and cerebral organization can be offered. It is suggested that lateralization of cerebral function in humans can be organized along a continuum of handedness, with those individuals who are strongly right-handed and have no family history of left-handedness being more highly lateralized for speech and visual functions, the verbal functions being left-hemisphere lateralized and the spatial functions right-hemisphere lateralized. At the opposite end of the continuum are the left-handed with a positive family history of left-handedness who have both speech and visual functions bilaterally localized. Bridging these two groups are the right-handed with a family history of left-handedness, whom one would expect to show greater bilateralization of function than do the right-handed with negative family history, but less than do the familial left-handed.

One group remains unaccounted for—the left-handed with no family history of left-handedness. Since the available evidence suggests that localization of function is identical with that of the right-handed with no family history of left-handedness, this group will be classified as identical with the right-handed. The validity of such a classification remains
to be established (see Hardyck, in press-b, for a more extensive treatment of this problem), but is experimentally testable.

5. The conclusion that the left-handed are cognitively deficient, or are the products of a high incidence of early brain insult seems to be an artifact of observations on clinic populations with whom self-report and casual observation have usually been used to determine handedness.

It is, of course, quite possible that a deficient subpopulation that is characteristically left-handed may exist. The studies of left-handedness and cognitive deficit offer little support for such a hypothesis, as regards the general population of left-handed. However, the studies of left-handedness in mentally retarded populations (Burt, 1937; Gordon, 1920; M. O. Wilson & Dolan, 1931) indicate a systematically higher incidence.

6. The items reviewed to date suggest a hypothesis—at present, highly speculative—about the possible relationships of observed findings to a genetic basis for both handedness and cerebral organization. The greater flexibility of the familial left-handed individual in recovering from unilateral cerebral insult seems well documented. It is reasonable to argue for a genetic basis for such mechanisms, as opposed to an environmental determination, since an environmental influence that affects cerebral organization for the familial left-handed and not the nonfamilial seems highly improbable at best. However, if the bilateral organization of the familial left-handed provides an evolutionary advantage, then the problem of apparent stability within the population must be faced. The evidence, though fragmentary, suggests that the incidence of left-handedness is relatively unchanged from Australopithecus through the Egyptians of 2500 B.C. to the present. By contrast, studies of population genetics (Cavalli-Sforza & Bodmer, 1971) indicate that a malaria-resistant gene such as Thalassemia can appear and reach stability in a population in about 70 generations.

A possible explanation for the apparent stability of left-handedness may reside in the fact that the relatively low incidence of cerebral injury does not have a strong effect on reproductive success. Thus, the particular gene complexes that give the left-handed an advantage in terms of protection from the lasting effects of cerebral trauma cannot become fixed in the population. In this context, Dobzansky (1970) has shown that a trait that is present in a small proportion of the population and that affords only a slight selective advantage will be subject only to the effects of genetic drift. However, it is also possible that bilaterality of cerebral organization and associated left- or mixed-handedness may be increasing in frequency in the human race, but at such a slow rate that changes are difficult to detect.

7. Some consequences of recent work (Levy, 1969; Miller, 1971; Nebes, 1971) have been tendencies to oversimplify findings and to produce overextended generalizations about the nature of human cortical functioning. Speculations about the function of the “left brain” and the “right brain” are an illustration of this tendency (Ornstein, 1972, 1973). Similarly, positions are taken on the “value” of lateralization, arguing that increased lateralization represents a superior cortical organization (Sperry, 1973).

There seems to be no basis whatever for continuing to regard the left-handed with the apppellations and stigmata that seem to have characterized them since Biblical times. In fact, a reasonable case can be made for the opposite viewpoint, since the evidence for deficit is minimal and the advantages of recovery of function in the event of brain damage are considerable. The phrase, “Two heads are better than one,” might well be applied to the unique advantages possessed by many of the left-handed.

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Received January 5, 1976