FUNCTIONAL BRAIN ASYMMETRY AND DICHOTICALLY-STIMULATED EAR PREFERENCE IN MUSICIANS AND NONMUSICIANS

by

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ABSTRACT

A left ear-right hemisphere superiority in the recognition of dichotically-presented melody segments has often been demonstrated in the general adult population. More recently a right ear-left hemisphere superiority has been shown by musicians in a similar monaural task. Both findings can be explained by current ideas on functional brain asymmetry and the co-operative roles of the cerebral hemispheres. Gestalt synthesis appears to be the main task of the right hemisphere, while phonological analysis seems to be the specialty of its counterpart.

This cortical organization is thought to apply only to right-handed people. Studies of left-handers have produced equivocal results, due partly to errors in definition and measurement. However, groups of left-handed subjects often fail to match the homogeneity of groups of right-handers, in terms of their scores on dichotic listening tasks, suggesting the presence of two, or more, distinct sub-groups within the former population. It has been difficult to find simple external behaviours which distinguish between the proposed sub-groups in terms of their cortical organization.

The purpose of the present study was fourfold. First, it was to replicate the finding of a left ear superiority for dichotically-presented musical stimuli in the general adult population. Second, it was to extend the finding of a right ear superiority in musicians to include a dichotic listening task, and third, to investigate the previously described lack of asymmetry, using a reliably measured group of left-handed people. Finally, it was decided to test the hypothesis that the left hemisphere becomes more active in this task as a person's musical ability increases.

The subjects were 64 human adults with no evidence of hearing loss, who were assigned to one of four groups. These were Right-handed Musicians, Left-handed Musicians, Right-handed Nonmusicians and Left-handed Nonmusicians. There were 16 subjects in each group.

Each subject was presented with a series of melody recognition tasks. On each trial, there was a short dichotic presentation of violin melody segments which was followed by a 5-second interval and the presentation of a binaural recognition foil. The subject's task was to decide if he had just heard the recognition foil, and, if so, to which ear had it been presented.

The results were largely as predicted. Musicians demonstrated a right ear superiority for this task, while nonmusicians performed better with the left ear. The difference between these groups was largely due to a higher right ear score for musicians, implying the increased

activity of the left hemisphere. The left-handed subjects, musicians or nonmusicians, showed considerably less ear asymmetry than the right-handers. However, as a group, their scores were more heterogeneous, emphasizing the need for a meaningful sub-division of these subjects.

The results suggest that the development of lateralization for music may parallel that for language. A holistic appreciation of music seems to be carried out mainly in the right hemisphere, but when the stimuli are to be meaningfully partitioned, a left hemisphere analyzing mechanism becomes active.

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CHAPTER I

REVIEW OF THE DICHOTIC LISTENING LITERATURE

Introduction

Hemispheric Asymmetry

The laterality of cerebral function has been known for thousands of years. This phenomenon was recognized by the Egyptians, at least as early as 3000 B.C. (Cadwallader, Semrau & Cadwallader, 1971). Portions of an ancient medical papyrus, which pertain to physiological psychology, describe the anatomy of the brain and the motor effects of neural damage. Hippocrates wrote about the duality of the brain about 400 B.C., and in the seventeenth century A.D., Sir Thomas Browne discussed the relationship between bodily control and the two hemispheres.

However, the modern history of hemispheric asymmetry began in the middle of the nineteenth century with the work of Broca, who connected aphasia with damage to an area of the left hemisphere. Hughlings-Jackson (1874), in extending the discussions of Bouilland on hemispheric dominance and handedness, stated that the hemispheres could not be mere duplicates of each other. He believed that the left hemisphere dealt with 'audito-articulatory' functions and propositional language, while the 'retino-ocular' functions of visual perception were ascribed to the right. Hughlings-Jackson, unlike Broca (1865), supported the idea of an incomplete lateralization of speech. He saw cerebral dominance as a relative concept, the degree of dominance being dependent upon the function under examination.

Two main factors led many later writers, such as Henschen (1926), to consider the left hemisphere to be the dominant one. The first was the consistent findings of the left-sided localization of speech functions, while the second was the strong contralateral connection between this hemisphere, and the usually-preferred, right hand. The right hemisphere was relegated to a minor, or even reserve, position.

More recently, ideas concerning the roles of each hemisphere have changed somewhat. The aptitude of the left hemisphere for the processing of speech remains, and has been extended to include reading and writing. Analytic and temporal processing has also been assigned to this hemisphere. Studies have shown that lesions to the right hemisphere can also produce specific functional deficits, thus tending to deny its minor role.

Bogen (1969) has summarized these right hemisphere disorders. He includes overattention to detail in drawing forms, topograph-agnosia, dressing apraxia, prosopagnosia, defects in appreciating a spatial whole, relatively poor scores on the Performance Scale of IQ tests, and amusia.

In addition, right hemisphere lesions have been shown to cause deficits in auditory perception and memory (Milner, 1962; Benton, 1965). The former author reported that while lesions to the left temporal lobe caused losses in the perception of, and memory for, speech, similar lesions in the right hemisphere produced losses in the perception and recall of nonverbal sounds. More specifically, the nonverbal sounds were melodies, tonal patterns and everyday environmental noises.

As the specialized functions of the right hemisphere have been discovered, so the theory of hemispheric asymmetry has changed. The relationship between the hemispheres is being thought of as one of co-operation, rather than competition. Their interdependence is illustrated in a statement by Levy (1974), which captures the spirit, if not the factual state, of current theory.

> The right hemisphere synthesizes over space. The left hemisphere analyzes over time. The right hemisphere notes visual similarities to the exclusion of conceptual similarities. The left hemisphere does the opposite. The right hemisphere perceives form, the left hemisphere detail. The right hemisphere codes sensory input in terms of images, the left hemisphere in terms of linguistic descriptions. The right hemisphere lacks a phonological analyzer; the left hemisphere lacks a Gestalt synthesizer.

The Functional Neuroanatomy of the Auditory System

A major portion of the research on hemispheric asymmetry has involved the human auditory system. Consequently, it is appropriate at this point to consider the functional neuroanatomy of this system, upon which the research is based. However, there is still much to be discovered about the central auditory pathways. In addition, much of the research has involved animal studies, mostly with cats and primates. These two factors temper this discussion.

The ear is the most external part of the auditory system. It consists of the pinna, a sound collector or deflector, which leads to a tube called the external auditory meatus. The medial end of this tube is sealed from the outside air by the eardrum, or tympanic membrane.

The eardrum provides a link between external sounds and the neural transducing mechanism. As the eardrum vibrates, due to sound waves, it moves a chain of three very small bones, or ossicles, which are located in the middle ear. These bones, the malleus, incus and stapes, transmit the motion to the oval window of the cochlea, or inner ear, which contains the neural transducing mechanism.

Generator potentials are thought to arise in the cochlea. Within this structure lies the organ of Corti, where the hair cells of the auditory system are to be found. The hairs of these cells are embedded in a relatively stationary gelatinous tissue called the tectorial membrane. When a sound wave enters the cochlea, the hair cells are rocked from side to side in a shearing motion. These motions are believed to be the stimuli that give rise to the generator potentials in these cells.

From the neural transducing mechanism, auditory information enters the central nervous system. The hair cells of the organ of Corti are innervated by dendritic processes from the bipolar cells of the spiral ganglion, which runs up the middle of the inner ear. The axons of the bipolar cells make up the afferent portion of the acoustic branch of the eighth cranial nerve.

Ascending pathways. Fibres from the cochlear portion of the eighth cranial nerve enter the lower brainstem at the lateral aspect of the inferior border of the pons. Each fibre divides into two branches. One branch goes to the dorsal portion of the cochlear nucleus, while the other goes to its ventral counterpart (Lorente de No, 1933). In both nuclei, synapses are made with second order neurons. The organizational pattern of both nuclei is complex, as they each contain many cell types and several kinds of axon endings. Rose, Galambos and Hughes (1959) explored these centres in the cat with microelectrodes, and found three separate regions, each with a tonotopical arrangement of neurons. The dorsal cells in each region had a high tuning point, but this became lower for the ventral ones.

The second order neurons of the cochlear nuclei divide into two approximately equal groups, which rise to the midbrain either contralaterally, or ipsilaterally.

The contralateral fibres emerge from the cochlear nuclei, cross the mid-line of the brainstem and ascend through a series of synapses to the auditory cortex. There are three groups of these contralateral fibres, one from the dorsal, and two from the ventral cochlear nucleus. They travel separate pathways through the reticular formation, and cross the mid-line to the vicinity of the contralateral superior olivary complex. Most of the second order neurons terminate and synapse here. The few which do not, continue to rise with the third order neurons. The superior olivary complex contains at least five separate nuclei, some of which are believed to subserve special functions.

The pathway of the ascending ipsilateral fibres is quite similar to those which cross over. However, all these fibres, from both cochlear nuclei, appear to synapse in the ipsilateral superior olivary nucleus. Tsuchitani and Boudreau (1966) suggest that the tonotopically organized area of the cochlear nuclei is repeated in the S-shaped part of the olivary complex on the same side. Their work with cats showed that low frequencies were represented by cells in the dorso-lateral arm of the S, but these increased as the microelectrodes were moved towards the ventromedial arm.

The next major relay station of the ascending auditory pathway is the nucleus of the lateral lemniscus of the reticular formation. Third order neurons rise from the contralateral superior olivary nucleus and combine with the ipsilateral fibres from the side to form an ascending tract called the lateral lemniscus. Many fibres do not synapse in the nucleus of the lateral lemniscus. Branches of the fibres which ascend in the lateral lemniscus go to the cerebellum, and to eye movement and pinna reflex centres in the reticular formation.

The fibres continue to ascend, reaching the inferior colliculus of the mid-brain, where the majority of the lemniscal neurons terminate. The inferior colliculus is a large highly organized nucleus known to have large numbers of afferent and efferent connections. At this level there is a partial decussation of fibres through the inferior collicular commissure, with both ipsilateral and contra-lateral synapses.

Fibres from the inferior colliculus, plus those of the lateral lemniscus which did not synapse here, join to form a tract known as the brachium of the inferior colliculus, and ascend to the medial geniculate body. The fibres terminate in this classical auditory-relay nucleus of the thalamus. There is evidence, however, that auditory transmission is not confined to the medial geniculate body of the thalamus. For example, Rose and Woolsey (1958),using a retrograde degeneration technique, implicated the pulvinar and anterior portions of the posterior group of thalamic nuclei in auditory transmission.

From the medial geniculate body, fourth-order neurons project, by way of the internal capsule, to the auditory cortex, i.e. to Heschl's gyrus in the posterior section of the superior convolution of the temporal lobe. Here again there is thought to be tonotopic representation of tones, as at the lower levels of the auditory system. Katsuki's (1961, 1962) studies indicate that the auditory cortex is activated by the timbre of complex sounds, the change in sounds over time, and the integration of sound sequences.

The pathway described is thought to be the major afferent one for neural impulses originating in the cochlea. It may be thought of as containing four major ascending tracts, two ipsilateral and two contralateral, thus permitting information from each ear to be represented in each hemisphere.

There is another auditory pathway through the ascending reticular formation, the area of the brainstem concerned with arousal. Its purpose is unknown, but it is suspected to be concerned with sensory integration, i.e. the facilitation and inhibition of sensory transmission at all levels of the afferent pathways (Hernández-Peón, 1961).

Although there is much crossing back and forth of fibres at the various auditory commissures, the projection to the thalamus and cortex is stronger for the contralateral ear (Penfield & Rasmussen, 1950). Rosenzweig (1961) found that the ratio of cortical representation between the contralateral and ipsilateral pathways was four to three. Ades and Brookhart (1950) interpreted the latency differences they found, at the level of the inferior colliculus, as showing that the contralateral pathway had fewer synapses, and, consequently, a more rapid transmission time. Many studies which involve clinical patients and low redundancy speech stimuli, e.g. that of Calearo and Antonelli (1963), have shown that a central lesion affecting the auditory system will produce the greatest deficit in the contralateral ear.

Descending pathways. Centrifugal projections for the auditory system have been described from the cortex to the cochlea. They roughly parallel the ascending tracts. These descending fibres have at least one synapse between the cortex and the cochlear nucleus (Desmedt, 1960), and four-fifths of them cross to the contralateral ear (Rasmussen, 1960).

This system, along with the reticular formation, is capable of modifying sensory input at all levels in the ascending pathway, by means of feedback loops (Livingston, 1959). For example, the olivocochlear bundle, from the superior olivary nucleus to the organ of Corti, is believed to have an inhibitory action on impulses originating in the cochlear nucleus. The descending fibres then are involved in the facilitation, inhibition, habituation and sensory integration of acoustic stimulation.

As an important part of perception involves efferent control, the fact that four-fifths of the descending fibres decussate lends weight to the concept of the superiority of the contralateral afferent pathways.

Anatomical asymmetries. Anatomical differences have been noted between the hemispheres in those cortical areas associated with speech and auditory processing. Connolly (1950) quotes several authors who found the left Sylvian fissure to be longer than the right. Both Broca's and Wernicke's areas border this fissure.

Pfeifer (1936) studied the structures lying on the upper surface of the temporal lobe. The anterior transverse gyrus of Heschl traverses this area in a postero-anterior direction. It crosses the upper surface of the temporal lobe in an anterior direction, and, when it reaches the Sylvian fissure, joins the superior temporal gyrus. Heschl's gyrus contains the primary auditory cortex, receiving the major outflow of neurons from the medial geniculate body. Between Heschl's gyrus and the posterior end of the Sylvian fossa lies the planum temporale, an auditory association area.

Pfeifer reported that on the left, the gyrus of Heschl was in general angled more sharply forward than on the right. Consequently, the planum temporale was larger on the left. Pfeifer also claimed that typically one finds only one transverse gyrus on the left, i.e. Heschl's, while two or more are found on the right.

Von Economo and Horn (1930) agreed with Pfeifer. They found that the left Sylvian fissure was longer in 18 of 20 brains. Heschl's gyrus was larger in 13 of these 20 brains, and smaller in only 2.

Geschwind and Levitsky (1968) studied 100 adult brains. They found that the posterior wall of the Sylvian fissure was angled back more sharply on the left in 57% of the cases, with equality in a further 25%. Also the greater backward extent of the Sylvian fissure and the greater forward angling of Heschl's gyrus combined to create a larger planum temporale on the left.

In a similar study,Waada, Clarke and Hamm (1975) measured hemispheric asymmetries in 100 adult and 100 infant brains. They found that the planum temporale was larger on the left side in about 90% of these cases, and that this asymmetry was noticeable as early as the 29th gestational week. The degree of asymmetry appeared to increase with age. Waada et al. believe these results show that the brain is predisposed for lateralization before the development of speech by the infant.

Therefore, certain cortical areas involved in the auditory system are larger in the left hemisphere.

Other anatomical asymmetries have been noted, concerning larger structures on the left. McRae, Branch and Milner (1968) studied the ventricular system by pneumocephalography and found that the right occipital horn was larger in only 13% of the cases. Di Chiro (1972) found similar asymmetries in cortical venous patterns.

One contradictory finding occurs in the previously mentioned study by Waada, Clarke and Hamm (1975). The frontal operculum was found to be slightly larger on the right side of the 200 brains they measured, the degree of asymmetry appearing developmentally constant. However, as Waada et al. point out, the results are tentative due to the technical problem of measuring the area of a curved surface from a photograph.

Dichotic Listening

In the past, study of the cerebral localization of function in normal subjects has proved difficult. The main reason for this is, as mentioned in the previous section, that both ears are connected to the auditory receiving areas in both hemispheres.

The technique of simultaneous stimulation has been widely used to overcome this problem. Loeb (1884) first used this method with animals. It fell into disuse, but was revived by Bender (1952), who used it as a clinical and experimental tool. Typically, parts of the body (Bird, 1964), or the visual fields (Teuber, Battersby & Bender, 1960) are stimulated at the same time, and the subject is asked where, or how many stimuli are received. The technique has been applied to the auditory system by means of dichotic listening, i.e. a different stimulus is presented to each ear simultaneously. Apparently, the competition between the two neural pathways is resolved by the temporary storage of one message and the processing of the other, which, presumably, is from the dominant pathway.

The dichotic listening technique has been widely used for the study of perceptual processing, verbal learning and cerebral dominance. The stimuli are usually presented well above threshold, and the subject is asked to recall, or recognize, them. Many kinds of stimuli have been used, such as spoken digits (Broadbent, 1954), music (Kimura, 1964), sonar signals (Chaney & Webster, 1966), words (Borkowski, Spreen & Stutz, 1965), and consonant-vowel combinations (Shankweiler & Studdert-Kennedy, 1967).

Broadbent (1954) used spoken digits in studying the recall of transmitted information in the presence of irrelevant noise. When he used a presentation rate of two pairs of digits per second, the subjects reported all the digits presented to one ear before reporting those presented to the other. Broadbent names this the ear order of recall (EOR). He also found that a temporal order of recall (TOR), i.e. digits reported in their original presentation pairs, was seldom used at this speed.

These results were interpreted by Broadbent as arising from the subject's inability to switch attention between channels rapidly enough to process all the incoming information. Under these sensory overload conditions, the subject attends to one channel at a time. Broadbent believed that the excess information was stored temporarily in a mechanism which was characterized by the rapid decay of memory traces. The greatest deficit in performance occurred in the second half of the recall span, in the information that had to be stored for the longest period of time (Inglis, 1965; Inglis & Ankus, 1965; Inglis & Tansey, 1967).

Satz, Achenback, Fennell and Pattishall (1965), also using digits as stimuli, performed an interesting experiment concerning ear order of recall. In the first part of the experiment, in a free choice condition, the subjects used EOR 76.42% of the time, and made significantly fewer errors on stimuli presented to the right ear. In the second part, when the subjects were instructed as to which ear they should report first, EOR still occurred 61.69% of the time. Using this technique, the greatest number of errors occurred in the ear reported last, especially if this was the left one.

The general findings of subsequent dichotic listening research are in agreement with other investigations of verbal learning and short-term memory. The subject's performance is affected by the meaningfulness and frequency of usage of the experimental stimuli. For example, dichotically presented single digits usually have a recall rate in excess of 90%, probably because of their high degree of familiarity, and the relatively high chance of their being guessed correctly.

Ear order of recall is also affected by the speed of presentation of the dichotic pairs. Slower rates of presentation, less than two pairs per second, make temporal order of recall easier to achieve. This is probably due to verbal rehearsal, which is made possible by the increased inter-stimulus-pairs time interval (Bryden, 1962).

Verbal Stimuli and Hemispheric Asymmetry

Kimura (1961a, 1961b) worked with patients who had epileptogenic foci in the left temporal lobe. She noted that they showed impairment in the perception of spoken digits presented to either ear, when compared to groups of patients with right temporal, or frontal lobe lesions.

She also noticed that, following a unilateral temporal lobectomy of either hemisphere, patients showed impaired stimulus recognition at the ear contralateral to the excised area. This was a somewhat expected finding, following previous electrophysiological research with animals (Rosenzweig, 1951; Ades & Brookhart, 1950). The contralateral connections between the ear and the primary auditory receiving areas are stronger than the ipsilateral ones.

Kimura decided that a strong contralateral signal was probably competing with a weak ipsilateral one in the auditory cortex of one of the hemispheres. As most people have the language functions located in the left hemisphere, this perceptual asymmetry should favour verbal stimuli presented to the right, rather than the left, ear.

Kimura's next experiment was with 120 patients who were scheduled for the surgical removal of sections of the brain, which were the site of epileptogenic brain lesions. First, the hemisphere dominant for speech was determined by means of Wada's sodium amytal test (Wada & Rasmussen, 1960). Next Kimura administered Broadbent's (1954) test. Left hemisphere dominant patients showed superior recall from the right ear, while the few with right hemisphere dominance showed the opposite effect.

The case of right hemisphere speech dominance is also a cause for speculation. Kimura notes that only 13 of her patients showed this phenomenon, and 9 of these had large lesions in the left hemisphere. In this latter group, the right hemisphere is both intact and dominant, showing that this right-sided dominance could be due to either the left hemisphere, or a non-pathological factor. Kimura concluded that the non-pathological factor was the more important, since two of her remaining right hemisphere dominant patients had lesions in that hemisphere, and still showed a superior performance with the left ear.

Kimura next compared two sub-groups of her patient population. She chose seven left-hemisphere dominant subjects, and seven with right hemisphere dominance, all of whom had extensive lesions of the left hemisphere. She found that all the subjects in both groups showed a preference for the ear contralateral to the dominant hemisphere. These conclusions may be criticized for the relatively small number of subjects used, and for the uncontrolled sizes, and sites, of the left hemisphere lesions. However, the results tentatively confirm the hypothesis that the dominant hemisphere is important in the cortical processing of spoken digits.

The finding of right ear superiority for speech has since been extended. Kimura (1963, 1964) found the same phenomenon over the age of 5 years, and in normal adults. Inglis and Caird (1963) observed this right ear superiority in adults up to the age of 70 years, while Jones and Spreen (1967) found it in mentally retarded children. When the stimuli were words (Borkowski, Spreen & Stutz, 1965), or consonant-vowel nonsense syllables (Shankweiler & Studdert-Kennedy, 1967), the same effect was observed. This right ear dominance has been replicated by many observers, and so may probably be generalized to most populations with left hemisphere dominance for speech. (In the studies mentioned, left hemisphere dominance was assumed on the basis of right-handedness [Goodglass & Quadfasel, 1954], and the results from left handers, where included, were analyzed separately.)

Future research may provide a link between this behavioural asymmetry and the anatomic differences previously mentioned.

Nonverbal Stimuli and Hemispheric Asymmetry

The research in this area began with the study of brain-damaged clinical patients. Then normal people were studied, followed by several interesting extensions of the phenomenon.

Clinical research. Milner (1962) used a binaural listening technique to investigate the effects of right temporal lobectomies on her patients. They showed selective impairment when tested with the Seashore Test of Musical Abilities (Seashore, Levi & Sactvit, 1939). When compared with normal subjects, her clinical patients showed a mean performance deficit of at least one standard deviation on the sub-tests of tonal memory, loudness, timbre and rhythm. This deficit was not apparent on the sub-test of pitch. When compared to left temporal lobectomy patients, the right temporal lobectomy groups were deficient on all of the sub-tests, the most marked differences being in tonal memory and timbre.

Milner's methodology may be criticized on several points. She used a relatively small number of subjects, i.e. 16 with right temporal and 22 with left temporal lobectomies. The scores of these patients were compared with Seashore's norms for 4,000 healthy adults, rather than with a matched control group of brain-damaged patients. The methods of test administration of the experimental groups was not directly comparable to that used in Seashore's normalization procedures. Also, the binaural stimulation means that the right temporal lobectomy patients were receiving ipsilateral and contralateral input into the intact left hemisphere, and vice versa. Finally, as recognition foils were used on the sub-tests of tonal memory and timbre, impairments of memory and perception were confounded.

However, the overall results of the experiment may be tentatively considered to imply that the perception, or recall, of some musical components, like timbre and rhythm, is dependent on neurons which pass through the right temporal lobe.

Milner, Kimura and Taylor (1965) concluded that musical sounds should demonstrate a similar, selective deficit in right temporal lobectomy patients. They used groups of right and left temporal lobectomy patients, a group of normal control subjects, and the stimuli, which lasted for three seconds each, were excerpts of bird songs. Both temporal lobectomy groups performed poorer than the normal subjects, but in a similar way to each other.

Shankweiler (1966a) used selections of well-known musical tunes and nursery rhymes as stimuli in his research. Again the subjects were right and left lobectomy patients, who were asked to name and hum the selections. As naming introduces a verbal component, Shankweiler expected the left temporal group to have difficulty with this task, but to show no impairment in melody reproduction. The opposite effect was expected with the right temporal group.

The results were a little surprising. As predicted, the left temporal group was superior to the right in the reproduction of tunes. However, a normal control group produced a significantly better performance than the left temporal group, on the same measure! Both these groups hummed significantly more tunes than they could name, but the right temporal group showed no difference in performance between the measures. Thus, the expected left temporal lobe deficit in naming was not produced. Instead, a significant, but unexpected, loss in recognition, or reproductive, abilities was noted.

If the concept of the functional specificity of the right temporal lobe is to be espoused, the deficits related to the left hemisphere must be explained. A logical, but conservative, explanation would be that damage to either hemisphere produces a functional loss. As Shankweiler's (1966a) study involved no brain-damaged control group, it could be assumed that the reproduction deficit was due to general brain damage. However, in Milner's study, a comparison was made between a group with frontal lobe damage, excluding Broca's area, and normal subjects, but no significant difference was found. This result indicates that the deficit is not linked to general brain damage.

All of the researchers offer reasonable explanations of the results. Milner's group believed that the multidimensional nature of the stimuli provided many recognition cues, thus preventing the detection of specific deficits. Shankweiler cites the close connection between the lyrics and the tune in popular songs as influencing right hemisphere performance. The loss of memory caused by the verbal defect of the left temporal lesion is then implicated in the defective reproduction of the tune.

Shankweiler's position is supported by more recent electrophysiological evidence. Schwarz, Davidson, Maer and Bromfeld (1974) took bilateral EEG readings from the occipital regions of the brains of their normal subjects, while presenting them with verbal and non-verbal stimuli. They used the decrease in generated alpha waves as an indicator of relative hemispheric activation. The spoken lyrics of a familiar song activated the left hemisphere, and whistling the tune activated the right, while singing the song produced the activation of both hemispheres.

Production of ear asymmetry. As a right ear superiority with verbal stimuli occurs only in the dichotic listening situation, with strong stimulus competition (Calearo & Antonelli, 1963; Dirks, 1964), a similar left ear occurrence was expected with nonverbal stimuli. In support of this position, Kimura (1964) mentioned an unpublished study where no ear differences were found when normal subjects were monotically presented with the timbre sub-test of the Seashore Test of Musical Abilities.

However, there is some evidence that strong stimulus competition may not be a necessary condition for the production of a left ear superiority. As mentioned above, Milner (1962), using binaural stimulation, found deficits in timbre and tonal melody among her right temporal lobectomy patients. Bakker (1967, 1968) presented digits and Morse code-like signals monotically to children between the ages of 6 and 13 years. Although developmental factors probably influenced the results, he did obtain a significantly superior left ear performance from the sound patterns.

Simon (1967) used a simple reaction time test with his subjects. They were presented with stimuli to the right ear alone, left ear alone, or both ears simultaneously. Binaural stimulation produced the most rapid response, but when the subjects did not know which ear was to be stimulated, they responded faster to the right ear. No differences were noted in the three conditions when the subjects knew to which ear the message was coming. Simon believed that he had demonstrated ear asymmetry with non-meaningful stimuli, adding that the results may be related to the subject's expectations concerning which ear is to be stimulated.

Other researchers have also produced ear asymmetry, using monaural stimulation. Bakker and Appelboom (1973) found that under conditions of ear order of recall, ear asymmetry could be detected by means of monaural stimulation. They concluded that ear asymmetry correlates positively with task complexity and difficulty. Doehring (1972) found a left ear superiority for the intensity discrimination of monaural tones, and this may be classed as a difficult task.

Types of nonverbal stimuli. Kimura (1964) used dichotic listening when she presented commercially recorded music to her subjects. The stimuli were 4-second solo excerpts from the Baroque composers, using woodwind and string instruments. The Broadbent test of ear order of digit recall was given to 20 normal female subjects, before administration of the melodies test. A right ear superiority for digits was found, while the left ear was superior for the melodies test. These results lend support to the hypothesis that the right temporal lobe plays a significant role in the perception of some nonverbal sounds.

On the basis of her experiments of 1961 and 1964, Kimura draws several conclusions regarding ear asymmetry and dichotic listening. She believes that the contralateral temporal pathways are stronger than the ipsilateral ones, and that the brain functions asymmetrically in the processing of verbal and nonverbal stimuli. The former are processed primarily by the left hemisphere in right-handed people, and the latter primarily in the right hemisphere.

Kimura's (1964) methodology was used by Shankweiler (1966b). However, his subjects were 45 patients with epileptogenic foci, who were scheduled for temporal lobectomies. They were tested pre- and post-operatively. At the time of the first testing, the right and left lobectomy groups did not differ significantly in accuracy of melody recognition. On testing post-operatively, it was found that no significant change had occurred in the overall melody test scores in the left temporal group, but the right temporal patients showed a significant impairment. As found in Kimura's (1961) study, the left temporal lobectomy group was superior in recognition of melodies presented to the left ear.

There is other evidence which supports the notion of the left ear's superiority in the perception of nonverbal sounds. An incidental finding of Chaney and Webster's (1966) study of multidimensional sounds was a left ear superiority for the perception of sonar sounds. Spreen, Benton and Fincham (1965) discuss a patient with a verified right temporal-frontal-parietal lesion, who demonstrated auditory agnosia for common environmental sounds, but no aphasia. The superiority of the left ear for nonverbal sounds has been further extended in normal subjects to include environmental sounds (Curry, 1967), emotions (Kimura & King, 1972; Carmon & Nachshon, 1973), and intensity discrimination (Doehring, 1972).

However, there is conflicting evidence regarding the superiority of the left ear in the processing of environmental sounds. As mentioned above, Curry (1967) obtained a significant left ear advantage with right-handed subjects.

This effect was not found in his group of left-handed subjects, even though, in the same experiment, they had shown a significant right ear preference for verbal material. Also, Spellacy (1969), in a similar study, failed to replicate Curry's finding of a left ear superiority for environmental sounds.

This discrepancy could be due to two facts. First, only in Curry's study did the subjects, in a pre-test situation, learn the verbal labels for the sounds they would be hearing, thus becoming familiar with the test stimuli. Secondly, there were differences in the lengths of the inter-stimulus intervals between the studies, and this factor was shown to be important in Spellacy's later work with music stimuli. This position is supported by the work of Neufeld (1971) who used Spellacy's dichotic stimuli and a short inter-stimulus interval to obtain a significant left ear superiority in children's perceptions of environmental sounds.

Extending the parameters. Spreen, Spellacy and Reid (1970) used music and tonal patterns in a dichotic listening experiment involving 48 undergraduate students. The music stimuli were solo violin passages of 2-seconds duration, but uncontrolled for musical key, tempo or rhythm. The tonal patterns were four pure tones, each of 500 msecs duration, and they were presented contiguously to make up a stimulus lasting for 2 seconds. An identification stimulus was presented to the subjects 1, 5, or 12 seconds after the presentation of the dichotic pair. They were asked if either of the dichotic stimuli was identical to the recognition stimulus. Of these recognition stimuli, 25% had been presented to the left ear, 25% to the right, and 50% to neither. Half of the subjects received stimuli at a high intensity, 70 dB, and the other half received stimuli at a lower intensity of 50 dB.

The results again supported the notion of a left ear superiority for musical stimuli. However, the size of the ear difference decreased as the time between the dichotic stimuli and the recognition foil increased. Spreen et al. suggest that the experimental effect is caused by perceptual processing differences between the hemispheres, rather than a special memory capacity in one.

Spellacy (1970) conducted a similar experiment. This time, he used pipe organ tones with differing timbres and tone pulses. These pulses were temporal patterns made up of 100, 200, 300, or 400 msecs duration, with patterns differing by inter-pulse interval. As in the Spreen et al. experiment, stimulus-recognition foil intervals of 1, 5, and 12 seconds were used.

There was some difference in the results, however. The laterality effects disappeared with the 12 second stimulus-recognition foil interval, and only the music condition produced a left ear superiority.

Spellacy believed that the disappearing laterality effects were not necessarily due to perceptual phenomena, as stated in the Spreen et al. paper. He pointed out that it could be the left ear which loses most information during the waiting period. Possibly the left ear-right hemisphere combination is superior perceptually, but inferior in terms of memory, the opposite being true for the right ear-left hemisphere combination.

Spellacy's later research (Spellacy & Blumstein, 1970a) led him to study the boundaries between the proposed verbal-nonverbal dichotomy. These authors used 58 right-handed male subjects with no histories of hearing defects. Interest was aroused by a result obtained by Shankweiler and Studdert-Kennedy (1967a), where no ear preferences were found for steady state vowels. Are vowel sounds processed as language or non-language? The subjects were divided into language expectation and non-language expectation groups, and presented with the dichotic stimuli.

The results appeared to be largely consistent with the subject's expectations concerning the kind of stimuli he would be receiving. Both groups showed superior recognition for consonant-varied syllables presented to the right ear. However, the language expectation group showed right ear superiority in the recognition of vowel-varied syllables, while the non-language expectation group showed left ear superiority for the same syllables. The subjects showed little difference in left ear performance level, but right ear performance was markedly different in the two groups.

In discussing their results, Spellacy and Blumstein cite personal communications with Dr. O. Spreen of the University of Victoria. While investigating the physical parameters affecting ear preference in dichotic listening, Dr. Spreen found that the right ear superiority for the recall of words disappears as high frequencies are eliminated by passing dichotic pairs through a low pass audio-filter. The right ear preference disappears as the speech frequencies associated with consonant identification are filtered out.

Taking Spreen's work, and their own results, into account, Spellacy and Blumstein propose the existence of a speech signal analyzer, in the left hemisphere, which is partially associated with the perception of high speech frequencies. The analysis produces, in the subject, the ability to identify marginal language sounds, like vowels. The ability to detect non-language sounds is reduced. Consequently, if the analysis inhibits perception of non-language sounds at the right ear, this in itself would be enough to produce an apparent left ear superiority for these sounds.

Spellacy and Blumstein (1970b) further explore the analysis of verbal and nonverbal signals. They cite Kimura (1964) as espousing an asymmetry of brain function hypothesis, which states that the performance superiority of a particular ear is a result of that ear being contralateral to the hemisphere dominantly involved in the perception of a given type of sound. Following their 1970a experiment, Spellacy and Blumstein's position is that their results are best interpreted by a one-sided asymmetry of brain function, associated with the language dominant hemisphere. Kimura's theory would predict that a strong right ear lateralization for language is associated with a strong left ear lateralization for non-language. The authors predicted that a strong degree of lateralization for one type of stimulus is associated with a weak degree of lateralization for the other.

The subjects were 116 right-handed, paid, adult, student volunteers, who had no history of hearing defects. They were assigned to a language or non-language set. Half of the dichotic pairs were CVC nonsense syllables, differing in either the initial consonant or medial vowel. The rest were context sounds designed to establish either a language or non-language set. For the language group, these context sounds consisted of one-syllable English words differing in either the medial vowel or initial consonant, while sung melodies and sound effects were used as context sounds for the non-language group. All the stimuli were created by human voices.

The results were similar to those obtained by Spellacy and Blumstein (1970a). In support of the asymmetry of brain function theory, there was a right ear dominance for language sounds and a left ear dominance for non-language sounds. When compared to nonsense syllable consonants, there was a superior right ear performance for real word consonants, perhaps due to the increased linguistic content of real speech. Melody recognition showed a left ear superiority, but the ear difference for sound effects failed to reach a significant level, although it was in the predicted direction. When music and consonant difference scores were compared, a significant positive correlation was obtained. Spellacy and Blumstein stated that this correlation indicated an active process in which increased asymmetry for one type of sound is associated with a decrease in asymmetry for the other type. Consequently, the observed changes were due to left hemisphere mechanisms, thus providing support for a unilateral, rather than bilateral, asymmetry of brain function.

Neufeld (1971) studied the developmental aspects of Spellacy and Blumstein's findings. Using their dichotic stimuli, he tested 208 children from grades two, four and six, with musical stimuli, sound effects and CVC nonsense syllables differing in medial vowel or initial stop consonant. He found a left ear advantage for music, sound effects and vowel-varied stimuli, due largely to a developmental decrease in right ear performance. Neufeld interprets these findings as lending support to Spellacy and Blumstein's hypothesis concerning the unilateral asymmetry of brain function, and the development of a left hemisphere speech signal analyzer.

In order to isolate the important parameters of the verbal-nonverbal dichotomy, the role of the human voice has also been investigated. It appears that it is the stimulus content of the vocal message, rather than the voice itself, which is the crucial factor. As previously mentioned, a left ear superiority for emotional sounds, such as laughing and crying, has been found by several authors (King & Kimura, 1972; Haggard & Parkinson, 1971; Carmon & Nachshon, 1973). King and Kimura (1972) used dichotic presentations and a verbal recall procedure, while Haggard and Parkinson (1971) used monaural presentation, masked by verbal babbling, and had a high verbal content in their stimuli. By contrast, Carmon and Nachshon (1973) attempted to remove all verbal components from their dichotic presentation-visual recall method. Thus three differing methods consistently yielded the same small left ear superiority for emotional stimuli, firmly establishing the existence of the effect.

These authors had difficulty in deciding which was the major factor in producing the left ear superiority. King and Kimura (1972) suggest that the lack of articulatory sound makes nonverbal sounds similar to vowels. However, Shankweiler and Studdert-Kennedy (1967a) found that vowels can be perceived equally well by each ear. Also Haggard et al. (1971) and Darwin (1971) have shown that under some conditions the right ear is superior for vowel sounds. Haggard and Parkinson (1971) suggest that it is the nature of the task which influences the direction of ear asymmetry, and they cite the findings of Nachshon (1970) and Spellacy and Blumstein (1970a) to support their argument.

Carmon and Nachshon (1973) offer an interesting, but speculative, answer to the question. They say that as Giannitrapani (1967) has shown the right hemisphere matures first physiologically, a possible explanation lies in the differential development of the hemispheres. Early types of learning, such as the perception of spatial, environmental and emotional stimuli, are better established in the right hemisphere. Therefore, possibly at that early developmental stage when the right hemisphere is more active than the left, engrams related to the emotions are imprinted more strongly in the former area.

Bartholomeus (Bartholomeus, Doehring & Freygood, 1973; Bartholomeus, 1974) has investigated stimulus effects in dichotic singing.

In her first experiment, she used musicians as subjects, and presented them with four kinds of stimuli, namely violin melodies, sung vowels, sung consonant-vowel combinations, and sung digital sequences. No ear asymmetry was found for any of the stimuli. Bartholomeus argued that the lack of a left ear superiority for violin melodies may be due to the fact that Bartholomeus et al. used different melodies than Kimura

(1964) and Spellacy (1970). However, this lack could be due to a combination of reasons, such as the small number of subjects per group, the 16-second interval between the dichotic stimulus and the final recognition foil, and the fact that the sought-after left ear effect had never been extended to a specialized population, like musicians. These methodological deficits prevent any realistic conclusions being drawn from the rest of the results.

In her second experiment, Bartholomeus (1974) compared dichotic singer and speaker recognition. Each of 22 right-handed undergraduate students were given two voice identification tests, which were similar in all respects save that the stimuli were sung on one test and spoken on the other. The results showed significantly more accuracy for speaker recognition, but no between-ear differences for either kind of stimuli. Bartholomeus interprets the findings as showing that sung and spoken voices are not processed in the same way. The lower accuracy for singer recognition may represent perceptual confusion as to whether to process the stimuli as language or music. In this experiment, the overall high levels of recognition accuracy may have masked any ear asymmetry.

The components of melodies have been studied, in an attempt to identify the key factor, or factors, that are perceived in musical stimuli.

Spellacy (1970) presented four kinds of dichotic stimuli to his 64 right-handed, young adult subjects. The stimuli were melodies, tonal patterns, rhythm and timbre. With half of his subjects, Spellacy used a 5-second inter-stimulus interval, and found a significant left ear superiority only with the melodies. However, there was a left ear superiority for the tonal patterns, which Spellacy feels may have been lowered by task difficulty, as indicated by the high proportion of false positive responses. No ear differences were found with the timbric stimuli.

In contrast with Bakker's (1967, 1968) studies, Spellacy obtained no ear differences for his rhythmic stimuli, which he likens to Bakker's Morse code-like signals. Bakker, however used immediate recall and monaural stimulation, thus Spellacy's task was more difficult as it contained a 5-second inter-stimulus interval and stimulus competition between the ears. These factors could account for the differences between the studies.

Since rhythm perception involves temporal discrimination, which is very important in language, the right ear might be expected to be superior for the processing of rhythmic stimuli. Indeed, Efron (1963) showed that the temporal discrimination of simultaneity and order is performed in the left hemisphere by right-handed people. However, Tsunoda (1968) has shown that when his subjects were reproducing rhythms by tapping, a delay in auditory feedback was more disruptive to the left ear, thus suggesting it to be more implicated than the right, in the perception of rhythm.

Gregory, Harriman and Roberts (1972) tried to clarify the problem. Their subjects listened to pure audiometer tones, presented alternatively to each ear at a rate of two per second. Each subject's task was to adjust the precise timing of the stimulus to one ear so that the rhythm appeared regular. In the experimental condition, where near-threshold stimuli were used, the results showed a significant difference of about 4 msecs between the conditions. Gregory et al. interpret this as showing that the stimuli to the right ear are delayed relative to the left. This suggests the dominance of the right hemisphere in the perception of rhythmic stimuli.

Essentially, the evidence for ear asymmetry in the perception of rhythm remains unclear. Doubt is cast upon the generalizability of Efron's (1963) results, as he used the visual and somatosensory modes rather than the auditory one. Also, Bakker's (1967) research involved children, and therefore may be confounded by developmental factors. Finally, Gregory et al. (1972) used very few subjects (n = 5), and an inappropriate statistical analysis. This leaves Tsunoda's (1968) finding of a left ear superiority and Spellacy's (1970) equivocal results. Obviously, further careful investigation is needed in this area.

Ear asymmetry in musicians. Another attempt at isolating the key components of melodic stimuli was made by Gordon (1970). He used 20 young, right-handed, male adults, whom he classified as musicians. Two tests of musical functions were devised so that the melody and rhythm were separated from chords and timbre. The melody and rhythm test consisted of dichotically presented Baroque melodies played on a recorder, an instrument largely lacking in timbre and chordal variation. These melodies were matched for rhythm and pitch. In the second test, a series of chords from an electric organ were presented dichotically.

Gordon's results show a slight, non-significant left ear superiority for melodies, and a significant left ear superiority for chords. However, the fact that in a pre-test situation involving digits, he failed to replicate a right ear superiority indicates the possible presence of extraneous variables in his experiment. Also previous findings of a left ear superiority for melodies have been confined to non-musicians, Bartholomeus et al. (1973) obtaining no asymmetry in her experiment where she used musicians as subjects. Nevertheless, Gordon's musicians did show a left ear superiority for chords, and he believed this finding was largely due to the non-temporal aspects of the stimuli. Presumably, Gordon believes it is the chordal and timbric aspects of the stimuli, which are processed in the right hemisphere, rather than the temporal and rhythmic qualities.

Cook (1973) also used musicians in his investigation of the perception of musical stimuli. His subjects were 20 students from the second semester of freshman music theory classes, and the task they were given involved the visual recognition, rather than auditory recall, of the stimuli. Dr. Cook's study is interesting in that he is not a psychologist, but a music teacher. Consequently, his perception of the problem is somewhat different. He himself composed the dichotic melodies, and recorded them simultaneously on two Wurlitzer electronic pianos. This technique, however casts some doubt on the simultaneity of onset of the stimuli. After hearing each pair of melodies, the subjects were presented with four musical phrase notations, and asked to identify the correct pair.

The results showed a significant left ear superiority for melody perception. Statistical analysis was by a non-parametric test, in a situation where most psychologists would have preferred a more powerful parametric measure. Nevertheless, a clear indication of left ear superiority was obtained for the processing of these stimuli.

Bever and Chiarello (1974) also used musicians as subjects in their experiment, but obtained different results.

They began their investigation with the notion that musicians and non-musicians process musical stimuli in different ways. They quote Werner (1948), who stated that in advanced musical apprehension a melody is made up of single tonal motifs and tones which are distinct elements of the whole construction. This fits with Meyer's (1956) idea that the recognition of "meaning" in music is a function not only of perception of whole melodic forms, but also of concurrent appreciation of the way in which the analyzable components of whole forms are combined. In other words, Bever and Chiarello theorized that musicians, because of their experience with the stimuli, would process speech and music in similar ways.

In order to test their hypothesis, Bever and Chiarello used two groups of right-handed subjects, and a set of 36 tonal melodies. The subjects were divided into non-musicians, those with less than three years of music lessons at least five years before the study, and musicians, those with more than four years of lessons who were practicing their art at the time. During each trial, the subject was presented monaurally with a 12- to 18-note tonal melody sequence. After a 2-second pause, a 2-note excerpt was presented to the subject, who was asked if it was part of the sequence, or if that sequence had been heard previously. A one and one-half octave scale was used, starting from the note C at 256 hertz. Each tone was 300 msecs long and of equal intensity to all the others. Three-quarters of the 2-note excerpts were from the tonal melodies, one-fourth were not. One-fourth of the melodies recurred as later stimuli. For one-half of the trials, the subject was presented with a tonal melody, while for the other half, he received a parallel set of materials in which the tone sequences were rearranged, disrupting the melodic line somewhat.

Bever and Chiarello found that musically sophisticated listeners could accurately recognize isolated excerpts of tonal sequences, while musically naive listeners could not. However, both groups could successfully recognize whole sequences. The nonmusicians performed this task better when stimuli were presented to the left ear, while the right ear was superior in the musician's group. The authors believed that most of the differences between the groups of listeners could be attributed to differential performances of the right ear. Left ear performance did not differ significantly between the groups. The results support Bever and Chiarello's notion that musically sophisticated subjects can organize a melodic sequence in terms of the internal relationship of its components.

These findings lend support to Levy's (1974) idea that the right hemisphere acts as a Gestalt synthesizer, while the left hemisphere contains a stimulus analyzer. Bever and Chiarello believe that as a person's capacity for musical analysis increases, the left hemisphere becomes more involved in the processing of music.

The question remains as to why the studies of Cook (1973) and Bever and Chiarello (1974) obtained conflicting results. Two possible explanations come to mind. First, Cook used dichotic stimulation, while Bever and Chiarello made their presentations monaurally, thus the competition between the auditory pathways was not the same. Secondly, their definitions of "musicians" are different. The crucial fact may have been that the musicians in the monaural study were currently practicing, but although Cook's subjects were in music theory classes, there may have been non-practitioners among them. In fact, it is possible that different definitions of the word "musician" could have contributed to the varied results of Gordon (1970), Bartholomeus et al. (1973), Cook (1973), and Bever and Chiarello (1974).

The present study is an attempt to clarify the differences between the results of these studies. Essentially, it is an extension of Bever and Chiarello's work, using dichotic stimulation, violin melodies, and perhaps a clearer definition of the word "musician."

CHAPTER II

THE RELEVANCE OF HANDEDNESS IN THE STUDY OF CORTICAL FUNCTIONING

Handedness has been noted since the beginnings of recorded history. The Book of Judges in the Old Testament of the Bible, and the works of Plato contain references to which hand men use to perform various tasks. With the growth of the human sciences, an obvious problem has been to account for left-handedness. For the neuropsychologist, handedness seemed like an obvious external index of brain function. This hypothesis was strengthened by the discovery of the clear connection between lesions of the motor cortex and contralateral hemiplegias. However, over the years, the studies of handedness have failed to shed light upon many areas of cortical functioning. Perhaps handedness has little relevance in the study of the human brain.

This chapter seeks to assess the value of a continuing study of handedness. Methods of assessment of laterality and causal theories are discussed, along with some of the more recent studies which attempt to link handedness to various aspects of cortical functioning. Final conclusions are drawn from this review, and suggestions made concerning the etiology of handedness.

The Measurement of Handedness

Over the years, various results have been obtained from studies allegedly measuring the frequency of occurrence of left-handedness. Hécaen and Ajuriaguerra (1964) cite 50 studies made over the last century, and note that the frequency ranges from 1% to 30%. For example, Wallin (1916) reports that 2.8% of the normal population is left-handed, while Dubar (1939) says the figure is 21.8%. More modern authors, such as Satz (1972), put the frequency of naturally occurring left-handedness at about 8%.

Levy (1974) speculates that the true incidence of sinistrality has, in the past, been masked by the social pressures of conforming to the norm of right-handedness. She believes that as this pressure has decreased over the last 50 years, so the incidence of left-handedness has increased, until it has recently reached a fairly stable level. The studies cited by Levy range from Hildreth's (1948) frequency count of 2.2% in 1932 to approximately 11% reported by McNamee (1968).

Other studies attempt to assess sex as a factor in the frequency of left-handedness. Hécaen and Ajuriaguerra published data from nine such studies. Seven of them state that men are in the majority of left-handed populations, in amounts ranging from 54% to 67%. The other two studies report that there are slightly more women in the left-handed population.

There are several reasons for these wide ranges of results. The most important is that many of the authors have operationally defined handedness in somewhat different ways. In connection with this, is the fact that the differences in percentages clearly depend upon the method of investigation. Also many of the studies used a small number of subjects, which obviously were not representative samples of the normal population. Finally, many of the studies involved different populations, ranging from elementary school students to manual workers. Of course, as might have been expected, age proved to be an important variable in the former group, thus invalidating some of the findings.

A selection of the definitions used, illustrates this difference. Brain (1945) believes that a person is right-handed if he uses his right hand for the finest and most precise movements, and if he carries them out best with this hand. Roudinesco and Thyss (1948) state that a left-handed person is one whose left hand is more skilful than his right, or who at least finds this to be so if no outside influence has thwarted his natural disposition. Rife (1922), using a questionnaire concerned with acts performed with one hand, assumes that a person is left-handed if he performs one of these acts with his left hand, and if he considers himself to be left-handed or ambidextrous. Hécaen and Ajuriaguerra (1964) say that the essential factor in the study of right- and left-handedness is the relative adroitness of the two hands, and the relationship between this adroitness and the frequency of manual preference. It appears that there is ample enough variation in these definitions to account for the variability of the results!

After defining the problem, a method of investigation must be selected. These methods may be divided into four types, namely morphological characteristics, questionnaires, tests of manual dexterity, and other tests.

Morphological Characteristics

Morphology in handedness concerns the asymmetry of the limbs in terms of bone and muscle development. This method reflects not only primary characteristics, but also the extent of use of the limb. The latter effect is shown in the wasted appearance of an arm after several months in a plaster cast. Morphological characteristics have been measured in terms of dynamometer readings, but they test strength and not skill, which may be the crucial measure in handedness.

Stambak, Monod and Ajuriaguerra (1960) attribute great significance to extensibility and synkinesis. Extensibility is shown in the upper limbs by the angle made by closing the forearm on the arm. Usually the angle of closure is more marked on the least-used side. The study by Stambak et al. showed that only 23% of a group of left-handed children showed greater flexibility on the left side. After the age of ten years, synkineses induced by the more skilful hand are decreasing; thus in a right-handed subject, the left hand brings about more synkinesis than it would in a left-handed one. Using this fact, the authors reported that about 24% of the children in their sample were left-handed.

There are several drawbacks with this method of investigation. As mentioned above, closure could be reflecting the size of the limb, while normal decreases in synkinesis do not appear to have been standardized. Also both studies have large groups of subjects, 19% and 28% respectively, who show no laterality as measured by the test. The lack of a treatment effect in these groups could be attributed to either crudity in the methods of measurement, or a poor choice in the population used to demonstrate these morphological characteristics. It is common to find that such groups are labelled 'ambidextrous', and then largely ignored.

Questionnaires

The big advantage with the use of questionnaires lies in the fact that they provide a large amount of information in a relatively small amount of time. There are many such lists of questions related to handedness, of which Bloede's (1946) is typical. He asks which hand the subject uses for each activity listed in the questionnaire. The usual items include threading a needle, eating with a spoon, blowing the nose, writing, drawing, playing tennis and using scissors.

There are usually 15 to 20 items on each list. Some questionnaires seek information concerning the inherited aspect of handedness, asking the subject to identify the people in his extended family who are left-handed.

The biggest drawback with the questionnaire method of investigation lies in the inaccuracy of the information gathered. It is likely that some of the subjects provide the experimenter with the information that they think he wants, while others are simply mistaken in their answers. These are the main sources of the inaccuracies.

A study by Satz, Achenbach and Fennell (1967) clearly pinpoints the problem. They were interested in the correlation between manual laterality and speech laterality. First, they asked the subjects, male and female college students, to classify themselves as being right-handed, ambidextrous, or left-handed. Then they tested them for laterality on dynamometer hand strength, finger tapping, and fine motor dexterity. Using these manual tests as the standard, they found, among their group of self-classified left-handers, 17% who were strongly right-handed and 22% who were ambidextrous. Results like this cast severe doubts on the use of questionnaires as a method of investigating handedness.

Tests of Manual Dexterity

Tests of manual dexterity have proved to be more reliable indicators of handedness than either morphological characteristics, or questionnaires. There are many different batteries of this kind of test, all of which cover similar material.

The tests of Clark (1957) are typical. The first test is of manual preference, and the subject is asked to unscrew the top of a bottle, touch an object above his head with one hand, and throw a paper ball, aiming at a point. The second test concerns comparative skill, the subject having to get five, small metal balls into a narrow tube with the aid of pincers. A note is made of the time taken for the task, using each hand in turn. The third test is of comparative rapidity in an activity closely related to writing, such as making little crosses. Again the difference between the hands is noted. In the fourth test, the subject is asked to write a set of numerals with both hands simultaneously, with the eyes closed. The experimenter looks for the possible appearance of mirror writing, which is believed to be a product of the dominant hand in these situations. Next comes the Van Riper Critical Angle Board Test, and finally a test of simultaneous diadocokinesis of both hands, in which the experimenter observes which hand fatigues more quickly, and on which side the movements first become disturbed.

These tests of manual dexterity appear to be much more sensitive to the detection of handedness, and consequently it is not surprising that many of the more recent studies, e.g., Kimura and Vanderwolf (1970) and Ingram (1973), use this technique. Some authors, such as Provins and Cunliffe (1971) and Satz (1972), have used a combination of questionnaires and tests of manual dexterity in their work.

The former study is of particular interest here, because the authors discuss the reliability of some motor performance tests of handedness. They used 20 normal male subjects, 10 right-handers, and 10 left-handers, who were matched for degree of handedness by answers to a questionnaire. The subjects were then tested on seven different motor tasks on two separate occasions. With the preferred hand, test-retest correlations of motor achievement proved significant on all tasks with the preferred hand. However, only three of the seven test-retest correlations for the non-preferred hand were significant. Only in two of the seven tasks was the difference in performance between the hands maintained. These two tests concerned handwriting and finger tapping.

These results show the reliability of manual dexterity scores for the preferred hand, and the variability of these scores for the non-preferred hand. Provins and Cunliffe speculate that this variability may account for the discrepancies found by Satz between self-classified left-handedness and test scores. The tasks where the difference scores are reliable, i.e., handwriting and finger tapping, are those in which one hand has been maximally trained, while the other has been virtually neglected. This indicates that the more reliable manual dexterity tests tend to emphasize learning rather than genetic influences.

Electromyographic Tests

Cernacek (1961) proposed a test of one-sided preference based on the results of electromyography of the motor spread to a symmetrical muscle during voluntary or conditioned contraction of a muscle on the other side of the body. This contralateral spread was noted in 77.6% of the test situations involving a group of 21 normal subjects. The frequency of contralateral motor spread is greater on the dominant side of the body. The main drawback with this test is that while it produces statistically significant results for groups of subjects, it is unreliable for individuals.

Waada's Sodium Amytal Test

Waada and Rasmussen (1960) proposed a method for the detection of language dominance, involving the injection of sodium amytal into the internal carotid artery. This always results in a contralateral sensory and motor hemiplegia and often a hemianopsia. If the injection is given on the non-dominant side, the patients deny having had a transitory paralysis, while if the dominant side is injected the temporary hemiplegia is admitted. Unfortunately, these injections are painful for the patient, and therefore are used only in cases of necessity, such as the diagnosis of brain damage.

From this brief review of the measurement of handedness, it is clear that a seemingly simple question is indeed complex.

It has been noted that there are several ways of defining the dominant hand: (a) it is the hand which the subject reportedly prefers; (b) it is the hand which is larger and stronger; (c) it is the hand which enables the subject to perform better on tasks of fine motor co-ordination; (d) it is reflected in the direction of the differential performance of the hands on tests of manual dexterity; (e) it is determined by physiological tests, involving either muscle activity or transitory paralysis.

It is not surprising under these circumstances that there is little agreement among authors as to the occurrence of left-handedness in the general population. However, several points do appear to be clear. First, the scores for the preferred hand on manual dexterity tests appear to be reliable. Second, there is a certain amount of variability of scores from the non-preferred hand on these tests. Third, this variability is, of course, reflected in difference scores. Fourth, the performance variability seems to be more pronounced in self-classified left-handers. And finally, learning seems to play an important part in those few activities, such as handwriting, where the relative performance of the hands remains constant.

The Development of Handedness

The age of onset of handedness is perhaps one of the best understood facets of the topic.

Careful observation of neonates and young children have been made. Gesell and Ames (1947) believe that laterality is first observed in the tonic neck reflex. In the infant, this reflex consists of an extension of the members on the side of the body to which the face is turned, while the opposite members are flexed. It is present 8 weeks after birth, is less evident at 12 weeks, and has usually disappeared by 20 weeks. According to Gesell and Ames, the spontaneous asymmetry of the first weeks is masked by symmetry at 5 to 6 months. After another month, the bilateral patterns are submerged, in their turn, by new unilateral patterns. Gesell and Ames believe that this is the point at which definite right, or left, handedness begins to develop. They were able to predict handedness from the tonic neck reflex in 14 of their 19 subjects. Most authors agree that no manual preference can be demonstrated before 7 months of age. Further data from the Gesell and Ames study showed that at 18 months, 68% of the sample used their right hand to hold a pencil, while at 24 months this figure had risen to 92%.

Some authors believe that there are fluctuations in handedness at various times during the developmental period. For example, Orton (1934) notes that periods of instability occur between 2 and 3 years and again between 6 and 8 years. However, it is generally accepted that unilateral hand preference appears in the young child within the first year of life, and becomes more strongly established between the ages of 2 and 5 years. Studies by Gesell and Ames (1947), Lippman (1927), Hildreth (1948, 1949), and Cernacek and Jagr (1969) support this hypothesis.

Ingram (1973) found that laterality among young children varied according to the task. Her subjects were 84 children, aged 3 to 5 years, who were classified as being right-handed following testing with a hand preference battery. The experimental tasks involved hand strength, finger tapping, hand positioning and finger spacing. Her results show that an asymmetry of motor functions was evident as early as 3 years, but that the preferred right hand did not possess universally superior manual skill. The right hand was found to be better on the hand strength and finger tapping tests, while the left hand was better on hand positioning and finger spacing.

This study by Ingram suggests that the development of handedness is a more complex process than it was originally thought to be.

Few of the studies concerning hand preference indicate changes in the proportions of handedness relative to age. However, Levy (1974) cites an experiment performed by Heinlein in 1929, which suggests that this may not be the case. Heinlein used a steadiness test, a tapping test, and a target test in order to assess manual dominance. On the steadiness test, she found a tendency for dextral preference to increase with age, while it decreased on the tapping and target tests. Hécaen and Ajuriaguerra's (1964) evidence seems to be in agreement with Heinlein's. They noted that the number of clearly left-handed children increases with age, while the numbers of right-handers and ambidextrals decreases.

There are several explanations for these results. If manual dominance can be assumed to be influenced by genetic factors, the phenotypic expression of the genotype should emerge with increasing strength as a function of maturation. Also, a successful attempt at using a particular hand is reinforced by success, thus increasing the tendency to use that hand on subsequent occasions. Finally, as Ingram (1973) suggests, some tasks may be performed more adequately by a particular hand.

The Genetic Component

Annett (1964) has proposed a genetic model to account for the variable frequency of left-handedness, and other phenomena connected with the topic. She proposes that handedness is determined by two alleles, D, which manifests right-handedness and R, which manifests left-handedness. D is usually dominant and R usually recessive, but there is partial penetrance of R in heterozygotes. The possibility that left-handedness is caused by an imperfectly recessive gene was suggested by Rife (1950). Rife's suggestion that heterozygotes may become right, left, or ambidextrous is a crucial factor in Annett's model.

She believes that the dominant cerebral hemisphere, meaning the hemisphere which leads in language functions, is closely linked with handedness so that: (a) dominant homozygotes (DD) are consistent right-handers with speech more highly developed in the left hemisphere; (b) recessive homozygotes (RR) are consistent left-handers with speech mainly in the right hemisphere; (c) heterozygotes (DR) may use either hand for skilled activities and develop speech in either hemisphere.

The majority of heterozygotes will develop right-handedness and left hemisphere dominance, but in some heterozygotes the recessive gene will produce tendencies to left-handedness. The sinistrality may vary from slight to strong, but careful examination should probably reveal the presence of the dominant gene in some skill with the right hand. If there should be any physical trauma to either hemisphere or the limbs, the heterozygote may develop the use of the alternate hemisphere and limb. Homozygotes injured in the hemisphere predisposed to become dominant will be equally unskilful with either hand.

Annett assumes that the proportions of D and R in a population would be 80% and 20% respectively. Therefore the resultant genotypes, DD, DR, and RR, would occur in 64%, 32%, and 4% of the population respectively. This would produce an incidence of left-handedness ranging from a minimum of 4% to a maximum of 36%. The degree of expression may be influenced by many factors, including age, sex and defects of the central nervous system. An assumed degree of expression of 25% would produce familial left-handedness close to the level reported by Trankell (1950).

Trankell's study took place in Stockholm. He found that of his 990 right-handed subjects, 23% had a left-handed relative in the extended family. With 613 left-handed subjects, this figure rose to 52%. He concludes, in agreement with Annett, that right-handedness is caused by a Mendelian dominant gene, while left-handedness is probably produced by a recessive one. He goes on to say that the role of the environment blurs the heriditary mechanism. Relying on the proportion of left-handed persons in the Swedish school population being 7% to 8%, he believes that two-thirds of the people with any predisposition to left-handedness have become clearly right-handed before school age.

Annett uses her model to explain three problems associated with handedness. In accounting for the finding of variability of left-handed test scores, she believes they are caused by heterozygotes, while recessive homozygotes are much more consistent left-handers. She accounts for the decline in left-handedness with increasing age by proposing that the dominant gene increases its control during growth. Social pressures, thinks Annett, can only be effective with heterozygotes who have a hereditary predisposition to use either hand. Handedness in the homozygote cannot be changed by social pressure.

Satz (1969) published a paper which supports Annett's position, and adds to the theory. He cites Rife's (1950) investigations involving handedness in twins, where a higher frequency of intra-pair differences was noted among twins who had a family history of left-handedness. (The subjects in the study were both monozygotic and dizygotic twins.) Rife postulated that those twins who show intra-pair discordance in hand preference are heterozygotes, whose environment in utero influenced their laterality.

Satz stresses two points from Rife's study. The first is the relationship between familial sinistrality and heterozygosity, and the second is the concept of plasticity of the ability to shift handedness in normal heterozygotic individuals. The implication is that twins who are heterozygous for handedness may be more affected by prenatal environmental factors than those who are homozygous.

Annett (1967) collected more data concerning the lateralization of handedness. With five groups of subjects, she used two questionnaires, while three other groups performed a series of manual tasks. Annett hypothesized a monofactorial model for the genetic basis of handedness, assuming the phenomenon to be caused by the factors l and r, representing left- and right-handedness respectively. She further assumed that the two factors should produce phenotypes in the ratios of $r^2:2rl:l^2$. The data from each of her seven groups of subjects, N = 1226, supported her hypothesis. Overall, 66% of her subjects were right-handed, 30% were ambidextrous, and 3.5% were left-handed.

However, on the basis of data collected from more than one generation, Annett changed her position. The results of her 1967 study now led her to conclude that handedness results from a polygenic distribution. This position was maintained in a later study (Annett, 1970), where she classified hand preference by an association analysis. Annett saw the polygenic foundation as being manifested in a continuum of handedness.

Annett's position has changed again over the last few years, and now she places less stress on the importance of genetic factors. She now believes that two main factors cause handedness (Annett, 1972). One is the normal distribution of the differences between the symmetrical halves of the body, which exist in all lateralized species, and are probably dependent on accidental influences in early development. The second, possibly a genetic factor, is specific to humans, and pushes the normal distribution of handedness towards dextrality.

Next Annett (1973) turned her attention to left-handers. This study indicated that the incidence of sinistrality in the children of two left-handed parents is dependent upon chance alone. In another study (Annett, 1974), a unimanual peg-moving task was given to families in which both parents were left-handed. Considerable pains were taken in order to remove from this study any families where the left-handedness of either parent was thought to arise from earlier trauma. When the scores from both hands of each subject were contrasted, the group mean for the children was 0.02 secs, as compared with -0.64 secs for their parents, and 1.00 secs for a control group of randomly selected children. Of the 45 children in the experimental group, 23 performed the task faster with their right hand, while 22 were faster with the left. Annett takes these results as further evidence that although right-handedness may be inherited, left-handedness is not.

In the light of this more recent research, it is rather surprising that Levy (1974) criticizes Annett's original genetic mechanism model. She believes that the model predicts a perfect correlation between cerebral dominance and handedness, except in cases of brain damage. Levy goes on to say that, according to Annett's model, left-handers should never develop permanent aphasia from a left hemisphere lesion. She then cites a study by Luria (1947), which disproves Annett's supposed hypothesis.

These criticisms appear somewhat harsh. Now that evidence, such as that of Blumstein and Cooper (1974), is indicating the active involvement of both hemispheres in the language processing of right-handers, and the problems mentioned in the measurement of handedness, it seems unlikely that perfect correlations can be predicted. Also, Annett originally thought that lateralization probably reached a maximum at some point in the maturation of the individual, by which time, even in ambidexters, much of the earlier plasticity is lost. Such an explanation could account for the incidence of aphasia in left-handers with left hemisphere lesions. Under such circumstances, it seems more appropriate to use the term "dysphasia" in describing the patients of Luria (1947). Possibly, Levy's criticisms are more in the way of justifications of the presentation of her own model of the genetic mechanisms involved in handedness and speech dominance.

Levy and Nagylaki (1972) postulated a genetic mechanism which could account for the four observed hand-hemisphere combinations. It is a twin locus model, with two alleles per locus. The L-l locus determines which hemisphere will be language dominant. The L allele is dominant and produces left hemisphere language, while the l allele is recessive and produces right hemisphere language. The second locus, C-c, decides whether hand control will be via pathways contralateral, or ipsilateral, to the dominant hemisphere.

A possible mechanism whereby this determination could be controlled is in the percentage of fibres which decussate in the brain stem.

This model yields nine genotypes, which result in four manual-cerebral phenotypes: (a) the locus-allele combinations of CCLL, CCLl, CcLL, and CcLl will produce right-handers with language primarily in the left hemisphere; (b) the ccll combination will produce right-handers with language primarily in the right hemisphere; (c) the ccLL and ccLl combinations will produce left-handers with language primarily in the left hemisphere; (d) finally, the locus-allele combinations of CCll and Ccll will produce left-handers with language primarily in the right hemisphere.

Levy and Nagylaki point out that their model can account for demonstrated recovery rates from aphasia. They assume that only LL genotypes will become permanently aphasic following lesions of the language areas of the left hemisphere. People with Ll, or ll, genotypes will recover from such lesions. Consequently, this accounts for the reported proportional recovery rates of right- and left-handers.

The authors suggest that people with the recessive homozygote at the Ll locus, i.e. left-handers with language in the left hemisphere, may have the most perfect bilateral symmetry of function. They use the aphasia recovery data to postulate a substantial degree of plasticity for language reorganization in such people. It could be that the degree of lateral specialization may be simply a function of the number of dominant L alleles which are present.

Annett's (1964) model, and that of Levy and Nagylaki (1972) are simple and attractive. However, it is much easier to account for the facts post hoc, especially if one can make large assumptions along the way. Unfortunately, in the light of Annett's later research, the simple elegance of the original models cannot be maintained. At the present time, the mechanism which controls the transmission of handedness remains elusive, and environmental factors may play a greater part than psychologists realized.

Pathological Factors

It has been reliably reported over the years that there is a higher frequency of left-handedness among certain clinical populations. Mentally retarded people and those suffering from epilepsy are two such populations. Hildreth (1949) and Bingley (1958) report that the incidence of left-handedness among these two groups shows at least a twofold increase over the incidence in normal, control children. They found an 8% incidence in their control groups and a 17% incidence among their experimental subjects. This is usually explained by postulating that the clinical populations have suffered damage to the left cortical hemisphere, which has caused a mild hypofunction of the right hand of natural right-handers, causing the child to use his left hand for manual tasks. Bingley calls this Pathological Left Handedness and stresses its difference from the inherited kind.

The frequency of left-handedness also varies quite widely between twin and non-twin populations. Nagylaki and Levy (1973), in reviewing the literature, reported that 10.9% of dizygotic twins were left-handed, while the incidence among non-twins was 6.6%. These authors concluded that the increased frequency in dizygotic twins was due to central nervous system damage, which had produced a switch in native handedness. In the state of New York in 1955, twins accounted for 3.1% of admissions to institutions for the mentally retarded, while only 1.9% of the general populations were twins. Gordon (1920) found that in eight sets of twins, the member of each pair who was mentally retarded, was also left-handed.

Satz (1972) has proposed an explanatory model for pathological left-handedness in order to answer the following questions: (a) Assuming that brain lesions are randomly distributed, why are there no reports of pathological right-handedness, in addition to pathological left-handedness? (b) What is the explanation for a consistent 17% incidence of left-handedness among certain clinical populations? (c) Why is this increased incidence of left-handedness reported consistently among mentally retarded and epileptic people, as opposed to other clinical populations, such as adult accident victims?

Satz begins by assuming that the normal population consists of 92% right-handers and 8% left-handers. With a clinical population, who begin with the same incidences, he assumes that there is a 21% shift in laterality caused by lesions in the contralateral hemisphere. Twenty-one per cent of the natural right-handers became pathologically left-handed, while the same proportion of natural left-handers became pathologically right-handed. The end product is a population with incidences of 17% and 83% of left- and right-handers respectively. Satz goes on to say that the ratio of PLH to PRH is estimated as 11.5:1, which is identical to the ratio between normal right-handedness and left-handedness. Therefore, the reason that pathological right-handedness is seldom discussed is that its true frequency is rare, i.e., it is restricted by the lower frequency of natural left-handedness in the population.

He derives five hypotheses from his model: (a) Four out of every five mentally retarded or epileptic subjects who are manifest sinistrals should have a primary lesion in the left hemisphere. (b) The incidence of manifest left-handedness will be raised primarily in brain-injured populations with perinatal, or early post-natal injury, i.e., while the functioning of the central nervous system is still relatively plastic. (c) If a mentally retarded, or epileptic subject is left-handed and has a left hemisphere lesion, there is a 71% chance that he is a pathological left-hander.

(d) There should be at least one pathological left-hander for every natural left-hander in these specified clinical populations. (e) The incidence of familial left-handedness should be higher in normal left-handed children than in brain injured left-handed children.

Satz tested his model on data from the book by Penfield and Roberts (1959). He found support for hypotheses (b), (c), and (d). The data did not contain information concerning hypotheses (a) and (e).

This model has many of the same merits and faults as the one proposed by Annett. It is attractive, logical, and fits most of the facts. However, the model would be hard to substantiate by predictive, hard-nosed experimentation. While mental retardation can be diagnosed at birth, specific brain damage seldom can. Some forms of mental retardation and the vast majority of epilepsies are diagnosed in early childhood. In both these situations, pathological handedness cannot be separated from the natural kind. It would probably be impossible to find unconfounded groups for experimental work.

The surprising fact arising from the model in question, concerns the shift in Satz's position. Three years earlier, he was espousing Annett's cause, while his present model conflicts with hers in some respects. For example, he seems to be saying that any contralaterally brain-damaged child can effectively switch hands, while Annett says this is impossible for homozygotic people. In fact, Annett's ideas about heterozygosity could deal quite nicely with pathological handedness, except for the reportedly consistent 17% incidence level, which anyway may not be a reliable figure, as noted previously. Annett would predict a more variable level of incidence. Also, she would find it much easier to account for the report by Hécaen and Ajuriaguerra (1964) of cases of infantile right hemiparesis in patients who still use their right hand!

The identification of pathology as one of the determinants of handedness may prove to be more important than Satz's model accounting for its incidence.

The Evolution of Handedness

There has been some speculation as to whether there is an evolutionary process behind the development of handedness. Of course, this must be described as laterality in all but the human species.

Warren (1958) reviewed the literature on this subject, and added his own experimental findings with cats and monkeys. He found a constant decrease in the percentage of individuals showing laterality preferences, moving up the phylogenetic scale from the rat to the chimpanzee. To summarize Warren's results, 85% of 105 rats, 71% of 51 cats, 57% of 101 monkeys, and 46% of 31 chimpanzees used a preferred limb in more than 90% of the tests given. From these results, he concludes that the evolutive tendency goes from initial strong preferences as regards laterality, in the lower species to an ambidexterity in the primates, including man. These conclusions strongly favour the influence of social factors on manual preference and relegate hereditary factors to a secondary place.

An important difference has been shown to exist between laterality in animals and handedness in man. Approximately half of each species has a left, or right, preference. In both rats (Peterson, 1934) and mice (Collins, 1968, 1969) selective breeding experiments have demonstrated that paw preference is without a genetic basis.

Right-handedness is a cross-cultural phenomenon. There is no evidence of cultures whose members are predominantly left-handed. This leads one to believe that genetic and evolutionary factors account for the origins of handedness.

Hécaen and Ajuriaguerra (1964, p. 117) discuss hypotheses pertaining to the survival value of right-handedness. One such idea suggests that the greater flow of blood to the left hemisphere facilitates the better adaptation of right-handed people to their environment, with the consequent survival of the fittest. Another theory suggests that in a fight, the right-handed primitive man was able to defend his heart with his left arm, while still continuing to fight. This was a situation in which the left-handed primitive man was inferior. This theory does not hold weight when one considers that most wild animals go for their victims' throat, which is also the target of the modern day soldier in hand-to-hand combat, the heart being comparatively well protected by the ribs.

However, there have been theories put forward which suggest that social pressures in the time of primitive man influenced the direction of handedness.

Blau (1946) points out that in Neolithic times, when primitive cultures began, stone knives made their appearance. When using these tools, one hand would have to be selected for a special activity, but the decision would still be by chance, or by accident. With the Bronze Age, the precision and complexity of the tool increased, and as it was better adapted to one hand than the other, it was necessary for the possessor to use the tool in the same way as the artisan who made it. From then on, manual preference was born, and it was transmitted to an increasing extent because of social rules and religious customs. However, the obvious drawback with such a theory is the assumption that handedness in the original artisans was not randomly distributed.

Hécaen and Ajuriaguerra (1964, p. 124) cite Hertz's theory that the origin of the preference of the right hand was a half-aesthetic, half-moral necessity. He believed that in the exterior world, as well as in the institutions of the primitive group, the law of polarity prevailed. As the universe was divided into light and dark, good and evil, it seemed logical that man should also be divided in this way. A symmetrical division of man divided him into right and left segments, and that good became associated with right, instead of vice versa, was a matter of chance.

Levy (1974) presents an interesting and original idea to account for the ratio of right- to left-handers in primitive societies.

She begins with the assumption that from the time of the Pliocene epoch, man-like creatures were predominantly right-handed. This assumption is based on the work of Dart (1949), who explored the domiciles of Australopithecus, a small-brained, low-browed, ape-like creature. Scattered around these living areas were the skulls of baboons. Most of these had been crushed by a weapon, which was held in the right hand. Levy concludes that the right-handers were consequently the best hunters. In other words, the more lateralized people killed more food, were stronger, and produced more healthy, right-handed offspring.

But how do left-handers come into the picture? There must have been some factors at work, which stopped them from dying out completely. Levy thinks that the brains of the left-handers were more symmetrical, thus making them more adept at tasks involving spatial concepts. Such a task might be the setting up of an animal trap, or a plan to drive a small herd of animals into an enclosed space.

Therefore, it seems reasonable to assume that each primitive tribe would contain a proportion of hunters, and a proportion of planners. The groups with either too many hunters or too many planners would have difficulty in obtaining enough food to eat. The groups with the best chance of survival would be those with a large majority of hunters, and a small minority of planners. Thus groups with these kinds of proportions of right- and left-handers were the most successful. Levy believes this to be the basis for the proportions of these populations found in today's societies.

These sociological speculations, while interesting, appear to be of limited importance in the present-day study of handedness and cortical functioning.

Perhaps it is worthwhile to mention a few of the more recent manifestations of social pressures, which may persist today in only the more primitive of the western sub-cultures. Undoubtedly, when the words "gauche" and "sinister" are used to describe left-handedness, they reflect the fact that for many years it was undesirable to be left-handed. Under these conditions, many parents and teachers tried to influence children to be right-handed. From this grew the modern day myth that forcing left-handed children to change hands causes stammering. This, of course, has not been substantiated by any scientific study. However, it is easy to see that in the last few hundred years, up until this century, social pressures have been in favour of the right-handed.

One sometimes reads and hears of the difficulties encountered by left-handed people. Mostly they are overstated. There are little inconveniences in the lives of these people, such as can openers and potato peelers, which appear to be more ably manipulated by right-handers. However, the concept of handedness does not include disabilities in the non-preferred hand, consequently most left-handers adapt to these minor inconveniences without much trouble. It simply is not very important that a left-handed person takes slightly longer to open a can of soup.

Perhaps only in the skill of handwriting is the left-handed person up against a real problem. As Hécaen and Ajuriaguerra (1964, p. 85) point out, the natural tendency in writing is to pull the pen across the page. For the left-handed child, this means writing from right to left across the page. As this is not acceptable, he must push the pen. For a child using a pen and ink, writing can thus present real problems. Pushing a pen nib will cause it to scratch the paper, and the writer, dragging his hand through newly constructed letters, seriously reduces the legibility of the work. This problem is not as evident in North America as it is in Europe, due to the ball-point pen. The ball-point is easier to push, and the comparatively dry ink reduces much of the "smudging." However, there is still a need for teachers who can instruct left-handers who are learning to write. Because the pen is pushed, writing involves a different physiological process than that used by right-handers.

In view of the attention given to the disadvantages of being left-handed, it is worthwhile to mention a social advantage enjoyed by these people. In sports, the left-hander often finds it easier to gain a place on the team. In cricket, for example, a team of eleven players is considered incomplete without an equal representation of right- and left-handed bowlers. If footedness can be included, the left-footed soccer player is at an advantage in almost half the positions on the field. This situation can be extended to include many team sports. Therefore, while the right-sider is competing with approximately 90% of the candidates for half of the team places, the left-sider is competing with only 10% for the other half!

There is no clear indication of the origin of social pressures concerning handedness. However, in western civilization, at least from the time of Christ until relatively recently, these pressures have favoured right-handedness. At the present time, it does not seem to make any great difference which hand a person uses. Probably, the left-hander has a real, but not insoluble, problem with handwriting.

The Relationship Between Handedness and Cortical Functions

Studies which reflect the relationship between handedness and cortical functions have been concentrated in two areas, which are the lateralization of speech based on underlying thought processes and the asymmetry of motor abilities.

The Lateralization of Speech

Developmentally, speech lateralization appears to occur after hand lateralization. A study by Basser (1962) indicates that speech becomes lateralized about the age of 5 years. His subjects were 30 children, aged 1 to 10 years, who presented lesions which had occurred after the acquisition of speech. With children below the age of 5, right hemispheric lesions did cause speech problems. However, this was not the case between 5 and 10 years, perhaps indicating that speech is lateralized in the left hemisphere by this age. Bryden (1974) indicates that speech lateralization is complete by the age of 10 years. Apparently the onset of handedness precedes the lateralization of speech by 2 or 3 years. Bever (1971) believes that aural lateralization also precedes speech lateralization by about 2 years.

A fairly obvious hypothesis arises from these differences in ages of onset. Assuming that the laterality of motor and sensory functions are already established in a child, the contralateral hemisphere will often be in a bilateral representation of speech. The authors conclude that while a definite relationship exists between handedness and speech laterality, the unilateral hemispheric specialization of speech is less strongly established in some people. (Again, it is worth mentioning that the subjects in this study were brain-damaged adults, who were candidates for neurosurgery, i.e., they are not in a normal population.)

The study by Satz et al. (1967), which was briefly mentioned previously, was concerned with the relationship under discussion. After assessing the handedness of his 113 college student subjects by questionnaires and manual dexterity tests, he gave them a dichotic listening task. Dichotic listening has been used as an index of speech lateralization in several studies, e.g., Kimura (1963). However, as Satz et al. point out, although dichotic listening has not yet been established as a valid index of speech lateralization, it is the most convenient technique available at the present time. In their study, all but 2 of the 58 right-handers were classed as left-dominant for speech, but the results for the other groups were somewhat unexpected. Over 90% of the ambidextrous group and 50% of the left-handed group were also left-dominant for speech.

Penfield and Roberts (1959) seem to be in general agreement with Satz et al. However, they are dealing with surgical cases, where the lesions in each hemisphere are not confined to the proposed speech areas. Consequently, their reported percentages are lower, but proportionally they are not too different from those mentioned in the previous study. They found that in operations on the left hemisphere, 69.8% of the right-handers, 20.8% of the left-handers, and 45% of the ambidexters demonstrated post-operative aphasia. The symptoms were shown by 0.4% of the right-handers, 17% of the left-handers, and none of the ambidexters after surgery on the right hemisphere. There were 522 patients considered in this report. These results indicate that for most people, speech functions are localized in the left hemisphere.

Kimura (1973) approached the problem from a different angle. She collected data concerning the free hand movements of her right-handed subjects during speech, proposing that those who were left-dominant for speech would move their right hands more frequently. Her findings suggest that speaking is strongly tied to other motor behaviours, as shown by the greater activity during speaking than during non-speaking activities. Free movements, those that did not bring the limb into contact with anything, occurred almost exclusively during speaking, while self-touching movements showed no asymmetry during speech. Kimura concludes that there is some system common to the control of both free movements and speaking, and for most people, this system is based in the left hemisphere. Furthermore, when the subject was engaged in a verbal task, fewer self-touchings were made with the right hand, whereas in a non-verbal task fewer self-touchings were made with the left hand. Consequently, Kimura believes that there is a contralateral relationship between speech localization and this form of handedness.

Levy (1973) makes an interesting point regarding handwriting and speech lateralization. Her main hypothesis concerns left-handed writers and the idea that about 55% of this group have language located mainly in the left hemisphere. She suggests that those left-handed writers who bend their wrists and point their pens towards their bodies belong to the left-hemisphere language dominance group. Left-handed writers whose pens point away from their bodies are thought to have language located mainly in the right hemisphere. Furthermore, the very few right-handed writers with language mainly in the right hemisphere will also bend their wrists, and point their pens towards their bodies. To show that her hypothesis is worthy of investigation, Levy observed 31 left-handed writers and found that 58% used the inverted hand position.

Levy proceeded to test her hypothesis by tachistoscopically presenting material to the right or left visual fields of her undergraduate subjects. These students were right-handers, left-handers who wrote in the normal fashion, and left-handers whose hands were inverted during writing. The four tests involved matching words to pictures, recognizing the correct sum of two digits, selecting a similar slanted line, and locating the position of a dot within a matrix.

A pre-test was used in order to determine stimulus exposure times. The stimuli here were alphabetic letters, and it was found that the Left Inverted Group needed a longer exposure time in order to reach the same degree of accuracy as the other two groups. Levy suggests that this may be due to a difference in brain organization between the Left Inverted Group and the rest of the subjects.

In the main experiment, significant differences were found between the groups on the word-picture matching test, and on the dot-matrix test. On both these tests, the Left Normal Group was significantly different from the other two, and this again is suggestive of differences in brain organization between the groups.

Levy, quite rightly, points out that these are tentative conclusions. She cites the failure of the word-picture test in replicating the well-established right field superiority for right-handers, and believes that this effect was confounded by the subjects' page scanning. She would also have felt more secure about her conclusions had she used a larger group of Left Normal subjects.

The attraction of Levy's idea lies in its application to the classification of left-handers. Should further research prove her hypothesis, left-handers can be simply classified into left and right language dominance groups, on the basis of their handwriting method.

All of the studies mentioned here admit to a relationship between handedness and cortical speech lateralization. It is the type and degree of the relationship which is in doubt. The variability in the results points either to a complex relationship, or to experimental errors in the measurement of these variables.

The Asymmetry of Motor Abilities

As mentioned in the section concerning the development of handedness, Ingram (1973) found that in young, right-handed children, aged 3 to 5 years, the left hand was superior in tests of hand positioning and finger spacing. In discussing why this was so, she notes that Vaughan and Costa (1962) report a higher proportion of ipsilateral motor and sensory deficits in patients with left cerebral lesions than in patients with lesions of the other hemisphere. Also Wyke (1968, 1971) found that people with left-sided lesions tend to show a bilateral impairment of arm movement, while people with right-sided lesions show only contralateral impairment. In agreement with this, Gazzaniga, Bogen and Sperry (1967), working with split-brain subjects, found that the greatest impairment of finger movement occurs when the right hemisphere is required to control posture-like movements of the right hand. The left hemisphere can direct such movement reasonably well with both hands.

Ingram's conclusion was that the evidence suggests that the non-preferred, left hand receives greater bilateral innervation than the preferred, right one. However, this is not enough to overcome hand preferences, although it may facilitate the fractionated movement of individual fingers.

There is evidence of a similar kind from the animal work of Brinkman and Kuypers (1972). They used split-brain monkeys employed in a visual-motor task, while one eye was covered and the tactile guidance of movements was largely prevented. They found that the connections of the descending neural pathways in the monkey suggested that each hemisphere controls independent arm, hand, and finger movements contralaterally, but mainly arm movements ipsilaterally.

An alternate suggestion, made by Ingram to explain these examples of left hand superiority, was that the results show the influence of the right hemisphere in dealing with spatial concepts. Bogen and Gazzaniga (1965) found that human split-brain subjects were more able to perform a block design test with their left hands. Buffery (1970) provides some evidence that this is also true of normal subjects.

Kimura and Vanderwolf (1970) have suggested that the preferred hand may be characterized by synergistic rather than discrete patterns of movement. The preferred hand is characterized by a more consistent temporal pattern of the movement than the non-preferred hand. These authors further suggest that if the superior ability of the preferred hand is motor sequencing, this may be in part attributable to left hemisphere motor systems which co-ordinate both manual skills and speech sequences. In other words, one hand, or hemisphere, is preferred because of its ability in sequencing.

Here, again, a relationship is suggested between handedness and cortical functioning. However, it is different from thq hypothesized causal relationship between handedness and speech development. With motor asymmetries, the conclusion is that they exist because of the superior innervation from the left hemisphere, the spatial abilities of the right hemisphere, and the sequential abilities of the left hemisphere.

Summary

Through the years, the outstanding problem in the study of handedness has been its definition. The problem remains today, due largely to poor experimental methodology. Probably, the best method of definition may be expressed in terms of that which is being measured. A standardized battery of manual dexterity tests, accompanied by a rigorous questionnaire, would give a composite score for each individual, similar to the ones obtained by Satz et al. (1967).

It is obvious from the data presented here that handedness does not represent a dichotomy, or even a trichotomy if one includes ambidexters. Handedness is a complex concept, and could best be plotted along a continuum, with absolute left- and right-handedness at its extremes. With a standardized assessment procedure and a distribution continuum, more reliable studies can be performed relating to the true distribution of handedness in the normal population.

It appears very likely that there is a genetic component in handedness. Several models have suggested a basis for its transmission, but, in actual research, genetic relationships have largely been masked by environmental influences. The nature-nurture problem in handedness appears to be a key factor, and until it is solved, no clear understanding of the basic mechanisms will emerge.

One of the surprising facts emerging from a study of the literature has been the lack of potency of social pressures. There are no really comprehensive social theories as to why the majority of humans are right-handed. The fact that right-handedness is a cross-cultural phenomenon emphasizes the power of hereditary and evolutional factors, rather than the effects of living in a particular culture. Although in the last fifty years, the taboos concerning left-handedness have been removed, there has been no large upsurge in the frequency of left-handedness. This again weakens the position of social pressures as determinants of handedness.

Overall, in terms of the general population, handedness is a mildly interesting, but relatively unimportant, phenomenon.

How important is handedness in terms of its relationship to cortical functioning? There is definitely a relationship between handedness and speech lateralization. However, the relationship is not a simple one. The considerable proportion of subjects who do not fit the contralateral hypothesis could be due to two factors. First, the hand and speech laterality relationship is more complex than it was first thought to be, and second, these subjects reflect some deficiency in the measurement of handedness. It seems worthwhile to try to clarify this contralateral relationship. Perhaps with reliable handedness tests and a distribution continuum, the prognosis of patients who are aphasic, or who may become aphasic due to surgery, can be accurately assessed. In the same context, the relationship between cortical functioning and motor asymmetries is worth pursuing in terms of the localization of brain functions.

CHAPTER III

PILOT STUDY

Introduction

Bever and Chiarello (1974) found a right ear preference in the detection of musical stimuli, when they used musicians as subjects. Previously, a left ear superiority had been noted on several occasions with nonmusicians (Kimura, 1964; Shankweiler, 1966b). As Bever and Chiarello point out, their finding may be due to the musicians' analytic perceptions of the melodies, as opposed to the gestalt synthesis of naive listeners. The subjects in the experiment were all classified as being right-handed, and were stimulated mon-aurally with tonal melodies.

The present study seeks to extend the findings of Bever and Chiarello. Dichotic violin melodies were presented to musicians and nonmusicians, both groups of which contained subjects who were classified as right- and left-handed.

Left-handed subjects were included in this study in order to lend support to Levy's (1969) proposition that this group lacks complete lateralization. Levy has shown that left-handers have a significantly larger Verbal-Performance difference in IQ, when compared to right-handers. She believes that the former group has two "left hemispheres," in terms of the functioning of the brain. Several studies, e.g., Branch, Milner and Rasmussen (1964), show that speech is less lateralized in left-handed people, and, logically, one may expect the finding to extend to musical stimuli.

Hypotheses

A review of the literature highlighted the above mentioned studies, and led to the formulation of the following hypotheses:

Hypothesis one. Musical stimuli are processed in the left hemisphere of musicians and the right hemisphere of non-musicians, when the subjects are right-handed.

Operationally, in a dichotic listening task involving violin melodies and right-handed subjects, musicians will correctly recognize more stimuli from the right ear, while non-musicians will demonstrate a left ear superiority.

Hypothesis two. Left-handers demonstrate incomplete lateralization, and hence will use both hemispheres in the processing of musical stimuli.

Operationally, in a dichotic listening task involving violin melodies, the performance of left-handers will be marked by a similarity of correct stimulus recognition between the ears, as opposed to the asymmetry of right-handers.

Hypothesis three. The degree of lateralization reflected in the subject's functional asymmetry for musical stimuli is related to his degree of handedness.

Operationally, the between ears difference scores for each subject on the musical dichotic listening task will vary systematically with the between hands difference scores of the six measures of handedness.

Method

Subjects

The subjects were 24 graduate and undergraduate students from the University of Victoria, whose ages ranged from 18 to 37 years. There were 9 men and 15 women. The subjects were assigned to one of four groups, namely Right-handed Musicians, Right-handed Nonmusicians, Left-handed Musicians, and Left-handed Nonmusicians. A musician was defined as a person who had taken at least four years of music lessons, and who was currently practicing the art for an average of at least one hour daily.

Hearing

The subjects were first tested for normal hearing. A Maico Hearing Instruments Audiometer (Model MA-17) was used for this purpose, and a series of tones was presented to each ear in turn, at an intensity of 40 db. The tones began at 500 kH_2, and ranged through 750, 1000, 1500, 2000, 3000, 4000, and 6000 kH_2 to 8000 kH_2. If a subject failed to indicate that he could hear any of the tone presentations, he was omitted from the study.

Handedness

Several indices of handedness were used, in order to arrive at a reliable, composite handedness score. They were:

1. A questionnaire, where the subjects were asked to pantomime each of the six prime handedness factors from Annett's (1970) association analysis.

2. The subject's own report of the incidence of left-handedness in his, or her, family.

3. Four sub-tests from the Harris Tests of Lateral Dominance (Harris, 1958): (a) writing speed; (b) dealing cards; (c) handgrip strength; (d) finger tapping.

For these last four indices, the score for each hand, on each task, was calculated as the mean of two trials. The resulting four trials for each task were run in the hand sequence of right, left, left, right, in order to counter-balance for practice or fatigue effects.

The subjects' performances on each sub-test were scored as recommended by Harris (1958). The result is a series of single scores, which were summed to produce a composite handedness score.

Dichotic Listening

Use was made of Spellacy's (1970) two-channel tape recording of melody segments, played on a violin. There were 96 pairs of these segments, each of 2 seconds duration.

Each pair was presented dichotically via a Sony Tape Recorder (Model TC-650) and headphones (Model DR-11). The intensity of sound was balanced for each channel, using a hand-held calibrator placed flush against the headphone cushions. The note intensities ranged between 63 and 65 dbs, with occasional peaks up to 68 db. The intensity peaks were randomized across channels. Any possible channel effect was counterbalanced by reversing the earphones on every other subject.

Each subject received 96 trials. A trial consisted of a simultaneous presentation to each ear of different violin melodies for 2 seconds, followed by a 5 second interval, and then the presentation of a binaural violin melody of 2 seconds duration. The subject's task was to decide if the foil melody was one of those just played dichotically, and, if so, to which ear was it presented. The subject recorded his answer by placing a check mark in the appropriate Left, Right, or Neither column of his answer sheet. Each trial was treated as a separate entity. The breakdown of recognition foil melody segments presented was as follows: 25% had previously been presented to the left ear, 25% had been presented to the right ear, and 50% had not been presented to either ear. The relatively large proportion of recognition foils falling in the "Neither" category was used to minimize the effects of a subject employing a "guessing" strategy.

A two-factor univariate analysis of variance was used to test for differences between musicians and nonmusicians, and left-handers and right-handers. The dichotic listening scores were used as the dependent variable. Each subject's score was calculated by dividing his total correct recognition score for the left ear by his combined, total correct, recognition score for both ears.

The relationship between ear difference scores and the various handedness measures was assessed by means of multiple regression.

Results

The two-factor univariate analysis of variance yielded a significant Musical Ability X Handedness interaction, $F\ (1, 20) = 7.55$; $p < 0.025$ (Figure 1, Table I). The main effect of Musical Ability was also significant, $F\ (1, 20) = 16.12$; $p < 0.001$.

Because of the significant Musical Ability X Handedness interaction, multiple regression programmes were run separately for musicians and nonmusicians. For the former group, $r^2 = 0.6021$, while for the latter, $r^2 = 0.7333$.

Discussion

The significant interaction between Musical Ability and Handedness appears to be based upon the differences in ear superiority between Musicians and Nonmusicians. That is,

FIGURE 1: Ear Asymmetry, Musical Ability and Handedness.

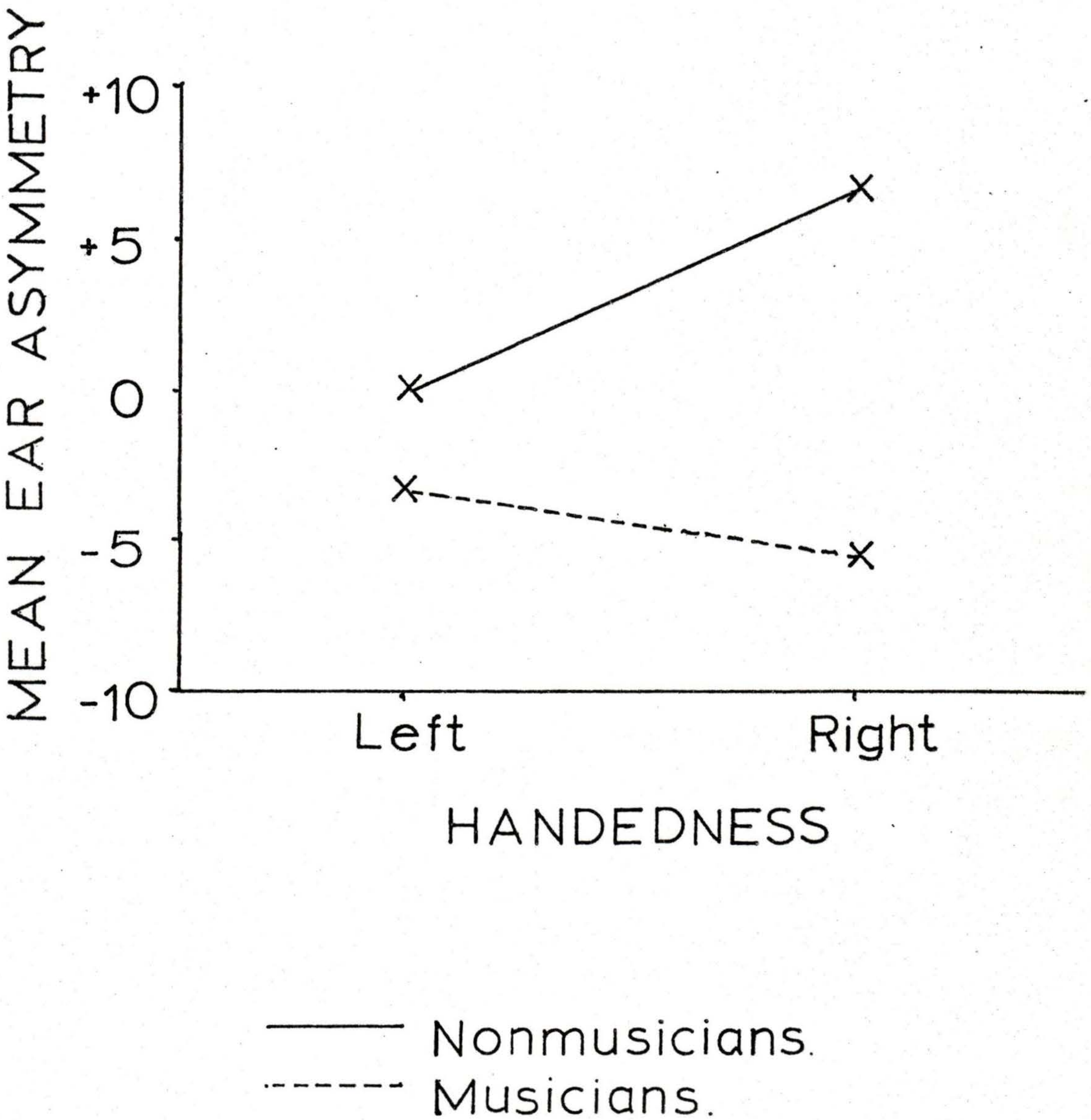

TABLE I

Pilot Study: Analysis of Variance Mean Ear Difference Scores

Source	SS	*df*	MS	*F*
Handedness (H)	58.225	1	58.225	2.911
Music Ability (M)	339.456	1	339.456	16.12**
H x M	158.930	1	158.930	7.55*
Error	421.088	20	21.054	
Total	977.692	23		

* $p < 0.025$

** $p < 0.001$

there is a relationship between right ear superiority and Handedness for Musicians, and a relationship between left ear superiority and Handedness for Nonmusicians. The results indicate that there is probably a stronger relationship in the latter case. This may be due to the fact that many musicians show less asymmetry of handedness, due to the fact that many instruments require the skilful use of both hands.

The structure of this Musical Ability X Handedness interaction also seems to be responsible for the failure of the main effect of Handedness to reach significance.

However, the results do lend tentative agreement to the hypothesis that left-handers in both groups show less asymmetry than right-handers. This result could be clarified if, in a subsequent experiment, the ear differences between left- and right-handers were analyzed without regard for sign.

The Musical Ability main effect, i.e., the significant difference in ear asymmetry, between Musicians and Nonmusicians, clearly supports Bever and Chiarello's (1974) position, and extends it to include dichotic listening tasks and violin melody stimuli.

The multiple regression analysis was also hampered by the significant interaction in the analysis of variance. It became obvious that carrying out a single multiple regression programme on all the data would be self-defeating. Consequently, the Musicians and Nonmusicians were treated separately. A tentative conclusion can be drawn that a relationship exists between the amount of ear asymmetry and the degree of handedness. This conclusion must be tempered by the fact that high values of r^2 will occur, regardless of a true relationship, as the number of dependent variables approaches the number of subjects in the sample.

A post hoc scan of the data revealed several other facts, which lead to interesting speculations. For instance, the differing asymmetry between Musicians and Nonmusicians appears to be caused by differences in right ear scores, lending support to Spellacy and Blumstein's (1970a) hypothesis concerning unilateral brain asymmetry. Also, in support of this, musicians appeared to claim more often that a melody presented to the left ear was heard in the right. It is almost as if some analytic mechanism in the left hemisphere of the musicians has been activated, and, while being adept at recognizing melodies, is less accurate with regard to their source.

As would be expected, the results also appeared to indicate that the Musicians are more proficient at this dichotic listening task. This showed in the total number of correct identifications, and the small number of false positive responses.

CHAPTER IV

MAIN EXPERIMENT

Introduction

In support of Bever and Chiarello (1974), the pilot study suggested that musicians use the left hemisphere of the brain in the processing of music, as opposed to the right hemispheres of nonmusicians. This successful finding led to the adoption of a similar procedure for the main experiment. However, several minor changes were made. One resulted from the quantitative problems involved in measuring handedness, while the others seek to explore the musician-nonmusician difference and necessitate the use of a more powerful statistical analysis.

Although the pilot study showed a qualitative relationship between handedness and ear asymmetry, the attempts to quantify this relationship were equivocal. The interaction between Musical Ability and Handedness cannot be adequately described by a multiple regression analysis. In addition, there is the problem of weighting each of the six measures of handedness. Was the Questionnaire more important than Writing Speed? If so, how much more important was it? At present, these questions cannot be answered. Therefore, it was decided to abandon the attempt to use the six measures to quantify the degree of handedness, using them instead to reliably produce a group of right-handers, and a group of left-handers.

Examination of the data, following the experiment, suggested two additional hypotheses. First, left ear scores seemed to be fairly constant between groups, while right ear scores fluctuated. As this phenomenon has previously been described as "unilateral asymmetry" (Spellacy & Blumstein, 1970a, 1970b; Neufeld, 1971), it seemed worthy of further exploration. Secondly, as might be expected, musicians appeared to be more successful with this experimental task than nonmusicians, and it was decided to check this statistically.

Hypotheses

As a consequence of the results of the pilot study, the main experimental hypotheses became:

Hypothesis one. Music is perceived primarily in the left hemispheres of musicians, and the right hemispheres of nonmusicians. Operationally, in a dichotic listening task involving violin melodies, musicians will correctly recognize more stimuli from the right ear, while the nonmusicians will demonstrate a left ear superiority.

Hypothesis two. Differences in the processing of musical sounds by musicians and nonmusicians are caused by the increased use of the left hemisphere in the former group.

Operationally, in a dichotic listening task involving violin melodies, there will be a significant difference between musicians and nonmusicians, as measured by the correct recognition scores from the right ear, but this difference will not occur between left ear scores.

Hypothesis three. Left-handed people have been described as having incomplete lateralization, and hence will use both hemispheres in the processing of musical stimuli. Operationally, in a dichotic listening task involving violin melodies, the performance of left-handers will be marked by a similarity of correct melody recognition between the ears, as opposed to the asymmetry of right-handers.

Hypothesis four. Musicians are more able than nonmusicians in recognition tasks involving music. Operationally, in a dichotic listening task involving violin melodies, musicians will be more successful than nonmusicians in recognizing which stimuli have been presented.

Method

Subjects

The subjects were 34 men and 35 women, whose ages ranged from 21 to 42 years. All of them were involved in post-secondary education at the University of Victoria, or the Victoria Conservatory of Music, or the Canadian Armed Forces School of Music (Esquimalt). The subjects were assigned to either a Musician or Nonmusician group. A musician was again defined as a person who had taken at least four years of music lessons, and was currently practicing the art for an average of at least one hour daily.

Hearing

The method used to test each subject for any hearing impairment was identical to the procedure used in the pilot study. Three male subjects had high frequency hearing losses and were eliminated from further participation in the study.

Handedness

The six measures of handedness which were used in the pilot study were used again.

However, this time there was a difference in the method of scoring these measures. In accordance with Harris' (1958) instructions, a subject's score on each measure was assessed as Strongly Right-handed, Moderately Right-handed, Ambidextrous, Moderately Left-handed and Strongly Left-handed. Numerical scores of +2, +1, 0, -1, and -2 were assigned to each respective category, and a resulting total score was calculated. Subjects with total scores between +4 and +12 were deemed Right-handed, while those with total scores between -4 and -12 were deemed Left-handed. Those subjects whose total handedness scores fell between +4 and -4 were categorized as being ambidextrous and eliminated from further participation in the study. There was one man and one woman in this category.

Dichotic Listening

The dichotic listening task was identical to the one used in the pilot study.

The results were analyzed by a multivariate analysis of variance (Clyde, 1969), using the Greatest Characteristic Root Test and univariate F tests for each dependent variable. There were 2 factors and 4 dependent variables. The Musical Ability factor had 2 levels, Musicians and Nonmusicians, while the Handedness factor also had 2 levels which were Left-handed and Right-handed. The 4 dependent variables obtained from each subject were: (a) the number of correctly recognized left-ear melodies, divided by the total number of correctly recognized left- and right-ear melodies. This was used as an index of ear asymmetry; (b) the number of correctly recognized left-ear melodies; (c) the number of correctly recognized right-ear melodies; (d) the total number of correct recognitions, i.e. left ear + right ear + neither ear. This was used as an index of task proficiency.

Results

There was a significant multivariate Musical Ability x Handedness interaction, GCR (1, 1, 27) = 0.204; $p < 0.03$. The corresponding univariate tests showed the interaction to be significant for Dependent Variables One and Three (see Table II).

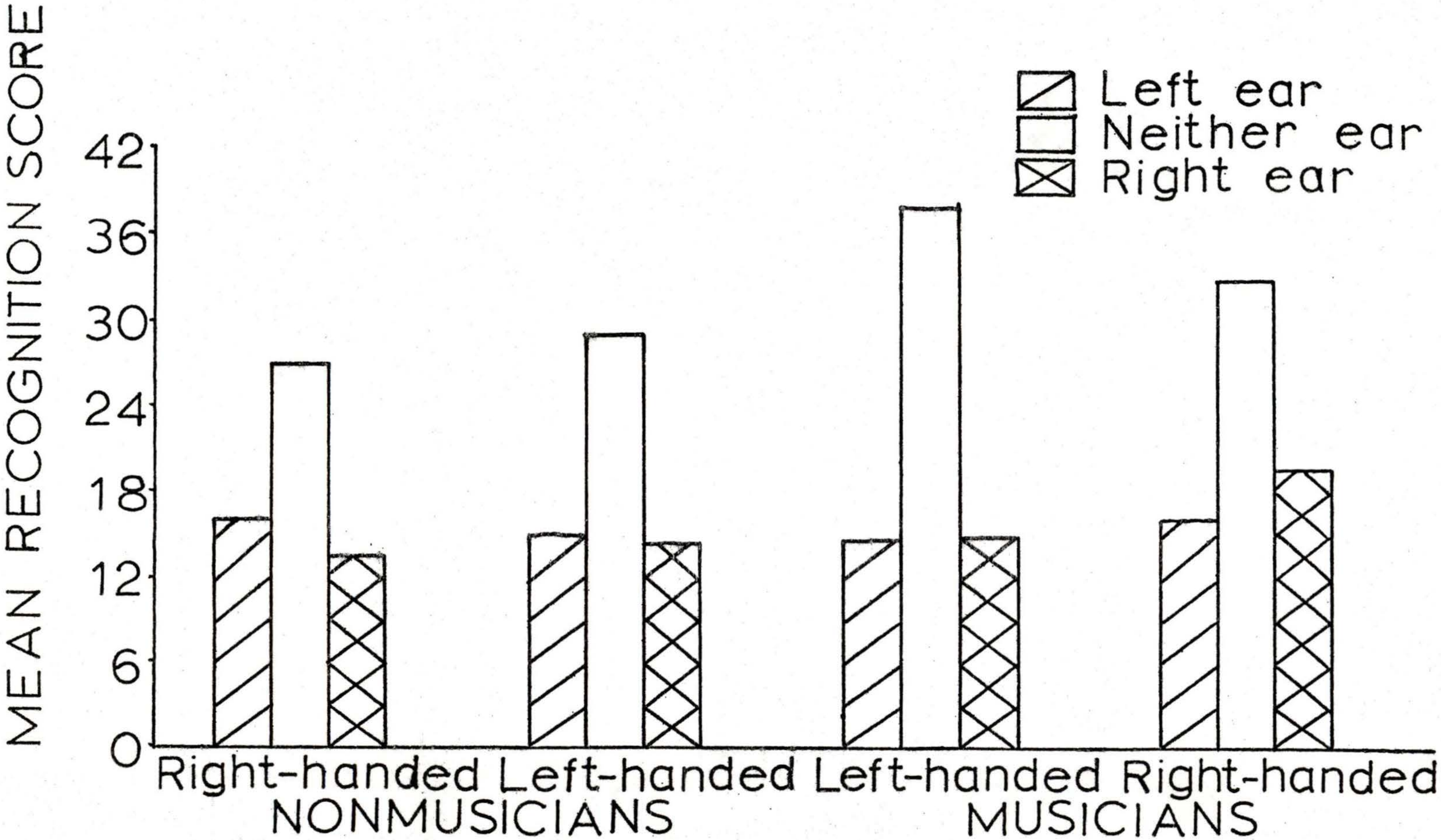

FIGURE 2

Melody Recognition

TABLE II

Main Experiment Multivariate Analysis of Variance

Musical Ability x Handedness Interaction

MULTIVARIATE ANALYSIS

GCR	S	M	N	P (GCR)
0.204	1	1	27	0.03

UNIVARIATE ANALYSIS

DVs	F(1, 60)	MS	*p*	SDFC
Ear Asymmetry	11.047	428.130	0.002	0.714
Left Ear Score	0.265	2.313	0.608	0.012
Right Ear Score	8.185	128.391	0.006	-0.396
Task Proficiency	2.245	161.576	0.139	0.021

There was also a significant multivariate main effect for the Musical Ability factor, GCR (1, 1, 27) = 0.810; $p < 0.01$. The corresponding univariate tests show the effect to be significant for Dependent Variables One, Three and Four (see Table III).

The multivariate test of the Handedness factor did not reach significance. Of the univariate tests, only that for Dependent Variable Three reached the required level of significance, $F(1, 60) = 6.238$; $p < 0.015$.

Discussion

The significant multivariate Musical Ability x Handedness interaction can be interpreted as demonstrating an incomplete lateralization of left-handed people (Hypothesis three). Handedness was a significant influence on the dichotic listening task, but affected the results in opposite directions for Musicians and Nonmusicians (see Figure 2). The univariate *F* tests showed that Dependent Variable One, Ear Asymmetry, and Dependent Variable Three, Right Ear Score, largely accounted for this effect (see Table II).

Whereas Right-handed Musicians and Nonmusicians obtained very different scores, those of the corresponding left-handed groups tended to be similar (see Table IV). Consequently, the strength of the Handedness factor was not sufficient to produce a significant multivariate main effect. While it is inappropriate to interpret univariate *F* tests under these

TABLE III

Main Experiment Multivariate Analysis of Variance

Musical Ability Main Effect

MULTIVARIATE ANALYSIS

GCR	S	M	N	P(GCR)
0.810	1	1	27	0.01

UNIVARIATE ANALYSIS

DVs	F(1, 60)	MS	*p*	SDFC
Ear Asymmetry	11.175	433.102	0.001	-0.464
Left Ear Score	0.027	0.238	0.869	1.123
Right Ear Score	10.579	165.961	0.002	-0.840
Task Proficiency	30.661	2206.466	0.001	-1.0003

TABLE IV

Main Experiment Group Means and Standard Deviations

Experimental Groups		Dependent Variables			
		1 Ear Asymmetry	2 Left Ear Score	3 Right Ear Score	4 Task Proficiency
Right-handed Nonmusicians	M	55.065	15.733	13.600	56.467
	(SD)	(8.837)	(2.987)	(4.940)	(9.999)
Left-handed Nonmusicians	M	51.239	15.125	14.063	58.125
	(SD)	(5.980)	(3.862)	(3.395)	(6.043)
Left-handed Musicians	M	51.124	14.625	14.500	66.813
	(SD)	(6.129)	(2.156)	(4.442)	(8.471)
Right-handed Musicians	M	44.518	16.000	19.750	71.563
	(SD)	(2.494)	(2.530)	(2.769)	(9.076)

circumstances, the significant Dependent Variable Three value does perhaps indicate that the Right Ear Score was the best of the measures used to discriminate between Right- and Left-handers.

Doubt arises as to whether these results reflected a real symmetry in the individual cortical organization of left-handed people, or the heterogeneity of performance of this group. The previously mentioned studies by Levy (1969) and Branch, Milner and Rasmussen (1964) do not differentiate between these interpretations in their findings.

Levy's (1973) study of handwriting among left-handed students begins to explore differences in the organization of cortical language functions in this group. Her hypothesis was that inverted left-handed writers have language functions located in the left hemisphere, while normal left-handed writers have it in the right. This hypothesis can be projected on to the present study. Those left-handed individuals who wrote with the hand inverted would be expected to show a left ear superiority in the recognition of the violin melodies, while the normal writers showed a right ear superiority.

There was some evidence that this was the case when ear asymmetry was measured by subtracting right-ear, correct recognition score from its left-ear counterpart. The normal writers among the Left-handed Nonmusicians had scores ranging from -5 to +1, while the scores of the inverted writers ranged from +4 to +6. However, there were only four subjects in the latter category.

Several interesting questions arise from this observation:

1. Are these differences in ear asymmetry sufficient to account for the apparent incomplete lateralization of left-handed people?

2. Do the inverted writers account for a major portion of the heterogeneity often found in the performances of groups of left-handers?

3. Why was there an absence of similar observations among the group of Left-handed Musicians, even though, as a group, they exhibited a similar degree of heterogeneity in their dichotic listening scores?

4. Why did some normal right-handed subjects write with an inverted left hand while performing the Harris Tests of Lateral Dominance (Harris, 1958)?

At present, any answers to these questions would be purely speculative. However, further investigations involving Levy's (1973) hypothesis might clarify these problems arising from individual and group differences among left-handed people.

The significant multivariate main effect for the Musical Ability factor underlies the major findings of this study. Three of the four corresponding univariate tests produced significant *F* values, each of which pertained to a specific experimental hypothesis (see Table III).

Dependent Variable One. This Ear Asymmetry variable showed that there was a significant difference between the Musicians and Nonmusicians. The group means (see Table IV) show that the Musicians demonstrated a right ear superiority, while the Nonmusicians performed better with the left ear. This finding was interpreted as supporting Hypothesis one, i.e. musical stimuli are processed in the left hemispheres of musicians, and the right hemispheres of nonmusicians. The result supports Bever and Chiarello's (1974) main finding, and extends it to include dichotic listening tasks.

Dependent Variable Two. This dependent variable was the Left Ear Score of each subject, and a difference between the groups was not found on this measure.

Dependent Variable Three. The Right Ear Score dependent variable did distinguish between the Musicians and Nonmusicians. As was predicted, the Musicians obtained significantly more correct recognition scores with this ear.

The results from Dependent Variables Two and Three, taken in conjunction, were interpreted as showing that the differences in ear asymmetry between musicians and nonmusicians are caused by the increased use of the left hemisphere in the former group (Hypothesis two).

This result was in agreement with Spellacy and Blumstein's (1970a) notion of unilateral brain asymmetry, and supported one of Bever and Chiarello's (1974) findings. It is thought that the naive subject, on hearing musical stimuli, perceives them with the right hemisphere by means of Levy's (1974) "gestalt synthesizer." However, the musician, while retaining his right hemisphere capabilities, can also analyze the stimuli in his left hemisphere, due to his experience with the "language of music."

This concept is supported by the comments of the subjects. After completing the task, several of the musicians commented that sometimes they recognized sequences of notes, especially if they could locate the first one on a musical scale, e.g. Middle C. On the other hand, nonmusicians were often unclear about their own identification strategies.

Dependent Variable Four. The Task Proficiency dependent variable, as expected, distinguished between the Musicians and Nonmusicians, with the former group being significantly more capable in recognizing the dichotically presented violin melodies (Hypothesis four). This result was also interpreted as giving additional support to the hypothesis of unilateral brain asymmetry. The Musicians appeared to be making increased use of their left hemispheres, without losing the abilities of the right sides of their brains.

Implications for Further Research

As mentioned above, the writings of Spellacy and Blumstein (1970a, 1970b) and Levy (1974) involve the functional asymmetry of the human brain. Progressing from Kimura's (1964) concept of bilateral brain asymmetry, these authors have concerned themselves with a unilateral functional asymmetry and the "co-operation" between the hemispheres. All of them mention the analytic functions of the left hemisphere, but Levy writes more specifically about the "gestalt synthesizer" of the right. The results of the present study clearly support these current theoretical ideas.

Here some aspects of a functional asymmetry involving music have been demonstrated, and they are perhaps analogous to the development of language lateralization. The "language of music," while it is a series of ill-understood sounds involving gross conceptualizations of rhythm, intensity, emotion, etc., is processed by the gestalt synthesizer of the right hemisphere. As this new "language" is learned, a language analyzer in the left hemisphere is activated and gradually breaks down the sounds into meaningful units. During this process, as with real languages, right hemisphere functions, such as emotionality of content, are not lost but are sometimes masked by the activity of the language analyzer.

If one considers music to be a language, several avenues for further investigations spring to mind. Of primary importance would be a longitudinal, repeated-measures design, where nonmusician subjects are given a dichotic listening task before, and after, a period of intensive musical training. Ideally, tests could be given at various other times during training, and one would expect to see a gradual improvement in the right ear score of each subject. Such a study would need the co-operation and assistance of at least one competent professional musician and teacher.

To extend the analogy of a language of music, reading music would be analogous to reading the printed word. Consequently, a study might be undertaken which involves nonmusicians, musicians who play by ear, and those who read music. Here again the right ear score would be an important criterion, and if the music readers obtained the highest scores, this would further enhance the position of those psychologists who support the hypothesis of the analytic functions of the left hemisphere.

The definition of a musician, which may have contributed to some of the conflicting results in this area (Gordon, 1970; Bartholomeus, 1973), remains an important issue. The present study, and that of Bever and Chiarello (1974) successfully used the same definition, but this is hardly adequate in terms of the development of musical competence. It would be productive if further investigations involved groups of differing levels of competence. For example, what would be the effects of differing daily amounts of practice time? Or, how would the age of onset of music lessons affect the amount of asymmetry in the adult musician?

Left-handed people, as a group, tend to cloud the issue of functional asymmetry. The heterogeneity of their performances in this and other studies, such as Satz (1972), Satz, Achenbach and Fennell (1967) and Provins and Cunliffe (1972) casts doubt upon the resulting lack of group asymmetry. It appears that a typical group of left-handers may, in fact, be composed of two, or more, sub-groups, each with its own cortical organization.

The problem has always been how to differentiate between these sub-groups of the left-handed population. Satz's (1972) hypotheses concerning pathological left-handedness are typical of the problem. His reasoning is logical, but how does one distinguish between pathological and natural left-handers in setting up an experiment? As stated previously, Levy's (1973) study concerning inverted handwriting among left-handers may prove to be a useful external index of cortical organization. Certainly, the few observations of inverted writers among the left-handed non-musicians in the present study show the idea to be worthy of further research.

The general methodology of this study could be applied to the problem. Groups of normal and inverted writers, both musicians and nonmusicians would complete the dichotic listening task. The inverted writers, who, according to Levy, have a speech analyzer in the left hemisphere, would be expected to perform in a similar manner to the right-handed subjects in the present experiment. The nonmusicians would demonstrate a left ear superiority, while the musicians would perform better with the right ear. The normal writers would be expected to show the opposite effect.

In summary, dichotic listening to musical phrases seems to provide a useful basis for studying the development of functional asymmetry in the human brain. The right hemisphere appears to deal mainly with gestalt concepts, while the left appears to be mostly involved in the analysis of the stimuli. However, the handedness factor tends to mask other findings, and left-handed subjects should probably be omitted from such studies, until more is known concerning the external referrents of their cortical organization.

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APPENDIX

Main Experiment: Number of Correct Recognitions

MUSICIANS							
Right-handers				Left-handers			
Subject	Left ear	Right ear	Neither	Subject	Left ear	Right ear	Neither
1	19	19	29	17	13	16	42
2	19	22	43	18	18	20	42
3	16	23	44	19	12	13	38
4	16	21	42	20	15	8	31
5	11	15	34	21	15	17	36
6	16	21	23	22	12	10	32
7	11	13	29	23	18	21	38
8	17	20	32	24	15	17	38
9	16	22	40	25	13	9	38
10	20	22	35	26	14	16	41
11	15	20	35	27	12	10	33
12	18	21	36	28	17	20	24
13	14	17	34	29	14	11	43
14	15	18	35	30	18	18	43
15	16	20	41	31	15	17	36
16	17	22	41	32	13	9	38
NONMUSICIANS							
33	20	16	32	49	12	12	43
34	16	11	35	50	21	21	24
35	19	10	38	51	9	13	31
36	12	7	40	52	17	16	15
37	16	20	35	53	9	11	38
38	17	13	37	54	21	16	17
39	16	15	20	55	15	9	44
40	13	15	28	56	15	11	28
41	15	20	18	57	12	17	32
42	12	4	17	58	13	12	23
43	12	7	24	59	21	17	25
44	18	18	23	60	15	14	29
45	21	18	25	61	13	12	30
46	18	17	22	62	14	10	30
47	19	16	23	63	17	19	24
48	12	13	22	64	18	15	29

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FUNCTIONAL BRAIN ASYMMETRY AND DICHOTICALLY-STIMULATED

EAR PREFERENCE IN MUSICIANS AND NONMUSICIANS

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