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Broca and Lashley Were Right: Cerebral Dominance Is an Accident of Growth

Thomas G. Bever

The more precocious development of the left hemisphere predisposes us in our first gropings to execute the more complicated material and intellectual acts with that half of the brain. . . . this specialization of function does not imply the existence of a functional distinction between the two halves of the brain.
Broca, 1865

On anatomical grounds alone there is no assurance that cerebral dominance is anything other than an accident of growth.
Lashley, 1937

Clinical and experimental evidence suggests that the left hemisphere of the brain is specialized for speech activity and the right hemisphere is specialized for many nonlinguistic functions.[1] The characteristic association of language with the left hemisphere raises two questions.

- Is cerebral asymmetry specific to each skill or to a general difference in processing style? Is the left hemisphere uniquely predisposed for language, or does language itself have certain properties that are always more easily processed by the left hemisphere?
- How specific must the evolutionary development be that could provide a mechanistic basis for the observed hemispheric differences? Is relational processing qualitatively "innate" to the left hemisphere, or does the left hemisphere assume relational processing because of a general quantitative difference between the hemispheres?

I shall agree with those who claim that there is a general difference in processing style between the hemispheres in adults; the left is dominant for relational processing, the right for holistic processing. Language is left-hemisphered because it typically requires relational processing. This claim has received some acceptance in the field.

Moreover, I also demonstrate that the available data are consistent with the view that at birth the only difference between the hemispheres is that the left hemisphere has more computational power. This implies that the evolution of asymmetries could be the direct result of the evolution of a general physical asymmetry (in size at birth, oxygenization, metabolic rate, perinatal maturation rate). As the quotations from Broca and Lashley show, this view is not novel. My present goal is to show that all the highly specific and intricate facts about linguistic and nonlinguistic asymmetries that have been recently documented can follow from such a relatively simple evolutionary development.

A CAUTIONARY NOTE ON AN EASY MISTAKE

Humans are the only organisms we know of that characteristically have both language and processing-related cerebral asymmetries. Reasoning of the post hoc ergo propter hoc variety can lead to the easy assumption that language capacity and cerebral asymmetries are directly related. An intuitive and strong version of this claim is the following: The critical mechanism underlying language is structurally innate in the left hemisphere. This claim can be turned around: If we can prove that the left hemisphere is innately structured for language, we have added evidence that language itself is innate. This interpretation could stimulate interest among linguists in the innate basis for cerebral asymmetries. But the innateness of language and of cerebral asymmetries are logically independent. Language could be learned and asymmetries innate, asymmetries acquired and language innate, both acquired, or both innate. At most, any unique evolutionary relation between cerebral asymmetries and linguistic capacity is a matter for empirical discovery: One cannot conclude anything about the (non)innateness of one from the (non)innateness of the other.

Why then, should we be concerned about cerebral asymmetries at all, if our main concern is with language? There are two reasons. First, despite their logical independence, there is a plausible empirical connection between language and asymmetries. We must determine whether this connection is causal or coincidental, if we are to see clearly into the biological mechanisms for the knowledge of language. Second, cerebral asymmetry is a robust instance of localization of brain function in humans. It is relatively easy to study

in normal and clinical populations. Accordingly, it serves as an empirically fruitful example of how functional localization can develop.

THE NATURE OF ASYMMETRIES IN ADULTS

Two interpretations of asymmetries have emerged in recent years. In one view each hemisphere is adapted to different skills—for example, language and mathematics in the left hemisphere, form perception and music in the right (Kimura, 1973). The alternative view was proposed a century ago by the neurophysician, Hughlings Jackson (1932). He related the hemispheric linguistic differences to differences in cognitive activity, suggesting that the left hemisphere is specialized for "propositional" organization while the right hemisphere is adapted for "direct associations" among stimuli and responses. Modern researchers have substantially generalized this differentiation to encompass a wide range of behaviors in normal subjects.

Many experimental and clinical investigators of hemispheric asymmetry agree on the fundamental nature of the processing differences between the two sides of the brain: The left hemisphere is supposed to be specialized for propositional, relational, and serial processing of incoming information, while the right hemisphere is more adapted for the perception of appositional, holistic, and synthetic relations. However, there is also a body of evidence suggesting that form perception and music perception are dominant in the right hemisphere.[2] How could such a skill-specific difference be consistent with the differentiation of hemispheric processing in terms of two kinds of processing? I shall show that studies of music and visual form that bring out right-hemisphere superiority are holistic tasks, either by virtue of the subjects' processing strategies (music) or by virtue of the simplicity of the stimuli (vision). Crucial experiments that bring out relational processing also bring out left-hemispheric dominance for music and form perception.

RELATIONAL AND HOLISTIC PROCESSING

We can make our discussions more precise if we have a formal definition of the difference between holistic and relational processing. Of course, we could treat each kind of processing as a primitive concept, but this would not leave us any way to decide a priori whether a particular task or behavioral strategy is itself holistic or relational.

Pretheoretically, the difference is intuitively clear. Holistic processing involves the direct association of a mental representation with a stimulus and response; relational processing involves at least two such associations, and the manipulation of a relation between the two mental representations. We can give a formal account of this difference in the following way: A holistic task involves the activation of one mental representation one or more times; a relational task involves the activation of at least two distinct mental representations and of a (nonidentity) relation between them.[3] It remains in part an empirical question whether this distinction is the behaviorally relevant one. The following sections demonstrate its adequacy, at least to a first order of approximation. These sections are organized according to predictions about types of processing rather than about types of skilled behavior.

Prediction 1. The kind of processing that subjects are asked to perform can determine which hemisphere is dominant in processing a stimulus.

SPEECH

Varying the task within a modality is a strong way of testing the claim that indeed it is the kind of processing that determines behavioral asymmetry, not the modality (language, music, vision). To show this, Richard Hurtig, Ann Handel, and I ran monaurally an initial-phoneme versus syllable-recognition experiment (Bever et al., 1976). We found that the time taken to recognize a syllable beginning with *b* is shortest when the materials are presented to the right ear and the subject responds with the right hand compared with other hand-ear configurations. There was no difference in amount of time to recognize an entire syllable, for example, *bik*. We verified this result in two paradigms; in one paradigm we alternated whether listeners were listening for an entire syllable target or an initial phoneme target; in a second paradigm we held the task constant but alternated the ear to which the stimulus was presented (see table 10.1).

The two tasks exemplify the formal distinction between the two types of processing. Recognizing a syllable (in a sequence of syllables) in terms of its first /b-/ sound requires perception of an initial part of the whole syllable and a decision that the first compo-

Table 10.1
Mean reaction time (msec) to identify a syllable in terms of the initial phone or whole syllable

	Left ear	Right ear	Right-ear advantage
Initial phone	369	348	+21
Syllable	259	258	+1
Phone-syllable	110	90	

Source: Bever, Hurtig, and Handel (1976), combining experiments 1 and 2, and right- and left-hand responses.

nent phoneme of that part is indeed /b-/. That is, this task is relational. The corresponding task of recognizing the syllable from a syllable target is holistic, involving only matching an initial part of the whole syllable against the expected "template."

Accordingly, this investigation shows that the same stimulus can be differentiated according to the kind of processing that the subject must carry out on the stimulus. If the subject must analyze the stimulus internally, then the condition in which only the left hemisphere is involved (right ear, right hand) is more facilitating than the other conditions. The syllable task, in which the subject listens holistically, shows no overall differences in this case. (It remains to be seen whether one can show a statistically reliable favoring of left-ear input with a linguistic stimulus.)

VISION

Recently, Hurtig (in preparation) ran a visual analog of the preceding experiment. Subjects saw brief presentations of nonsense figures. In critical cases these figures were followed by the same figure or by a more complex figure of which they were a part. Subjects were to say yes as quickly as possible in either of these cases and no in control negative cases. Hurtig found that correct responses were faster and more frequent in the left visual field (right hemisphere), when the second figure was the same figure. Correct responses were faster and more accurate in the right visual field (left hemisphere) when the second figure included the first. That is, the holistic visual task stimulated left-field superiority, while the relational visual task stimulated right-visual-field superiority.[4]

Hurtig's experiment is a direct investigation of the holistic/relational distinction in vision. It demonstrates that the dominant side for form perception can be reversed from left to right if the kind of visual processing is shifted from holistic to relational. If this is so, why do the overwhelming majority of studies claim to show a left-field superiority? The explanation is methodological.

Visual stimuli must be presented outside of the fovea to be completely lateralized neuroanatomically. Consequently, such experiments characteristically use visual stimuli simple enough to be differentiated in the visual periphery (for example, recognition of the angle of line, recognition of a simple geometric figure). Overall performance on complex stimuli in the periphery can be so low that observed laterality differences might not be statistically meaningful. The methodological requirement that the visual discrimination task must be simple when stimuli are in the visual periphery may account for the apparent right-hemisphere dominance for vision that is claimed in the literature; the simple recognition tasks are characteristically holistic. This leads to the prediction that complex figures might be better recognized in the right visual field.

To test this, Victor Krynicki (1975) used a figure-recognition task with brief presentations of irregular eight- and sixteen-sided geometric figures.[5] In one situation the subjects had to recognize rapidly presented stimulus figures from a target set of twenty. While the success rate was low, the sixteen-sided figures (but not the eight-sided figures) were identified better in the right visual field. Krynicki suggested that the subjects recognize the complex figures in terms of isolated visual features (such as a jagged edge or a particular angle), thus requiring relational processing and a consequent left-hemisphere superiority. The basis for this assumption is that a large number of complex and similar figures would be easiest to differentiate, identify, and recognize in terms of some criterial visual feature that distinguishes it from the others in the target set.

In a second task subjects made same-difference judgments on pairs of figures. On positive trials the second stimulus was a rotation of the first. There was a left-visual-field superiority for both eight- and sixteen-sided figures. This result was predicted by the view that holistic processing is relegated to the right hemisphere and the assumption that recognizing a figural rotation is a holistic task that can operate on the gross contour of the stimulus. In this condition both eight- and sixteen-sided figures showed a left-visual-field

superiority, suggesting that figure complexity was not an effective variable. Also the rotation task was more difficult than the direct recognition task. This shows that task difficulty per se is not the relevant variable, only that complex stimuli usually are more likely to be perceived relationally.

If such results hold up in other paradigms, they will show that the frequent claim that vision (of nonlinguistic stimuli) is dominant in the right hemisphere was based on research involving simple holistic processing tasks; relational processing can stimulate left-hemisphere dominance in visual recognition of nonlinguistic stimuli.

The critical experimental demonstrations of this claim are cases of right-field superiority in usual tasks. Goldberg et al. (1978) found such an effect for the recognition of irregular many-sided figures (roughly, replicating Krynicki's results). Their interpretation is that right-field superiority emerges because such complex shapes are "codable in a discrete set of features" and the left hemisphere is adapted to such codes. (Their proposal is similar to the one in this paper, except that it incorrectly predicts that simple geometric figures would be better perceived in the right visual field.)

Krynicki had also monitored the average evoked response (AER) activity at the right and left parietal scalp positions. Subjects in the rotation task showed greater electrical activity in the right hemisphere than the left (regardless of the original stimulus visual field). The same subjects in the complex-figure-recognition task showed greater AER activity in the left hemisphere (also regardless of the input stimulus field).

The study of patients with unilateral brain lesions can provide a "converging methodology" to confirm the results of such neurophysiological asymmetries in normals (although patients with such lesions present self-compensating bilateral systems with unilateral damage, rather than isolated unilateral systems). In this case one would predict that patients with left-hemisphere lesions will be selectively impaired on a relational visual task while patients with right-hemisphere lesions will be relationally impaired on a holistic visual task. Veroff (1978) found exactly such a difference. She had patients place in correct order a randomized sequence of cartoons depicting a common change in category (for example, a tadpole becoming a frog). She found that changes of location are more impaired in right-hemisphere patients, while changes of category are more impaired in left-hemisphere cases. She concludes, "Patients

with right hemisphere damage [were] impaired on . . . [configurational] processing and patients with left-hemisphere damage were . . . impaired on . . . [categorical] processing" (p. 139). Veroff's task is a nonstandard experimental task adapted to the special needs of working with patients. However, we can distinguish her "configurational" task as holistic, since the object in each picture of a sequence remains the same; the "categorical" task is relational, since the object in each picture is different, yet related to the previous one. In this sense her results provide independent clinical confirmation of the behavioral difference found in normals.

The overall result of these studies is that that the left hemisphere can be dominant for visual processing, if the task is relational.

Prediction 2. If one shifts ontogenetically from holistic to relational ways of perceiving a stimulus, one should also shift from being right-hemisphere dominant to being left-hemisphere dominant for that stimulus.

The perception of music has so far been a well-documented exception to the differentiation of the hemispheres according to relational versus holistic processing. Melodies are composed of an ordered series of pitches and hence should be processed relationally, and be dominant in the left hemisphere rather than the right. Yet until recently the recognition of simple melodies was usually reported to be better in the left ear than in the right.[6] This finding is prima facie evidence against the functional differentiation of the hemispheres; rather, it seems to support the view that the hemispheres are specialized according to stimulus-response modality. Such conclusions, however, are simplistic; they do not consider the different kind of processing strategies that listeners use as a function of their musical experience.

It has long been recognized that the perception of melodies can be a gestalt phenomenon. That is, that a melody is composed of a series of isolated tones is not relevant for naive listeners; they focus instead on the overall melodic contour. The view that musically experienced listeners have learned to perceive a melody as an articulated set of relations among components rather than as a whole is suggested directly by Werner (1948). "In advanced musical apprehension a melody is understood to be made up of single tonal motifs and tones which are distinct elements of the whole construction." This is consistent with Meyer's (1956) view that 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 the whole forms are combined. If musically naive listeners normally treat a melody as a holistic gestalt, then the processing account of the difference between the two hemispheres predicts that melodies will be processed better in the right hemisphere for such subjects. If experienced listeners normally treat a melody as a relational sequence, then they should show a corresponding right-ear superiority. It is significant that Gordon (1970), the first recent investigator who failed to find a superiority of the left ear for melody recognition, used "college musicians" as subjects; the subjects in other studies were musically naive (or unclassified).

If music perception is dominant in the right hemisphere only insofar as musical form is treated holistically by naive listeners, then the generalization of Jackson's proposals about the differential functioning of the two hemispheres can be maintained. To establish this we conducted a study with subjects of varied levels of musical sophistication that required them to attend to both the internal structure of a tone sequence and its overall melodic contour. The listener's task is sketched as follows:

hear melody	2 sec pause	hear excerpt	say if excerpt was from melody	say if melody was heard before in the experiment

We found that musically sophisticated listeners could accurately recognize isolated excerpts from a tone sequence whereas musically naive listeners could not. However, musically naive people could recognize the entire tone sequences and did so better when the stimuli were presented in the left ear; musically experienced people recognized the entire sequence better in the right ear (table 10.2). This

Table 10.2
Recognition of whole melodies (percentage correct)

	Left ear	Right ear	Right-ear advantage
Musicians	44	57	+13
Nonmusicians	54	36	-18
Musicians' advantage	-10	21	

Note: Percentages are corrected for guessing.

demonstration of the superiority of the right ear for music shows that it depends on the listener's musical experience; it demonstrates that the previously reported superiority of the left ear was due to the use of musically naive subjects, who treat simple melodies as unanalyzed wholes.

We also compared the performance of a group of choir boys with nonmusical boys from the same school on a similar task.[7] The choir boys performed more effectively on stimuli presented to the right ear, while the musically naive boys performed better on the left-ear stimuli. Since half the choir boys cannot read music (they memorize their parts), this could not be due to mapping the music onto a score or note names. It is also possible in principle that developing musical ability is not the cause of left-hemisphere dominance but its result: It might be that those boys who are *already* left-hemisphered for music are thereby more musical and that is why they join the choir. This possibility is inconsistent with several facts. First, the boys join the choir for a mixture of social and financial reasons (choir boys received a scholarship to their school). Second, the longer a boy was in the choir the more pronounced his right-ear dominance (compared with nonchoir boys in the same age and grade).

Our interpretation is that musically sophisticated subjects can organize a melodic sequence in terms of the internal relation of its components. This is supported by the fact that only the experienced listeners could accurately recognize the two-note excerpts as part of the complete stimuli. Dominance of the left hemisphere for such analytic functions would explain dominance of the right ear for melody recognition in experienced listeners; as their capacity for musical analysis increases, the left hemisphere becomes increasingly involved in the processing of music.

These studies have received considerable attention and some replication. (Specific issues raised by these studies are discussed in the appendix to this chapter.) First, Gordon (1975), who had run the study with "college musicians," reanalyzed his data. He found that subjects who performed better on his melody-recognition task tended to perform relatively well on right-ear stimuli while this was not true of the subjects who did not do well overall. P. R. Johnson (1977) reported a replication of our melody-recognition results with dichotic stimuli. R. C. Johnson et al. (1977) examined the effects of whether the musicians could transcribe music or not; they found a significant right-ear advantage on a melody-excerpt-recognition task

only for subjects who could transcribe music. However, combining the results of Johnson et al. for the two groups of musicians who can read music (which embraces our original definition of musician) and comparing the Johnson et al. musicians with the nonmusicians yields a pattern of results similar to Johnson's and ours.

Three other recent studies on melody perception have used experimental paradigms that bring out right-ear superiority in both musicians and nonmusicians (see the appendix for a discussion of the reasons for this result). These results give support to our underlying original claim that music is not uniquely processed in the right hemisphere. Furthermore, in each of these three experiments the musicians were relatively more right-eared than the nonmusicians (table 10.3). For this comparative analysis I considered only tasks that came reasonably close to replicating our original paradigm; the melodies were presented only a few times at most and were tonal (see the appendix).

Finally, a startling fact about EEG activity gives independent validity to our claim that musicians process melodies in the left hemisphere, nonmusicians in the right. Hirshkowitz, Earle, and Paley (1978) showed that electrical activity at the scalp is greater on the left side for musicians listening to melodic sequences, while it is greater on the right site for nonmusicians.

Prediction 3. Variation in the complexity of syntactic structure should stimulate greater correlations with behavioral difficulty when heard in the right ear than in the left.

Language is an intrinsically relational task. The cognizance of a sentence characteristically requires both isolation of the phrases and an intuitive understanding of their relations to each other in the whole sentence. If the left hemisphere carries out relational processing, then the perceptual strategies that listeners use to analyze relations among the words in sentences must be indigenous to the left hemisphere. This is reflected in an overall superiority of the right ear for sentence recognition, compared with sequences of random words. In one experiment subjects heard ten monaural seven-word sentences (for example, "They in fact did seem very nice") constructed by splicing from a randomly recorded list. After each sentence, there was a two-second silence, followed by a number from which subjects counted backwards by threes for five seconds and then recalled the sentence. Subjects performed better on recall of

Table 10.3
Summaries of studies on melody perception by musicians and nonmusicians

Study	Left ear	Right ear	Right-ear advantage
Johnson[a]			
Musicians	16.0	19.8	+3.8
Nonmusicians	15.7	13.7	-2.0
Musicians' advantage	0.3	6.1	
Johnson et al.[b]			
Musicians	4.9	4.5	+0.4
Nonmusicians	6.5	6.7	-0.2
Musicians' advantage	1.6	2.2	
Gaede et al.[c]			
Musicians	10.87	10.00	+0.88
Nonmusicians	12.19	11.48	+0.71
Musicians' advantage	1.32	1.48	
Gates and Bradshaw[d]			
Musicians	0.83	1.10	+0.27
Nonmusicians	0.14	0.35	+0.21
Musicians' advantage	0.69	0.75	
Gordon[e]			
Musicians	15.3	17.6	+2.3
Nonmusicians	14.7	16.7	+2.0
Musicians' advantage	0.6	0.9	

Sources: Johnson (1977, table 1); Johnson et al. (1977, table 1); Gaede et al. (1978, table 1); Gates and Bradshaw (1977, table 2); Gordon (1978, table 1).
Note: Advantage scores compensate for whether the raw scores are based on correct responses or errors.
a. Scores are the mean number of correct positive responses.
b. Musicians are their groups 1 and 2; nonmusicians are their group 4. Scores are the mean number of errors.
c. Groups the means of their high-aptitude and low-aptitude subjects. Scores are the mean number of errors.
d. Groups the means of male and female subjects, responding to long and short excerpts, from their unfamiliar melodies. The scores are means of presented *d*'s.
e. Excludes subjects performing at chance level. Scores are number correct (out of possible 24) on dichotic melodies differing in rhythm.

sentences heard in the right ear; however, there was no difference in recall of the same word sets reordered into random sequences ("nice in seem did fact very they") (table 10.4). The syntactic organization of the sequence is critical to bringing out the asymmetry.[8]

I also examined performance in this immediate verbal task with sentences that varied according to the negative, passive, and question constructions, and their combinations.

The bug bit the dog.
The dog was bitten by the bug.
The bug did not bite the dog.
Did the bug bite the dog?
The dog wasn't bitten by the bug.
Was the dog bitten by the bug?
Didn't the bug bite the dog?
Wasn't the dog bitten by the bug?

Sentences heard in the left ear generated about the same number of meaning-preserving errors as in the right ear (passive to active, question to negative question). However, sentences in the right ear were recalled with far fewer meaning-changing errors (passive to negative, question to active) (table 10.5). This kind of result was confirmed by a separate study using the same paradigm and varying only the position of an adverb and verb particle.

The waiter quickly sent back the order.
The waiter quickly sent the order back.
Quickly the waiter sent back the order.
Quickly the waiter sent the order back.

Table 10.4
Immediate recall of sequences arranged in sentence order and random order (percentage correct)

	Left ear	Right ear	Right-ear advantage
Sentence order	54	65	+11
Random order	4	4	0
Sentence advantage	50	61	

Source: Bever (1971, table 2).

Table 10.5
Errors to sentences in immediate recall

	Left ear	Right ear	Right-ear advantage
Meaning-preserving errors	16	19	-3
Meaning-changing errors	16	5	+11

Source: Bever (1971, table 3).

In this paradigm subjects made more syntactic recall errors (incorrect adverb or particle placement) to sentences presented to the right ear (table 10.6).

All these studies demonstrate the same principle: The right ear processed sentences more immediately for meaning. I have argued elsewhere that comprehension proceeds in part by the application of perceptual strategies, which map surface sequences onto underlying representations (Bever, 1970). A basic strategy of speech comprehension is one that maps a noun-verb-noun (NVN) sequence onto the grammatical relations "actor, action, object." This strategy accounts for the fact that the first sentence is easier to compare with a picture than the second sentence.

1. They are fixing benches. (progressive construction)
2. They are performing monkeys. (participial construction)

In the first sentence the NVN pattern conforms to the expectation expressed by the strategy, while in the second it does not. Jacques Mehler, Peter Carey, and I tested the comprehension of these sentences monaurally to see if the comprehension time between sentences like 1 and 2 would differ more in the right ear than in the left. Listeners heard five sentences structurally like the first or five sentences like the second and matched each one to a picture; the sentences were always presented to the same ear for a particular subject (Carey et al., 1970). The results are summarized in table 10.7. The predicted differences occurred for sentences heard in the right ear, but the results were actually the reverse numerically for those heard in the left ear. The average comprehension time for the two constructions together was similar in the two ears. However, the right-ear presentation differentiated the constructions according to their conformity with the perceptual strategy while the left-ear presentation did not.

Table 10.6
Syntactic errors in sentences with adverbs and particles

	Left ear	Right ear	Right-ear advantage
Percentage of syntactic errors	52	77	25

Source: Bever (1971, table 4).

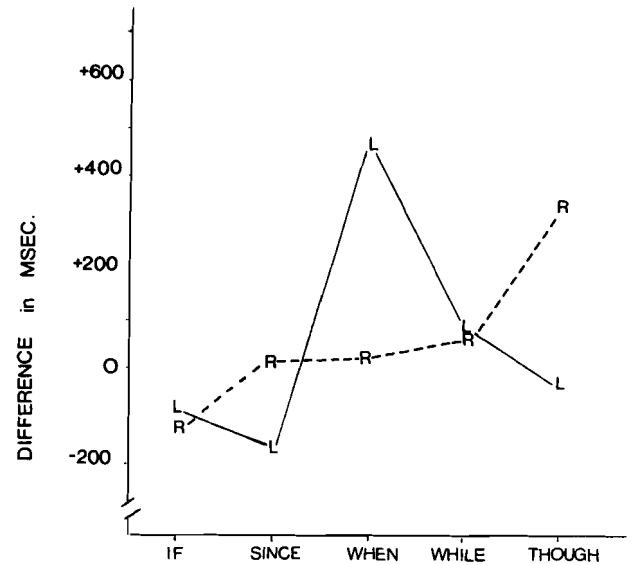
Table 10.7
Mean latency (seconds) to match pictures to progressive and participial sentences

	Left ear	Right ear	Right-ear advantage
Participial	0.98	1.29	-0.31
Progressive	0.96	0.79	+0.17
Difference	0.02	0.50	

Source: Bever (1971, figure 3).
Note: Subjects without experience.

The preceding experiment is devoted to a perceptual strategy that applies within a single clause. David Townsend and I have also examined sentences with different kinds of relations between main and subordinate clauses. In this experiment we probed for subjects' coding of the meaning of a clause by interrupting a monaural presentation of it with a potential paraphrase on a slide (subjects were to say yes when the paraphrase was appropriate). In both ear presentations subjects recognized such meaning-related material from main clauses faster than from subordinate clauses—suggesting that the meaning of a main clause is more immediately processed regardless of ear presentation (Townsend and Bever, 1978).

The main-subordinate difference bears an orderly relation to the strength of the causal link between the main and subordinate clause set up by each subordinating conjunction. For example, a causal "if" or "since" clause can be an explicit cause of what follows, while an "although" or "while" adversative clause must be explicitly not the cause of what follows; a "when" clause is neutral. In a sense the causal subordinate clauses do not depend on their main clause for interpretation, while adversative clauses do, since the information in the main clause clarifies which part of the subordinate clause is adversative. This formal difference is reflected behaviorally among sentences presented to the right ear (see figure 10.1). The



10.1
Response time differences between initial main clauses and subordinate clauses with different conjunctions (subordinate time – main time) in recognizing a subsequent paraphrase. (L = left ear; R = right ear)

main-subordinate difference is large for adversative subordinates and slightly reversed for causal subordinates, with temporal clauses intermediate.

We interpreted this and related results as showing that an interclausal comprehension strategy involves recoding an initial subordinate clause semantically, insofar as it can be a clause independent of a following main clause. This strategy does not characterize the responses to sentences presented to the left ear; there is no orderly relation (at least to do with causality). Rather, all the main-subordinate differences are similar to one another, except "when" clauses, which occasion much longer subordinate clause response times. This result may be of interest in relation to the occasional claim that the right hemisphere has a special difficulty with temporal order (but see Veroff, 1978). In any case it shows that biclausal sentences presented to the left ear are not subjected to the semantically systematic initial comprehension strategies that apply to right-ear input.

If the left-ear presentation does not show evidence of perceptual strategies, how are sentences understood at all in that condition?

One possibility is that the information is transmitted to the left hemisphere by way of the corpus callosum, thus circumventing the application of the strategies but leaving intact other mechanisms of perception. A second possibility is that the monotony of the task of hearing the same kind of construction type repeatedly in these experiments allows for the formation of a holistic schema in the right hemisphere.

Prediction 4. People who are relatively skilled in a modality are more left-hemisphered for relational tasks and more right-hemisphered for holistic tasks.

It would be easy to think of the general situation I have been outlining as one in which the two hemispheres share certain capacities but the left hemisphere takes on the development of special, or "complex," knowledge. This falsely predicts that relational skills are relatively more lateralized to the left hemisphere in highly skilled subjects, while there is no subject difference in the lateralization of holistic tasks. Rather the data suggest that being skilled at a modality involves being more left-hemisphered for relational tasks in that modality and more right-hemisphered for holistic tasks in that modality. This implies that holistic processes have certain independent properties, rather than simply being the mental chaff left behind by the relational processes.

RELATIONAL STRATEGIES

We can examine the behavioral asymmetry differences between musicians and nonmusicians to verify the independent lateralization of relational and holistic processes. Processing music can involve certain relational tasks (novel melody recognition) in which musicians are more right-eared than nonmusicians; it also involves holistic tasks (chord recognition or familiar melody recognition). The first question is, Why do musicians perform better on melody tasks presented to the right ear than on those presented to the left? Is it because their right-ear performance improves, or because the left-ear performance decreases, or both? We found no significant difference in the left-ear performance between musicians and nonmusicians; the musicians performed better than nonmusicians in the right ear, but the left-ear performances were the same (table 10.2). The same

was found by Johnson. The same relative results were found by all the other studies summarized in table 10.3. In every study of unfamiliar melody perception, musicians are better than nonmusicians in the right ear to a greater degree than in the left ear. This suggests that the left hemisphere of musicians is particularly better at this task, while the right hemisphere is not worse.

It is possible that musicians are genetically left-hemisphered for music before they study it; that is, they do not become left-hemisphered as a function of learning relational melodic strategies. Final proof of this genetic hypothesis will require longitudinal investigation of children who are and are not studying music. However, we can examine musicians' performance on holistic musical tasks, to see whether such tasks are left-hemisphered as well.

HOLISTIC TEMPLATES

Music also offers holistic tasks that, unlike melody recognition, remain holistic regardless of one's musical skill. Chord perception (for people without perfect pitch) is one example; the independent notes of a chord cannot be identified by normal listeners, except by virtue of their contribution to the "color" of the chord. This makes chord perception a strong test of the formal explication of the relational-holistic differentiation. The notes of a chord are "related" to each other; indeed, the chord depends for its character on such a relation. But perceiving a chord is not a relational act in the technical sense of the term. While the perception involves a relation between two notes, it does not require separate identifications of the two notes independently *and* in relation to each other. This may clarify what should have bothered the acute reader in my discussion of visual asymmetries. For example, why is recognizing a rotated or displaced figure a holistic task; such recognition presupposes a relation just as a chord presupposes separate notes (physical movement). The answer is that the object is set only in relation to its (identical) self; therefore the rotation task does not meet the "found" criteria of relational processing.

What occurs in highly skilled musicians? Do they become less left-hemisphered for chords (because of a "migration" of music to the left hemisphere?), or do they become more right-hemisphered? The answer is the latter. Gaede et al. (1978) and Gordon (1978) tested

chord recognition in musicians and nonmusicians. They both found that musicians are more left-eared on chord tasks than nonmusicians (table 10.8).

Why should this be so? One possibility is that holistic processing strategies can be learned. I shall call such strategies *templates* because they are processes that do not require any internal analysis. In this view musicians develop (or "have") chordal templates which they apply to chord tasks, heightening the superiority of left-ear performance on such tasks. If the template interpretation is appropriate, then even short or frequently repeated melodies might be holistically processed by musicians. (All the studies that show a significant right-ear superiority in musicians use relatively long melodies or melodies that occur only once or twice in the experiment.)

It should be possible to construct a holistic melody-recognition task. For example, if melodies are very short, listeners may be able to apprehend them holistically without internal analysis. In any case their brevity precludes the application of musically sophisticated strategies. Short atonal melodies might also resist the application of usual melodic strategies (in Western-trained amateur musicians). Finally, very familiar melodies or ones that are repeated many times during an experiment could be perceived holistically by way of constructed templates. Gates and Bradshaw (1977) presented subjects monaurally with ten- to fifteen-note familiar tonal melodies (melodies chosen to be familiar, repeated fifteen times during the course of the experiment). They found that recognition of excerpts from such melodies was numerically better in the left ear than the right for musicians (with no difference for nonmusicians). Johnson et al. (1977) found a similar asymmetry for the recognition of monaurally presented short, nontonal, random sequences of pitches. Finally, Zatorre (1978) found a similar effect by combining these stimulus parameters. He presented short (six-note) melodies a minimum of seventeen times and found that musicians performed better on stimuli in the left ear, and did so to a greater extent than nonmusicians.

The previous studies demonstrate that musicians are more left-eared for holistic tasks while being more right-eared for relational tasks; that is, the right hemisphere "learns" (or if musicians are genetically preformed, "has") templates that increase the efficacy of holistic processing.

If performance improves by way of acquired templates in the right

Table 10.8
Summaries of studies of holistic musical tasks in musicians and nonmusicians

Study	Left ear	Right ear	Right-ear advantage
Gordon[a]			
Musicians	16.9	14.6	-2.3
Nonmusicians	15.1	14.3	-0.8
Musicians' advantage	1.8	0.3	
Gaede et al.[b]			
Musicians	8.21	9.00	-0.79
Nonmusicians	9.94	10.08	-0.14
Musicians' advantage	1.73	1.08	
Gates and Bradshaw[c]			
Musicians	1.88	1.56	-0.32
Nonmusicians	0.61	0.65	+0.04
Musicians' advantage	1.27	0.91	
Johnson et al.[d]			
Musicians	4.6	5.7	-1.1
Nonmusicians	6.7	7.0	-0.3
Musicians' advantage	2.1	1.3	
Zatorre[e]			
Musicians	73	67	-6
Nonmusicians	63	59	-4
Musicians' advantage	10	8	

Sources: Gordon (1978, table 3); Gaede et al. (1978, table 1); Gates and Bradshaw (1977, table 2); Johnson et al. (1977, table 1); Zatorre (1978, figure 2).
Note: Studies and subjects are the same as in the corresponding studies in table 10.3, except where noted.
a. Scores are number correct on chord recognition.
b. Scores are mean errors on note discrimination in chords.
c. Scores on familiar melodies.
d. Errors on short random-pitch sequences.
e. Scores are the percentage correct recognition of short, repeatedly presented dichotic melodies. See the appendix to this chapter.

hemisphere, the difference between musicians and nonmusicians should reside mostly in an improvement in the left-ear performance rather than a decrease in right-ear performance. This is numerically the case in each of the five recent studies that bring out an overall left-ear superiority (table 10.8).

In brief, being musically sophisticated is associated with an advantage in the left hemisphere for relational processes applied to music and in the right hemisphere for holistic musical tasks. Musicians are not more left-hemisphered for music; rather they are more differentiated hemispherically. The hypothesis that complex holistic templates can be learned from experience raises the possibility of a developmental pattern in which people oscillate between first treating a skill holistically, then relationally as experience with it increases, and then holistically again (with higher-order holistic templates the second time). The next section explores face recognition as potentially such as skill.

FACE RECOGNITION: A DEVELOPMENTAL CASE STUDY

A general point of this chapter is that language is characteristically a left-hemisphered skill because most language behaviors involve relational processing. Language is of more interest than many other skills, such as long division or skiing, because it is an indigenous part of all cultures, shared by all "normal" individuals. The ability to recognize faces also seems to be a likely candidate for a culturally universal skill (though it would be less surprising to find a culture in which individuals are not recognized by their faces than to find a culture in which nobody speaks a language). The recognition of familiar faces is important to consider because it is generally viewed as a function of the right hemisphere. This would be a prima facie counterexample to the proposal in this paper that a distinct processing style, not skill, is associated with the hemispheres. Of course, it is possible that faces are always recognized holistically, and that is why face recognition is right-hemisphered. However, I will argue that the generally accepted facts about face recognition are best understood as involving both right and left hemispheres, depending on the way a face is recognized. This variability is a function of such factors as the developmental stage of normal children or neurological state of brain-damaged adults. A full review of the face-recognition literature is beyond the scope of this paper. The

reader should consult Carey (1978) for a recent review of most of the facts that I shall discuss.[9]

Typical specific phenomena are the following:

1. The bilateral recognition of photographs of acquaintances is good with little change, starting at age five years (Carey and Diamond, 1977).
2a. Inverted photographs of acquaintences are poorly recognized in children and adults, except
2b. At ages twelve to fourteen (Carey and Diamond, 1977).
3a. By age eight years, people recognize photographs of familiar people better in the left visual field except
3b. Famous faces (movie stars, and so forth) are better recognized in the right visual field (Marzi et al., 1974).
4a. The recognition of recently presented faces is based on paraphernalia (hats, glasses) until age ten, when each face becomes a perceptual constant. The overall ability to recognize recently presented faces increases with age up to age fourteen except
4b. At ages twelve to fourteen there is a decrease.
5a. Recently presented faces are recognized equally well in the visual fields between ages seven and ten; at ten they are better recognized in the left visual field. This asymmetry continues throughout life except
5b. At ages twelve to fourteen, the left and right visual fields perform equally well (Leehey, 1976).
6. The recognition of upside-down presentations of recently presented faces is poor throughout life.
7a. With (posterior) right-hemisphere lesions, adults cannot recognize recently presented faces, but
7b. Right-hemisphere-damaged adults can recognize familiar faces, and
7c. In certain cases, characteristically with bilateral (posterior) lesions, adults cannot recognize familiar faces but can recognize recently presented ones.

Carey argues that facts such as these (except 3b, which appeared after Carey, 1978, was written) suggest that there is, in effect, an organ of face recognition, which inhabits (and is facilitated by) a particular region of the right hemisphere. A hypothesis is that this organ has two related physiological substructures in the right

hemisphere, an early maturing one for familiar faces and a later maturing one for unfamiliar faces.

This hypothesis is certainly possible. If true, it would serve as a clear example of a maturationally based sociopsychological skill. However it is a very strong position and it cannot explain any of the exceptions noted in 2b, 3b, 4b, 5b, 7b. There is, moreover, a weaker hypothesis that would account for all the stipulated facts. The principles are the following.

A. Recognition of a small number of frequently presented family members and caretakers is important for the child.
B. The face offers a relatively constant and distinctive configuration for each person.
C. There are several ages when the number of individuals to be distinguished increases rapidly (in the social selection of subjects discussed in the literature): (1) at ages five to seven (when a child enters grammar school); (2) at ages twelve to thirteen when a child enters high school).
D. The left hemisphere emerges developmentally as dominant for relational processing, and the right hemisphere for holistic processing.
E. Holistic templates of increasing complexity are constructed developmentally as a result of being repeated in relational analysis.

Principles A–C are obviously true, at least at a nontechnical level; D and E have been postulated earlier in this paper to account for other data. It remains to show how A–E describe facts 1–7 (I take the nonexceptional facts first).

1. Principles A and B combine to predict the early emergence of family (and friend) face recognition.
2. Upside-down familiar faces are of no special import (and rarely experienced).
3. Principles A, B, and D together predict that familiar face recognition will emerge as a special right-hemisphere skill in childhood. Repeated presentation of the same small number of faces could build up a multiple representation of each that could be represented holistically.
4. To recognize discriminatively a recently and briefly presented face requires the ability to quickly form a discriminative representation of it. In children this should be reflected in a range of set cues (eyeglasses, beard, total shape). With development, practice, and an increasing number of faces (implied by principle C1) an overall holistic framework could develop.
5. Some of the distinct facial cues may bear a relation to the whole face, at first being an initial approximation of a facial configuration. Accordingly, the recognition is sometimes relational sometimes holistic, leading to no overall asymmetry until age ten, when an overall holistic facial configuration is accumulated.
6. Recently presented upside-down faces should not show any interaction with ordinary face recognition and no developmental change related to face recognition.
7. If the right hemisphere is the repository for the overall face schema, then damage to it should damage new face recognition.

These facts are all related to the role of the right hemisphere in the emergence of particular holistic template patterns, first for family members and friends and then a more general all-purpose configuration for the rapid representation of new faces. These facts are also the nonexceptional ones. Consider now an exceptional fact (3b), that famous faces are better recognized in the right visual field. Famous persons are characteristically known for a particular facial attribute, usually through photographs alone (for example, Yul Brynner, Howdy Doody, Will Rogers, Santa Claus, Bugs Bunny, Richard Nixon). In fact, many such personages are facially defined by their main characteristic (Brynner by baldness, Doody by freckles, Claus by a beard, Bunny by teeth and ears, Nixon by jowls). A photograph of such personages can vary widely except for that characteristic and still be recognized, which is also why professional comics can do effective imitations of famous people. Thus famous faces might well be recognized by recourse to such isolated features in relation to the whole face; such processing would by definition be better carried out by the left hemisphere.

This kind of interpretation can also explain fact 7b, that right-brain-damaged people can recognize familiar faces; ex hypothesi they do so by reference to certain isolable features of their friends' and relatives' faces (in the traumatic absence of being able to rely on their right hemisphere). They remember that grandpa is bald, grandma wears glasses, junior has freckles. Accordingly these patients can rely on metonymous relational processing for recognition of familiar faces.

These interpretations suggest that adults can recognize faces rela-

tionally. This offers an explanation for a nexus of exceptions to the developmental pattern. At about age thirteen children temporarily lose the right-hemisphere dominance for recognizing new faces (5b). Principles C and E explain this as a function of the reorganization of facial templates, based on the many new faces that a child undertakes to recognize at that age. During this period there is greater interaction between relational and holistic processing as new configurations are being formed. This would also explain the compound perception of upside-down faces (based on isolated features processed in the left hemisphere). In this view the decrease in recognition of familiar faces occurs because of the unaccustomed (and less efficient) left-hemisphere processing.

Finally, we can explain the most bizarre fact of all—that certain patients, with bilateral lesions, can recognize new faces but not old (7c). To explain this we must first recall that reciprocal inhibition of function governs the interrelation of the hemispheres. When a particular function is being carried out in one hemisphere, the same function is inhibited in the corresponding area of the other hemisphere. This mechanism explains why a skill that is overlearned in one hemisphere cannot be easily transferred to the other if the first is damaged. The healthy hemisphere inhibits the damaged one but cannot itself carry out the skill. Complementary inhibition also explains why recovery of a trained function in a damaged hemisphere can occur if the opposite untrained hemisphere is damaged. The damage to the untrained hemisphere releases the trained one from its inhibition, since both hemispheres are now damaged and neither inhibits the other. The originally trained hemisphere can now carry out some of the skill (albeit less well than an undamaged hemisphere), leading to a partial recovery of function.

Suppose, as Carey argues, that the rapid encoding of a new face depends on a highly overlearned facial configuration that is multiply interpreted in adulthood more than any single face (since every normal face implies the configuration). If only the right hemisphere is damaged, access to the general configuration is lost because of the inhibitory action of the left hemisphere. If the left hemisphere is damaged as well, the right hemisphere is released from inhibition and can carry out some of its original functions, especially the one that was most overtrained, the encoding of a new face.

In brief, if one takes the position that face recognition is a highly valued activity potentially carried out by each hemisphere in the

manner appropriate to that hemisphere, then all the stipulated facts can be explained, including those that are exceptional on the previous view that perception is an "organ" with two intrahemispheric sites[10].

We can also make predictions about new facts. One of the easiest to test would be the developmental prediction following from principle C2. Some time between two and seven children should become temporarily worse at face recognition and should also become relatively more left-hemisphered for it. This follows from the hypothesized shift from holistic to relational face processing that occurs under the impact of abruptly having to learn many new faces. Mehler (personal communication) has found some evidence related to the former prediction. Children do temporarily become less able to identify recently presented visual shapes between the ages two and seven. It remains to be seen whether this is true of face recognition in the same kind of paradigms used with adults.

The data on face recognition is consistent with the view that faces can be recognized relationally or holistically, depending on the developmental stage and neurological state of the subject. Such consistency does not disprove the view that normal adult face recognition is a right-hemisphere "organ," nor does it deny the importance of maturational factors in the development of this capacity. It does demonstrate that face recognition is not a counterexample to the main thesis of this chapter.

HOW DOES CEREBRAL ASYMMETRY COME TO EXIST?

The previous review documents the claim that the left hemisphere is dominant for relational processing and the right for holistic processing. What is the basis for this difference? The simplest answer would be the claim that it is innate in an interesting sense (as opposed to the sense in which everything about the hemispheres assumes a physiological representation). A substantive proposal is that the hemispheres process information in different ways at birth due to a direct genetically determined asymmetry that governs some physical aspect of neurological functioning. I shall call this the innate structure theory (IST).

Grosso modo IST is the only choice. How can a processing asymmetry exist without some genetically preconditioned physiological basis? The more interesting question is, What is the simplest physio-

logical difference between the hemispheres at birth that could account for the functional asymmetries of adulthood?

The ontogenetic formation of regular relations between brain and behavior is a dynamic process of growth. The source of cerebral asymmetries must exert its influence during at least a decade while brain structures and behavioral systems emerge. Suppose the only difference between the hemispheres is that the left hemisphere is more capable during early childhood. That is, suppose that the two hemispheres function identically at birth but that the processing capacity of the left hemisphere is larger. This substantive claim, together with several other independently justified premises, is sufficient to account for the early appearance of cerebral asymmetries and their continuous development.[11] There are various models of how a quantitative asymmetry could result in the commonly observed qualitative asymmetries. The essential premises are the following.

1. Learning a relational skill involves more processing than learning a holistic skill.
2. Each hemisphere has anatomically specified cortical zones; each zone is physically predisposed to carry out certain functions, (due to its direct sensorimotor connections, functionally available cortical connections, or internal organization).
3. Any given hemispheric zone has a finite learning capacity.
4. When a skill is learned by one hemisphere the corresponding anatomical area of the opposite hemisphere is inhibited from expressing (or acquiring) that skill.
5. The left hemisphere is more powerful computationally than the right (at least during the years two to six), in the sense that it can simultaneously process a greater number of mental representations at a given maturational stage.

The first premise is a tautology and the next three premises are widely accepted.

The formal definition of the two kinds of processing automatically guarantees, *ceteris paribus*, that relational processing is more demanding than holistic. Since the formal definition of relational processing presupposes two simultaneous independent mental representations, it must be more complex than holistic processing which involves only one such representation. It is a commonplace view that intrahemispheric localization of function can be influenced by

anatomical connections to other cortical areas and to particular peripheral organs. It is not controversial to suggest that, like the brain as a whole, each part of it can account for the learning of so much and no more. Contralateral hemispheric suppression of attentional processes and learning functions has received systematic experimental investigation in animals and is generally accepted for humans.[12]

The last premise is not as commonly assumed, though some arguments are plausibly consistent with it. First, systematic investigations of infant brains have brought out specific zones in which the left hemisphere is larger or more convoluted than the right at birth Recently, Corballis and Morgan (1978) have argued that a maturational gradient in favor of the left hemisphere would explain the left-hemisphere priority for language and complex motor behavior (on the assumption that they are the highest-priority skills to the exclusion of spatial organization, for example). However, they offer no independent evidence from human development. (But Brown and Jaffe (1975) and Whitaker (1978) argue that the left hemisphere matures more *slowly*.) Notice that principle 5a does not directly specify the physiological basis for the computational superiority of the left hemisphere; the left hemisphere could mature more quickly (and therefore can compute more at a time) or less quickly (and therefore is more adaptable to learning new kinds of computations).

Let us stipulate that principles 1–5 are true. Why would they lead to the observed asymmetric specialization of the left hemisphere for relational processing and the right hemisphere for holistic processing? The basic concept is that zones in the more powerful hemisphere (the left) end up carrying out the more demanding mental processes (relational). It is intuitively clear that this would occur reliably only if the acquisition of different kinds of skills is allocated to distinct brain zones (premise 2), each of which has limited capacity (premise 3). If each hemisphere had an arbitrarily large capacity, the computational superiority of the left and the relative difficulty of relational processing would be moot. Also, if there were no complementary inhibition between corresponding zones in the two hemispheres, multiple exposure of tasks would ultimately lead to bilateral representation and expression of every skill.

Still to be demonstrated is why a quantitative superiority of the left hemisphere does not predict dominance for all processing. For

purposes of this discussion, the relevant feature of the quantitative model is that a hemispheric asymmetry of size $f(n)$ for learning an n-step skill is $(f(n))^2$ for learning a $2n$-step skill. If holistic tasks involve processing one mental representation and relational tasks involve processing two or more mental representations, then the hemisphere asymmetry will always be larger for relational than holistic tasks.

By hypothesis the left hemisphere learns all skills more efficiently. However, the stronger asymmetry for relational tasks automatically leads to a greater initial relational superiority in the left hemisphere during early childhood than holistic superiority. Each left-hemisphere zone will tend to become relatively specialized at an early age more often for relational tasks than for holistic tasks. After that, all new kinds of operations must be learned by the right hemisphere. If these operations are themselves roughly evenly distributed between relational and holistic ones, then the end result will be that the right hemisphere becomes relatively dominant for the elaborated holistic operations.[13]

This model would allow us to argue that the marked qualitative difference in the hemispheres results from a small quantitative difference in computational power, interacting with the dynamics of mental growth and the formal differences in complexity of the different kinds of operations. In brief, there is a class of models in which language, the quintessential relational skill, is acquired by the left hemisphere, because of a modest quantitative superiority of the left hemisphere.

SOME APPARENT EMPIRICAL COUNTEREXAMPLES

The preceding model is based on assumptions about normal growth of brain-behavior interrelations. The most obvious counterproposal is that the left hemisphere is dominant for language and relational tasks because of a unique structural attribute that makes language possible in that hemisphere. Two kinds of human populations offer evidence bearing on this proposal. First, prelinguistic infants might show a behavioral asymmetry in favor of language. Second, people with one hemisphere removed might exhibit the normal capacity of the other hemisphere in isolation.

Systematic research on infants is scant, since most methods have

only recently been developed. A few experiments have found asymmetries in evoked response, measured on infants' skulls, stimulated by language versus music or flash versus speech.[14] This research is consistent with the following generalization: Complex stimuli (natural speech sounds) are more often processed in the left hemisphere. But that is what one would expect after a few months from the dynamic developmental model I have suggested. The finding that speech sounds evoke left-hemisphere response and music tones or white noise evokes right-hemisphere response is consistent with the fact that speech is a more complex waveform than music or undifferentiated noise. Furthermore, research during the last year has demonstrated that the left-hemisphere-evoked response in infants differentiates acoustic-voicing-onset variants of the same consonants (as categorized by adults) while the right hemisphere does not. The right hemisphere does, however, differentiate different consonants. Only the left hemisphere differentiates consonants that differ in place of articulation, an acoustically complex property. Both the right and the left hemisphere differentiate relatively steady tonal properties. Even in the infant only certain, complex characteristics of speech, *not* speech as a whole, are lateralized to the left hemisphere (Molfese, 1978).

This volume contains recent findings relating to the behavioral limitations of the surgically isolated right and left hemispheres (Dennis, chapter 9, this volume). Such cases are interesting and well worth pursuing. The linguistic capacity of the derelict right hemisphere at first seems impressive. However, the precise experimental results with such patients are also consistent with the following summary. The surgically isolated right hemisphere processes language less well than the surgically isolated left hemisphere. This finding does not invalidate the dynamic model of asymmetries in favor of IST for several reasons. First, according to the quantitative hypothesis, the right hemisphere is slower at multirepresentational tasks. Since language behavior is normally based on the intact left hemisphere, many language processes considered normal may themselves be predicated on an active short-term memory of a certain size and a perceptual mechanism of a certain speed. If the lone right hemisphere operates more slowly than the left (as it does, by my hypothesis) then it might appear to be relatively impaired on normal language tasks. (This point is like that raised against using

IQ tests to measure the intellectual capacity of minority groups; that is, the lone talking right hemisphere is a minority that is not taken into account in the majority measures of linguistic capacity.)

A second, more baffling, but potentially devastating point is that these subjects started out life with one extremely abnormal hemisphere. This must lead to some abnormality in the initial wiring of the normal hemisphere, thereby rendering abnormal the performance of the remaining hemisphere after surgery. (I am indebted to N. Geschwind for bringing this point to my attention.)

The most impressive fact is that the lone right hemisphere learns language at all. Surely, the strong structural theory of the usual dominance of the left hemisphere would not allow for that.

CONCLUSION

I have shown that language could be left-hemisphered because it characteristically involves relational activity and because the left hemisphere is dominant for all relational processing. I have shown further that the left hemisphere could become dominant for relational processing if there were a slight quantitative superiority in processing during childhood. In this view we must yet account for the evolution of a quantitative increase in the number of mental representations and relations that can be processed simultaneously and the emergence of a quantitative hemispheric asymmetry in functioning. Such evolutionary developments are prodigious. But at least we are relieved of the burden of accounting for the specific qualitative facts of hemispheric asymmetry.

Of course one could argue that it is easier to comprehend these asymmetries if one assumes an innate structural qualitative difference in the hemispheres. One could argue that asymmetries in other species give precedence to such innate structural differences. One could argue that the early appearance of phonetic asymmetries demonstrates an innate qualitative peculiarity of the left hemisphere.

Of course, one could. But first we must demonstrate that the prima facie simpler and more generally motivated explanation of the same facts is inadequate.

Broca had a hunch that qualitative asymmetries are the normal outcome of a quantitative perinatal asymmetry. Lashley supplemented this with the view that general laws of growth account for

the emergence and localization of brain function. I have argued that these old suggestions can explain all the currently known facts about asymmetries.

APPENDIX: Five replications of relative right-ear superiority among musicians for processing melodies and one methodologically based failure to find this

Bever and Chiarello (1974) reported that melody recognition was better in the right ear than the left for musicians but the reverse for nonmusicians. Their theoretical position was that musicians have a set of melody-processing strategies that reflect the music they have heard and played. These strategies facilitate the mental description of a melody in terms of its component motifs and the relations between the motifs and the whole melody. Accordingly, musicians process melodies relationally, in the technical sense defined earlier (and thus better in the left hemisphere). Nonmusicians do not have such motif strategies and, insofar as they deal with them at all, must process melodies holistically (and thus better in the right hemisphere).

Bever and Chiarello's theoretical position motivates a number of design parameters in studying this phenomenon.

SUBJECTS

They excluded subjects with known hearing loss in either ear, self-reported tone-deaf subjects, and those with self-reported perfect pitch. Such subjects are incapable of or could avoid classifying a melody as a melody. They are not appropriate. All subjects were right-handed.

Musicians included only currently active amateur musicians. Nonmusicians included only those who never had more than a few years of training, not less than six years before the experiment.

Bever and Chiarello used these definitions as selection criteria to ensure a clear differentiation of subject groups. The musicians could all read music (usually they could sight-read with proficiency). Most

could take simple musical dictation (being an active amateur musician often involves making minor corrections on a score, copying brief passages of another part). Bever and Chiarello did not test for musicality, either among the musicians or nonmusicians. They avoided using musicologists and composers as subjects because their pilot research had indicated that such listeners treat the experiment as an intellectual puzzle, apparently suspending normal listening strategies.

MATERIALS

Bever and Chiarello used eight-note to twenty-note tonal melodies. They reasoned that melodies must be long enough so that short-term memory limitations are exceeded; only then do listeners need to apply recoding strategies. (Of course, this leaves open the possibility that musicians use such strategies anyway.) The melodies were tonal;that is, they were in the same key, began and ended on the tonic, or implied a harmonic modulation, following standard laws of tonal melody formation (no major leaps with a melodic phrase, preparation or filling-in of leaps that do occur). This constraint ensured that the stimuli would be susceptible to standard occidental music-recoding strategies.

PROCEDURE

Ear Presentation

The stimuli were presented monaurally and in blocks to the same ear. Bever and Chiarello were concerned with the characteristic performance of each ear alone, not with the ear performance when the ears compete actively (as in dichotic listening) or in anticipation (when the listener does not know which ear to attend most). Dichotic presentation of music involves a special problem that does not arise for speech: the tendency to fuse the competing stimuli into one musical whole. Charles Ives aside, simultaneous presentation of different melodies is a common integrative task for music listeners; the normal listener may integrate the two separate melodies in a dichotic task, producing a third stimulus.[15] This problem is ecologically distinct from that of speech. Disentanglement of competing speech messages is a listening problem (the so-called cocktail party problem). Luciano Berio aside, several simultaneous speech messages

must ordinarily be kept distinct, not integrated. Accordingly, it may be an ecologically acceptable technique to use dichotic listening with speech, but it is not acceptable with music.

TASK

Bever and Chiarello required listeners both to recognize whether a melody was repeated and to recognize an excerpt from each melody. The effect of this double task was to reduce the possibility that listeners would encode the stimuli in an arbitrary or task-specific memory code. While listening to each melody they had to process it for immediate recognition of the following excerpt.

Each melody was presented only once (except for the positive repeated melody trials). Repeated presentation of a complex melody could allow both musicians and nonmusicians to build up a relational representation; repeated presentations of a simple melody, ex hypothesi, could allow all subjects to build up a holistic template. Single presentation follows the usual practice in psycholinguistic research on normal sentence comprehension—consider the absurdity of an experiment on normal speech comprehension involving the presentation of the same sentence fifty times.

Five recent experiments, each by different researchers in different laboratories, have included studies related to the main finding of Bever and Chiarello. They all report superior performance in the right ear for musicians, a finding generally unexpected before Bever and Chiarello. They all appear to report a numerically greater right-ear superiority for musicians than for nonmusicians. However, the differences among the experiments are worthy of comment and may be useful as a guide for further experimentation.

Two experiments replicate Bever and Chiarello fully. Not only do musicians show a right-ear superiority, but nonmusicians show a left-ear superiority. These experiments differ from the other three in that they present each stimulus to a given subject only once.

Johnson (1977) used two-second violin melodies differing in pitch and rhythm, presented in dichotic pairs with a following binaural probe. On half the trials the probe was not one of the stimulus melodies; on the other half it was. The subjects' main task was to say whether the probe was one of the just-heard dichotic melodies. The musicians were people with at least four years of music training, who were "currently [playing] . . . for . . . at least one hour

daily." He also tested the subjects for normal hearing. He contrasted right-handed and left-handed subjects. The results for right-handers conformed to Bever and Chiarello exactly (table 10.3). The results for left-handers are much less extreme. Johnson concludes that "this result supports . . . they hypothesis that musical stimuli are processed mainly in the left hemisphere of musicians and the right hemisphere of nonmusicians."

Johnson et al. (1977) used short tonal, conventional melodies each presented once monaurally, followed by four binaural melodies. The task of the subjects on each trial was to identify which of the binaurally presented melodies they had just heard. They also used random pitch and rhythm sequences and random pitch sequences. Their subjects included nonmusicians, musicians who play instruments without being able to read and transcribe music, musicians with reading ability, and musicians with reading and transcribing ability. Only the last two groups are likely to correspond to Bever and Chiarello's musicians. (Almost no active amateur musician cannot read music; indeed most can also transcribe it. On the other hand musicians who play without reading music may not be similar to Bever and Chiarello's nonmusicians.) The last two groups of musicians in Johnson's study perform similarly to musicians in the previous studies, in comparison with the (nonsignificant) tendency of nonmusicians to perform better in the right ear (table 10.3) They conclude that "comparisons of error scores by ear and by types of musical stimuli confirm the findings of Bever and Chiarello" (p. 296).

Johnson and Johnson et al. show a reversal of ear superiority between proficient musicians and others. Three other paradigms have brought out right-ear superiority in all subjects, in contrast to the traditional claim that music is univocally right-hemisphered. Furthermore, each study brings out numerically more right-earedness among musicians than among nonmusicians.

Gates and Bradshaw (1977b) used a complicated stimulus paradigm varying familiarity of melodies, tonality, and the length of excerpts used in a recognition task. Their experiment VI contrasted musicians (defined as potential professionals) and self-classified nonmusicians. Subjects were required to decide whether a long (five-note) or short (two-note) excerpt was contained in a preceding melody. The false trials were transpositions of a correct sequence (five-note false probes) or a pair of notes from the melody with a missing

intervening note (two-note false probes). The unfamiliar melodies were retrograde and retrograde inversion transformations of the equal-duration familiar tonal melodies.

They derived δ' analyses for each melody condition using hit and miss rates as well as confidence ratings. They found an overall superiority of the right ear for both kinds of probes in musicians and nonmusicians. Table 10.3 presents the averages of the δ's presented in their table II, for illustrative purposes. (Note that averaging δ' across groups does not necessarily produce the exact δ' that would be produced by analyzing all the data in a single group.) Overall the right-ear effect is numerically stronger among musicians, although this is strongly true of males and weakly reversed among females. They conclude (inter alia) that "in opposition to the widely-held views of right hemisphere 'dominance' for music, this result supports the claim of Bever and Chiarello (1974) for left-hemisphere involvement: however, contrary to their suggestion that musical training determines hemispheric specialization, the present findings indicate differential processing within, as well as between, musically selected groups of subjects" (p. 403).

The problem for them and us is to explain why all the subjects appear to have processed the unfamiliar stimuli better in the left hemispheres. Their unfamiliar melodies may have had peculiar nonmelodic properties, since they were created by transformations of standard melodies. They were also presented four times, perhaps enough to stimulate analysis of each into component phrases, but not enough to provide the basis for a total gestalt of each. Finally, the false probes were extremely similar to correct probes, perhaps accounting for the need to listen analytically, and also accounting for the fairly low overall detection rate. Gates and Bradshaw do not report the true and false-positive rates separately; it is possible that all the δ' differences are the result of different rates of false-positive responses.

Gaede et al. (1978) examined the effect of the subject variable *musical aptitude*. They reasoned that aptitude would ordinarily correlate with proficiency and that the previous research on musicians might demonstrate an effect, not of musical training, but of musical talent. They used a standard binaural test of melodic aptitude, which they describe as requiring subjects to report how each of a number of melodies differs from a presented standard melody. They used this test to segregate high- and low-aptitude nonmusi-

cians and musicians (the musicians had at least five years of instrumental lessons, within the most recent five years). They then presented another melody memory test monaurally; on each trial a second melody was either identical to the first or differed by one note. The melodies were four to ten notes long.

All subject groups performed better in the right ear than in the left ear. (Table 10.3 groups the data across aptitude to demonstrate the consonance of their results with those of Bever and Chiarello.) They showed that the right-ear advantage is greater among musically experienced subjects. This difference is mostly due to subjects with high aptitude. Contrasting their results with those on a chord-perception task (which shows a left-ear advantage overall), Gaede et al. conclude that "the kind of processing applied to a musical stimulus (or in an experiment, required by the task) can determine which hemisphere is dominant." They also report a significant effect of musical aptitude on overall performance and argue that their significant effect of experience shows that aptitude is the relevant variable.

This conclusion is explicitly consistent with the view that there are different modes of melody analysis, relational and holistic. Furthermore Gaede et al. found no significant ear difference effects as a function of either experience or aptitude, so the experiment could simply be viewed as a failure in that regard. Their results can be interpreted as showing that musically untrained people may nevertheless possess musical skill. The binaural test of aptitude is very similar to the later experimental test. It is also ambiguous; it may be a test of raw aptitude (whatever that is) or a test of musical experience incorporated without instrumental training. After all, there are many people who are avid musical auditors without being recently trained performers.

Conversely, Gaede et al. have also shown that if a trained musician is poor at one musical task (the binaural aptitude test) he or she is poor at another musical task (the monaural memory test). That there are unmusical musicians and musical nonmusicians is important to have documented, but their results suggest that this is not an important variable in ear superiority.

Gordon (1978) was concerned with exploring whether it is the rhythmic pattern or pitch sequence that can be dominant in the left hemisphere. This was a curious goal, for several previous experiments that had revealed right-ear superiority used melodies lacking any internal rhythmic variation (Bever and Chiarello, 1974). However, Gordon presented two-second melodies dichotically that differed in either rhythm pattern (same note sequence) or note sequence (same rhythmic pattern). Subjects then had to choose among four binaural probe melodies, noting which they had just heard. Subjects were right-handed musicians and nonmusicians discriminated by the same criteria used by Gaede et al.

Gordon did not find any ear effects for melodies differing in notes. However, rhythmic differences did bring out an overall right-ear superiority, which is numerically larger among musicians than nonmusicians. (Table 10.3 presents the mean time positions, excluding subjects performing at chance levels, as does Gordon.)

Gordon's results join the ranks of those recent studies that elicit a right-ear advantage for melody processing. It remains for us (and Gordon) to understand why this different pitch task did not bring out any asymmetry, regardless of subjects, despite the previous reports of asymmetries in the processing of nonrhythmic melodies.

One possible interpretation is the difficulty of separating two dichotic melodies on the same instrument, which maintain strict parallel rhythm. The listener's tendency may be to hear such sequences as two-note chord sequences, rather than two separate melodies. (For this reason, identical rhythm among voices is forbidden, even in standard counterpoint.) Thus the task may have been a mixture of melodic-sequence processing and chord processing, eliciting no overall ear asymmetry effects. (The separate rhythm stimuli approximate an accepted occidental music form, the canon, in which one voice alternately follows and leads another voice in a sequence.)

Finally, I would like to consider a possible nonreplication of the result (Zatorre, 1978). In the text I interpret Zatorre's method as an example of a holistic musical task. However, since he takes his results to be a disconfirmation of Bever and Chiarello's results, I include his study in this review. Zatorre contrasted musician and nonmusician performance in a carefully constructed experimental design. All subjects were right-handed with no reported sinistrality in their immediate family. Subjects listened to eighteen six-note "melodies" produced by a tone generator. On each trial one of the eighteen melodies was paired dichotically with one of the others; following the dichotic presentation, subjects heard four melodies

binaurally and had to choose which two they had heard. Table 10.4 shows an overall left-ear superiority on this task which is numerically stronger for musicians than for nonmusicians (the numbers in this table are read from Zatorre's figure 1 and so are approximate). Accordingly, Zatorre concludes, "These findings imply that melodies are processed by the right hemisphere regardless of training."

It is useful to understand why Zatorre's method did not replicate the previous findings. First, like Gaede et al.'s familiar melodies, Zatorre's melodies were each repeated at least seventeen times as a stimulus and an unclear (to me) number of times as a possible recognition foil. The repetition alone might account for the holistic processing of the melodies with constructed perceptual templates. Second, the method of presentation and probing was identical to that of Gordon's different-pitch task, although Gordon used larger and rhythmically varying melodies, again raising the possibility that subjects fused the dichotic sequences into sequences of two-note chords. Finally, melodies of only six notes might be processed holistically, especially in conjunction with the frequent repetition. They certainly would not ordinarily exceed short-term memory limits and therefore would not require relational processing. For these reasons, Zatorre's method would be expected to bring out holistic processing of melodies, if anything can. Accordingly, Zatorre is best viewed as a replication of Kimura (1964), not a nonreplication of the studies reviewed here.

CONCLUSION

These studies demonstrate that melody processing is not univocally superior in the left ear. Variations in stimuli, tasks, and subjects can each bring out a right-ear superiority. What these variables have in common is a differentiation of the kind of processing the subjects apply. When the processing is relational, right-ear superiority emerges.

ACKNOWLEDGMENTS

This research was supported by a grant from the Spencer Foundation. I also wish to express thanks for the critical advice of C. Daiute and the assistance of J. Robbart in the preparation of this manuscript.

NOTES

1. The literature on cerebral asymmetries has grown so fast in recent years that it is pointless to list the relevant publications. Recent comprehensive collections of articles are in Harnad et al. (1977), Segalowitz and Gruber (1977), and Kinsbourne and Smith (1974).

2. D. Shankweiler, *Journal of Comparative Physiological Psychology* 62 (1966): 115; M. S. Gazzaniga and R. W. Sperry, *Brain* 90 (1967): 131; J. E. Bogen, *Bulletin of the Los Angeles Neurological Society* 34 (1969): 135; J. Levy-Agresti and R. W. Sperry, *Proceedings of the National Academy of Science, USA* 61 (1968): 1151; B. Milner and L. Taylor, *Neuropsychologia* 10 (1972): 1; J. Bogen, in *Drugs and Cerebral Function*, ed. W. L. Smith. Springfield, Ill.: Thomas, 1972, pp. 36–37; B. Milner, in *Interhemispheric Relations and Cerebral Dominance*, ed. V. B. Mountcastle, Baltimore, Md.: Johns Hopkins University Press, 1961.

3. This formal analysis includes the unanalyzed pretheoretic terms *representation, activation, relation,* and *task*. Ultimately these terms themselves must be specified within a theory of cognitive action. For the present discussion the main role of the formal statement is to demonstrate that whatever the ultimate cognitive theory turns out to be, relational and holistic processing can be reduced to the same theoretical primitives, and it will always be the case that relational processing is more complex than holistic processing, at least because relational processing involves the activation of more mental representations. Thus whether the processing of a particular relation is complex or cost-free, relational processing is always more computationally demanding than holistic processing. (See premises 1 and 5.)

4. A full report can be obtained from R. Hurtig, Department of Psychology, Iowa University, Iowa City, Iowa. Hurtig monitored EOG to ensure proper eye fixation.

5. Krynicki also monitored EOG for proper eye fixation, as well as having an ancillary nonsense fixation task. Subjects responded immediately after seeing a brief presentation of the complex figures. Dee and Fontenot (1973) have reported that as the interstimulus interval of complex figures increases, recognition becomes relatively better in the left visual field. (They also report a superiority—nonsignificant in their results—in the right visual field for immediate recognition.) Birkett (1978) reports no asymmetry for twelve-sided figures, midway in complexity between Krynicki's eight- and sixteen-sided figures.

6. The basic reference is Kimura (1964). Others include F. J. Spellacy and S. Blumstein, *Journal of the Acoustical Society of America* 49 (1971): 87; O. Spreen, F. Spellacy, and J. Reid, *Neuropsychologia* 8 (1970): 243; D. Kimura, *Cortex* 3 (1967): 163. See also J. Bogen and H. Gordon, *Nature* (Lond.), 230 (1971): 524, for clinical evidence for the involvement of right-hemisphere functioning in singing.

7. More details of this experiment can be obtained from me. We used a yoked design; for every choir boy there corresponded a nonchoir boy of the same age, grade, and handedness.

8. This experiment was first reported in Bever (1971). In all the experiments reported from our laboratory, subjects were right-handed, native speakers of English with no known hearing defects. See also Frankfurter and Honek (1973) for a replication.

9. A modified view of Carey's 1978 position is presented by Carey and Diamond, chapter 5, in this volume. Face recognition asymmetries are now at least as well studied as music perception asymmetries and therefore warrant as much detailed review as is presented in the appendix to this paper. I limit myself primarily to Carey (1978) because, unlike most, she presents a coherent theory of the phenomenon as well as a representative review of relevant facts.

10. Of course face recognition can still be viewed as a mental organ despite its hemispheric diaspora.

11. An earlier version of this theory was presented in Bever (1975).

12. See, for example, Kinsbourne, (1975).

13. There are a number of specific models of how this works out. A simple one is based on the assumption that the mean time for a single mental representation to be processed by time t is r for the right hemisphere and $r-k$ for the left hemisphere. Suppose that each mean has the same normal distribution with a standard deviation d and with overlap. The proportion of times that the left hemisphere will complete its processing first (and inhibit the right from further processing or learning on that occasion) is a direct function of d. However, if the skill has two representations that must be processed serially, then the proportional advantage of the left hemisphere is greater than for a skill involving one mental representation. Characteristically for a skill involving n mental representations, the disparity between the two hemispheres is $f(n/\sqrt{n})$ because the standard distribution increases as the root of the mean). Since the expression increases as n increases, the more complex the skill, the greater the asymmetry in favor of the left hemisphere.

An alternative view allowing functional equality of the hemispheres is that the left hemisphere is more powerful just during the period when language is being learned and for that maturationally accidental reason, language is left-hemisphered. (Such a view is consistent with the proposals of Corballis and Morgan, 1978.) That view is not tenable for number of reasons. First, language learning extends over a long period, roughly from ages two to ten years. If that is the period when the left hemisphere is more powerful, then that theory is virtually the same as the one in this paper. Furthermore, the maturational coincidence theory cannot explain why all relational tasks are left-hemisphered, even those that may be learned much later in life (music). To explain that would require a mechanism like generalization to explain

nonlinguistic relational processing in the left hemisphere as a generalization of the basically linguistic relational processing.

14. See Entus (1977), Davis and Wada (1977). The latter is particularly interesting because the authors propose that the left hemisphere of infants produces a more coherent evoked response, which may reflect its greater computational capacity.

15. Fusion of dichotic notes into central chords is reported in Efron, Bogen, and Yund (1977).

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III

Studies of Neural Mechanisms Underlying Language in the Adult