The integrative action of the cerebral hemispheres

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In four experiments, right-handed subjects were asked to identify uppercase letters presented tachistoscopically in the right (R) or left (L) visual field or in both visual fields simultaneously (RL). When R, L, and RL trials were randomized together and RL trials consisted of the same letter in each visual field (Experiments 1 and 2), 11 of 21 male subjects (Experiment 1) and 9 of 18 female subjects (Experiment 2) showed a strong left-visual-field advantage, and the remainder in each experiment showed an equivalently strong right-visual-field advantage. When the RL trials consisted of a different letter in the two visual fields (Experiment 3), a consistent right-visual-field advantage was observed. It is argued that these results reflect predominantly analytical (left-hemisphere) processing of "different" pairs and relatively holistic processing of "same" pairs, which induces a shift toward a right-hemisphere advantage in some subjects. The main purpose of three of the four experiments was to test five probability models of hemispheric integration: (1) statistical summation, which assumes that the hemispheres operate independently; (2) redundancy, which assumes that RL decisions reflect only processing by the more specialized hemisphere; (3) complete dependency, according to which RL decisions are the mean of R and L decisions; (4) integration, which assumes that R and L decisions can be represented as vectors in a joint RL space; (5) correlation, according to which the R and L decisions are assumed to be statistically dependent. Whether R, L, and RL trials were randomized together or RL trials were presented in separate blocks, models 1 and 4 could be clearly rejected. In general, the best predictor of RL performance was model 5. It is argued that the hemispheres function as an integrated system in letter identification.

Experimentation over the last 25 years has clearly demonstrated differences in the specialization of the cerebral hemispheres. Although the older tradition of "cerebral dominance," the idea that one hemisphere is largely redundant (Young, 1962, for example, described the right hemisphere as a "vestige"), has lost ground to the notion that the hemispheres function in some integrated way (e.g., Dimond, 1972; Dimond & Beaumont, 1974), research continues to be concerned with the functions of each hemisphere separately, as though the hemispheres operated in virtual independence. Experimentation with normal subjects has followed the pattern of clinical research that focuses upon the distinct contributions of each hemisphere, of investigations that have, for example, catalogued the deficiencies resulting from traumatic injury to one hemisphere, or that have used split-brain patients (e.g., Gazzaniga, 1970), in whom processing in the surgically separated hemispheres may be studied. With normal subjects, we have devised methods (e.g., tachistoscopic presentation to the visual hemifields; dichotic listening) that in effect

allow us to mimic results obtained from split-brain patients.

Since we have designed experiments explicitly to point up differences between the hemispheres, we have few data and little theory (but see Dimond, 1972) on how information is integrated between the hemispheres. Physiological studies certainly suggest that both hemispheres are jointly involved in processing. Evoked-potential data support the view that the two hemispheres cooperate in the production of speech (e.g., Grabow & Elliott, 1974), and studies of regional cerebral blood flow as an index of hemispheric activation have typically emphasized the variation in the degree of hemispheric specialization, both within and between individuals (e.g., Gur & Reivich, 1980). Moreover, the most severe aphasias following brain injury appear to result from bilateral lesions (Bogen, 1969).

In this connection, the behavioral work of Hines (1975) and of Dimond (1972; Dimond & Beaumont, 1972) is particularly important because they have concentrated on the integration of information between the hemispheres in perceptual and perceptual-motor tasks. Hines (1975) has argued explicitly that the hemispheres do not function as separate channels, at least when stimuli are unilaterally presented to the right or left of a fixation point. Dimond and Beaumont (1972) have shown that symmetrical half-figures are

The research for this study was supported by a grant from the National Science and Engineering Research Council of Canada. Thanks go to Roseanne Armitage and Barbara Collins for running subjects and to John Bell for preparation of stimuli. Address requests for reprints to: Bill Jones, Department of Psychology, Carleton University, Ottawa, Ontario K1S 5B6, Canada.

more rapidly recognized as matching when they are presented to the two hemispheres than to either hemisphere separately. Dimond (1972) has argued that the cerebral hemispheres constitute a "two-brain" system in which the functions of each hemisphere interlock closely. However, his work has not been based upon explicit models of the integration processes. He has tended to accept that superior efficiency of two-hemisphere processing indicates a degree of integration. However, in the present experiments the applicability of a probability model that predicts greater accuracy on the basis of independence of the hemispheres for a letter identification task is examined.

If letters of the alphabet are presented in the right visual hemifield (R) or the left visual hemifield (L) or if the same letter is presented simultaneously in both hemifields (RL), the experiment involves either the separate stimulation of each hemisphere, since information presented to one visual field is transmitted to the contralateral hemisphere, or the transmission of the information to both hemispheres at the same time.

The basic experiment has much in common with studies of bisensory detection and recognition (e.g., Craig, Colquhoun, & Corcoran, 1976; Dougherty, Jones, & Engel, 1971; Eijkman & Vendrik, 1965; Fidell, 1970; Loveless, Brebner, & Hamilton, 1970) and with comparisons of binocular and monocular information processing (e.g., Townsend, 1968). The basic dependent measures are the probabilities (P) of a correct decision for either visual field, P_R and P_L , and for the two fields in combination, P_{RL} . At least the following integration models are a priori plausible descriptions of processing in the RL condition.

Complete independence of the two hemispheres. The hemispheres may operate without coordination, in the sense that information presented to the two visual fields provides two statistically independent opportunities for the subject in the RL condition to reach a correct decision. We need to find the probability of making a correct decision when information is given in the right or in the left visual field, that is, the probability of the union of the two events. Since the two hemispheres are independent by hypothesis, it is simple to show that

$$P_{RL} = P_R + P_L - P_R P_L. \quad (1)$$

Equation 1 has been referred to as "statistical summation." The model predicts fairly efficient RL performance in comparison with performance in the better of the two single hemispheres. A version of Equation 1 has been extensively studied in bisensory experiments, in which it appears in most cases to overpredict performance (Dougherty et al., 1971; Loveless et al., 1970).

Complete redundancy of one hemisphere. Under this assumption, information in one visual field is effectively ignored or processing in one hemisphere is completely inhibited in the RL condition. The subject's decisions reflect only the output of the more efficient, more specialized hemisphere. In other words,

$$P_{RL} = \max P, \quad (2)$$

where $\max P$ is the greater of P_R or P_L . This equation can be taken to represent the notion of cerebral dominance.

Complete dominance. Information from the two visual fields is combined, and RL decisions represent an average of the performance in the R and the L conditions. Assuming equal weighting of the two sets of information, P_{RL} is given by

$$P_{RL} = \frac{1}{2}(P_R + P_L). \quad (3)$$

An analogous model has been reasonably successful in predicting binocular integration of information (Townsend, 1968).

Integration of information in a common space. Assume that observations with respect to each visual field can be represented according to the classical signal detection model (Green & Swets, 1966) by normal equal-variance distributions of "signal + noise" and "noise." We may now associate with each visual field the signal detection parameter, d' , and therefore have d'_R , d'_L , and d'_{RL} as indices of recognition accuracy for the R, L, and RL conditions, respectively. Further assume that d'_R and d'_L can be represented along orthogonal axes and that d'_{RL} is a vector in the joint RL space. It follows that

$$d'_{RL} = (d'^2_R + d'^2_L)^{1/2}, \quad (4)$$

the vector sum of d'_R and d'_L (Green & Swets, 1966). In other words, a single decision is made on each RL trial on the basis of an integration of information from the two hemispheres. Of the five models discussed here, Equation 4 predicts the most efficient RL performance, although, like Equation 1, it appears in general to overestimate bisensory detection and recognition (e.g., Craig et al., 1976; Fidell, 1970; see, however, Dougherty et al., 1971).

Information in the right and left visual field is correlated. We assume that observations in the right and left visual fields are statistically dependent, that is, that the cerebral hemispheres cannot be considered as independent, isolated processors of information. Craig et al. (1976) have shown that modifying Equation 1 to include a covariance component provides a reasonable fit to bisensory detection data (see also Eijkman & Vendrik, 1965). The model given by Craig et al. may be written, *mutatis mutandis* for

P_{RL} , as follows:

$$P_{RL} = P_R + P_L - P_R P_L - \phi [P_R(1 - P_R)P_L(1 - P_L)]^{1/2}, \quad (5)$$

where ϕ can be interpreted as a nonnegative correlation coefficient with an expected value .5 that indexes the degree of agreement between inputs to the two hemispheres.

In a formal sense, Equation 1 is a special case of Equation 5, since if $\phi = 0$, the two expressions are identical. Yet the substantive implications of the two equations are quite different. If $\phi = 0$, the events "correct decision on the right" and "correct decision on the left" are independent and the two hemispheres can plausibly be regarded as isolated and distinct. If $\phi > 0$, the two events covary and one may argue that the hemispheres should be considered an integrated system.

We should also note that in some circumstances Equations 2 and 5 may be difficult to distinguish. It is evident that, as ϕ increases, the predicted value of P_{RL} under Equation 5 must decrease. It is not difficult, therefore, to construct examples for which Equations 2 and 5 predict identical values of P_{RL} because of the value of ϕ . Nevertheless, it is worth including the comparison between the two equations, since values of ϕ remain to be empirically determined. It is entirely plausible at the moment that only low and insignificant values of ϕ will be obtained, in which case Equation 5 would predict higher values of P_{RL} than Equation 2, or that values of ϕ will tend toward unity and thus produce lower values of P_{RL} under Equation 5 than under Equation 2.

Recognition of single letters unilaterally presented in the right or left visual fields has typically shown a right-visual-field advantage in accuracy (e.g., Bryden, 1965; Cohen, 1976; Jones, 1980a; Polich, 1978) and has been described as a verbal task dependent upon left-hemisphere specialization (Bryden, 1965). However, there is reason to suppose that a left-field advantage should be observed in some circumstances. Bryden and Allard (1976), for example, have noted an interesting dependence of hemifield differences upon the typeface. Possibly some typefaces encourage a holistic pattern-matching process, which may result in a right-hemisphere advantage (see Allard, 1972; Bradshaw, Bradley, Gates, & Patterson, 1977), while an analytical feature-by-feature comparison of letters may reveal the specialization of the left hemisphere (Allard, 1972). There is some evidence that both analytical and holistic processes are typical of letter comparisons (e.g., Taylor, 1976).

EXPERIMENT 1

Method

Subjects. The subjects were 21 male right-handed undergraduates

and faculty who had volunteered their participation. Handedness was assessed by means of a standard questionnaire (Oldfield, 1971). None of the subjects had any familial history of sinistrality, and none were observed to write in a "hooked" style (cf. Levy & Reid, 1978).

Apparatus and Materials. Stimulus slides were constructed so that uppercase letters could be back-projected from a random-access projector (GAF Autofocus) fitted with an electronic shutter (Gerbrands Model 66) controlled by locally constructed timing equipment.

The letters were Letraset Helvetica Medium, a font without serifs and with lines of equal thickness. When projected, each letter subtended approximately $.25 \times .15$ deg and each letter appeared at an angle of 7.5 deg right or left (or right and left) of the midline. The subjects were positioned with a chinrest and a head clamp to control the position of the head.

Procedure. On each trial, the subject was instructed to fixate a central field marker. A letter was presented for 90 msec in one of the two visual fields, or the same letter appeared for 90 msec in both visual fields simultaneously. The three visual-field conditions were randomized across trials, and each letter was presented twice in a random sequence in each condition. The subject was required to name the presented letter. Responses were recorded by hand.

Results and Discussion

Table 1 gives mean P_R , P_L , and P_{RL} for the experiment. It is apparent that accuracy for the two visual fields was approximately equivalent and that accuracy in the RL condition was 7%-8% in excess of accuracy for the single-field conditions. Analysis of variance showed a significant effect of condition [$F(2,40) = 4.81$, $p < .05$], and Newman-Keuls comparisons showed that the probability of a correct decision was significantly higher ($p < .05$) in the RL condition.

The failure to observe a mean difference between the visual fields is unusual. Visual-field differences measured as the absolute difference between P_R and P_L were, however, quite high, with a mean of .12. Ten of the subjects showed a right-field advantage (the RVF group; mean difference = .11), and 11 showed a left-field advantage (the LVF group; mean difference = .12). Mean probabilities for the two groups are also shown in Table 1.

When the data were separately analyzed for subjects showing an advantage in either visual field, an interesting difference became clear. The effect of conditions must be significant for both groups. However, for the LVF group, RL accuracy was significantly higher ($p < .05$) than max P (P_L), whereas for the RVF group, P_{RL} and max P (P_R) were statistically equivalent. Variation in P_{RL} was also significantly

Table 1
Means and Standard Deviations for P_R , P_L , and P_{RL}
(Experiment 1)

Subjects	P_R		P_L		P_{RL}	
	Mean	SD	Mean	SD	Mean	SD
All	.671	.081	.678	.077	.759	.085
RVF	.727	.053	.614	.053	.725	.107
LVF	.620	.070	.736	.046	.789	.041

greater between RVF subjects than between LVF subjects [$F(9,10)=6.81, p < .01$].

Given these results, a separate comparison of models is warranted for the two groups. Since Equation 4 predicts d' values and not the underlying probabilities, observed and expected values of d' under the five models were computed by treating P_R , P_L , and P_{RL} as the probabilities of a correct response for a 26-alternative forced-choice procedure (see, e.g., Elliott, 1964, for computational details). Observed and expected values of d'_{RL} are shown in Tables 2 and 3 for LVF and RVF subjects, respectively.

It is immediately obvious from Tables 2 and 3 that Equations 1 (statistical summation) and 4 (integration) predict performance in excess of observed values. Only two subjects (Subject 4 in the RVF group and Subject 9 in the LVF group) outperform expectations under Equation 4.

Table 2
Observed and Expected Values of d'_{RL} for Male Subjects
in the LVF Group (Experiment 1)

S	Ob- served	Expected				
		Models				
		1	2	3	4	5
1	2.75	2.42	2.58	2.52	3.56	2.80*
2	2.80	3.22	2.72	2.29	3.32	2.88*
3	2.65	3.17	2.43	2.32	3.29	2.63*
4	2.80	3.54	2.80	2.60	3.71	2.99*
5	2.75	3.46	2.65	2.55	3.61	2.93*
6	2.86	3.52	2.80	2.58	3.69	2.87*
7	3.12	3.44	2.72	2.52	3.59	2.82*
8	2.86	3.50	2.65	2.58	3.66	2.82*
9	3.17	3.49	3.03	2.44	3.04*	2.99
10	3.03	3.34	2.58	2.45	3.48	2.87*
11	2.80	3.33	2.52	2.45	3.48	2.66*
$\Sigma(O-E)^2$		3.03	.60	2.01	5.14	.25
Relative Fit		12.28	2.44	12.18	20.78	1.00

Note—S = Subjects. *Denotes the best fit for each subject.

Table 3
Observed and Expected Values of d'_{RL} for Male Subjects
in the RVF Group (Experiment 1)

S	Ob- served	Expected				
		Models				
		1	2	3	4	5
1	2.16	3.26	2.65	2.37*	3.39	2.72
2	2.75	3.56	2.80	2.77*	3.72	3.07
3	2.52	3.40	2.75	2.47*	3.53	2.80
4	3.39	3.17	2.58	2.29	3.28*	2.71
5	2.79	3.51	2.72*	2.58	3.67	2.93
6	2.65	3.39	2.72*	2.47	3.53	2.84
7	2.79	3.58	2.86*	2.62	3.73	2.99
8	2.58	3.42	2.58*	2.52	3.56	2.81
9	3.03	3.38	2.58	2.49	3.52	2.80*
10	2.02	3.00	2.22	2.19*	3.10	2.74
$\Sigma(O-E)^2$		6.17	1.21	1.69	3.29	1.68
Relative Fit		5.10	1.00	1.40	6.85	1.39

Note—S = Subjects. *Denotes best fit for each subject.

Table 4
Values of ϕ^* for Each Male Subject in the LVF and RVF Groups
(Experiment 1)

Subject	LVF	RVF
1	.6154	.5769
2	.3462	.4231
3	.5769	.6154
4	.5000	.5000
5	.5000	.5385
6	.6346	.5385
7	.6154	.5385
8	.6731	.5962
9	.5000	.5796
10	.5385	.2692
11	.7115	

*All values are significant beyond $p < .05$.

The sum of squared differences between observed and expected values, $\Sigma(O - E)^2$, provides a measure of the efficiency of each model. The relative fit, or relative efficiency, of each model is the ratio of $\Sigma(O - E)^2$ for the particular model to the minimum value of $\Sigma(O - E)^2$. The correlational model (Equation 5) provided the best fit for the LVF group and, in fact, for 10 of the 11 subjects in the group. RVF subjects were more variable. The redundancy model (Equation 2) provided the best overall fit, although it was the best fit for only 4 of the 10 subjects and, as I have noted, Equation 2 may not be readily distinguishable from Equation 5. Equation 5, the correlational model, and Equation 3, the complete dependence model, were indistinguishable in terms of $\Sigma(O - E)^2$. However, Equation 5 was the best fit only for Subject 9, and 4 subjects were best-fit by Equation 3.

Values of ϕ , the index of association between the right and left visual fields, are shown in Table 4 for individual subjects. These values were used to fit Equation 5.¹ The index was computed as the proportion of agreements between the subject's decisions for right- and left-visual-field letters. All values of ϕ were significant at at least the .05 level. Significant values of ϕ demonstrate that R and L decisions are in agreement more frequently than would be expected if the two sets of decisions were statistically independent (cf. Craig et al., 1976).

The difference in the direction of the visual-field advantage between the two groups can only be explained speculatively at this point on the basis of assumed processing strategies. If the right hemisphere is specialized for holistic processing, reliance upon a pattern-matching strategy may have produced the left-visual-field advantage in about half the subjects. Similarly, a right-field advantage may be subserved by underlying left-hemisphere specialization for analytical processing. Confusion matrices for the two groups tended to be similar but difficult to evaluate, since each 26×26 matrix contained a large number of zero entries. To facilitate comparison,

Table 5
Nonzero Values of η_{ij} for the RVF and LVF Groups
(Experiment 1)

Letter Pair	RVF	Letter Pair	LVF
M-W	.19	O-Q	1.15
H-U	.17	C-G	.21
O-Q	.17	C-O	.12
P-R	.17	B-D	.11
C-G	.13	A-J	.09
H-N	.11	V-Y	.09
V-X	.10	K-X	.08
H-K	.07	B-P	.07
H-M	.07	M-Q	.07
B-G	.07	M-N	.07
D-H	.06	E-F	.06
D-Y	.06	F-P	.04
H-T	.05		
C-P	.04		
D-G	.04		
F-P	.04		
N-U	.04		
J-U	.04		

Luce's index of confusability, η_{ij} (Luce, 1959, 1963), was computed for each letter pair. Luce's choice model from which the index is derived has been shown to provide a reasonable fit to a complete confusion matrix for uppercase letters (Townsend, 1971). The index is defined by

$$\eta_{ij} = \left(\frac{P_{ij} P_{ji}}{P_{ii} P_{jj}} \right)^{1/2},$$

where P_{ij} is the probability of responding with the j th letter given the i th stimulus letter, and so on. If either P_{ij} or P_{ji} is zero, then η_{ij} is necessarily zero. Nonzero values of the index can be thought of as an interval scale representation of the mutual confusability of the letter pairs. As η_{ij} increases, the letter pairs become more confusable. Nonzero values for either group are given in Table 5. Only four pairs (M-W, O-Q, C-G, and F-P) resulted in nonzero confusion values for both groups. The LVF group had particular difficulty with circular forms (O-Q, C-G, C-O), whereas the RVF group appeared more likely to confuse rectangular forms. The letter H is involved in one-third of pairs producing nonzero η_{ij} values in the RVF group, although it does not appear in any of the pairings in the LVF group.

These differences may have resulted from the use of a predominantly holistic strategy on the part of LVF subjects and of a predominantly analytic strategy on the part of RVF subjects. To confuse O and Q (the major confusion in LVF subjects) is, given the typeface, to fail to notice the presence of a feature, the oblique stroke on the Q, and may be evidence for holistic processing. M and W, on the other hand, can be broken down into approximately the same features, while the difference between H and N lies not in the presence or absence of a feature, but in a difference between features

(whether the stroke between the vertical bars is horizontal or oblique). The difference between H and U can be described roughly as a difference in the position of a feature. Is the horizontal bar placed centrally between the vertical bars or at the bottom? Of course it cannot be maintained that subjects use one strategy exclusively. For instance, O and Q are mutually confused by RVF subjects, although not to anything like the same extent as by LVF subjects.

EXPERIMENT 2

In this experiment, the results of Experiment 1 were generalized to a group of female subjects. It has been argued that cerebral lateralization is less extreme in women than in men (e.g., Jones, 1980b; Levy & Reid, 1978), particularly if the task is verbal in nature. In principle, therefore, a female subject group may allow examination of Equations 1 through 5 when the hemispheres display equipotentiality.

Method

The procedure followed that of Experiment 1 precisely, except that the subjects were 16 right-handed females, who had no history of familial sinistrality and who used the normal writing posture.

Results and Discussion

Mean values of P_R , P_L , and P_{RL} are given in Table 6. There was little difference between the means of the R and L conditions, and, in fact, analysis of variance showed no significant differences between the three conditions [$F(2,30) = 2.17$]. However, as in the male group in Experiment 1, and contrary to the hypothesis of equipotentiality in females, they showed a large mean absolute difference between the visual fields, with eight subjects falling in the RVF and LVF groups (Table 6). For both groups, RL performance was significantly more accurate ($p < .01$, Newman-Keuls) than performance in the poorer unilateral condition. All in all, the pattern of data in Tables 1 and 6 is very similar, although females tend to be more accurate.

Tables 7 and 8 give observed and expected values of d' under Equations 1 through 5 for the LVF and RVF females, respectively. The values of ϕ used to fit Equation 5 are given in Table 9. The correlational model is the best fit for the RVF group, although Equations 2 and 3 are also reasonably well supported. The correlational model provides a good fit for the

Table 6
Means and Standard Deviations for P_R , P_L , and P_{RL}
(Experiment 2)

Subjects	P_R		P_L		P_{RL}	
	Mean	SD	Mean	SD	Mean	SD
All	.747	.113	.756	.066	.806	.033
RVF	.817	.063	.720	.041	.805	.023
LVF	.677	.111	.792	.069	.807	.042

Table 7
Observed and Expected Values of d'_{RL} for Female Subjects
in the LVF Group (Experiment 2)

S	Ob- served	Expected				
		Models				
		1	2	3	4	5
1	2.94	3.94	3.11	2.90*	4.13	3.11
2	2.86	3.90	3.11	2.86*	4.09	3.10
3	2.94	3.37	2.52	2.49	3.52	2.75*
4	3.11	3.25*	2.52	2.38	3.38	2.72
5	2.86	3.67	2.79*	2.79	3.85	2.94
6	3.22	3.40	3.11*	2.38	3.59	2.69
7	2.94	3.80	3.03*	2.79	3.98	3.04
8	2.65	3.91	2.94*	2.90	4.10	3.10
$\Sigma(O-E)^2$		5.35	.73	1.55	7.47	.77
Relative Fit		7.33	1.00	2.12	10.23	1.05

Note—S = Subjects. *Denotes best fit for each subject.

Table 8
Observed and Expected Values of d'_{RL} for Female Subjects
in the RVF Group (Experiment 2)

S	Ob- served	Expected				
		Models				
		1	2	3	4	5
1	2.79	3.54	2.65*	2.61	3.70	2.94
2	2.94	3.65	2.86	2.68	3.81	2.90*
3	3.11	3.94	3.27	2.84	4.13	3.15*
4	2.86	4.32	3.53	3.15*	3.54	3.37
5	2.94	3.79	2.94*	2.79	3.96	3.06
6	2.86	3.58	2.72	2.65	3.75	2.90*
7	2.94	3.75	3.03*	2.75	3.90	3.03*
8	2.94	3.92	3.03*	2.90	4.12	3.05
$\Sigma(O-E)^2$		6.74	.54	.36	9.51	.32
Relative Fit		21.06	1.69	1.13	29.72	1.00

Note—S = Subjects. *Denotes the best fit for each subject.

Table 9
Values of ϕ^* for Each Female Subject in the LVF and
RVF Groups (Experiment 2)

Subject	LVF	RVF
1	.7305	.5577
2	.7115	.7115
3	.6346	.7115
4	.5577	.7885
5	.6923	.6346
6	.5385	.6538
7	.6923	.6346
8	.7115	.7885

*All values are significant beyond $p < .05$.

LVF group, although Equation 2 provides a slightly better one.

Values of r_{hj} for the female group are given in Table 10. Although more letter pairs were mutually confused by females than by males, the pattern of results is again comparable. The most troublesome pair for the RVF group remains M and W, and O and Q continue to produce the greatest confusion in the LVF group.

At this point it is worth compiling the data from Experiments 1 and 2 in a single table. Table 11 shows values of $\Sigma(O - E)^2$ for each of the five models summed across the 37 subjects. The correlational model provides the best fit, although that of Equation 2 is almost as good, as may be expected given appropriate values of ϕ .

EXPERIMENT 3

Although lateral asymmetries in letter recognition have not been entirely consistent (see White, 1972), the combination of findings of no mean difference between the visual fields and a large mean absolute difference between R and L conditions is certainly unusual. The breakdown of subjects into RVF and LVF groups was purely empirical, although there was some evidence of strategy differences between the two groups, as indicated by somewhat different patterns of mutual confusability of the letter pairs.

The factors that may normally explain variation in lateralization are of dubious relevance here. Factors such as sex, handedness (e.g., Jones, 1980b; Levy & Reid, 1978), and perhaps writing style (Levy & Reid, 1978; but see Weber & Bradshaw, 1981) that are probably responsible for the general variation in hemispheric specialization were controlled in the experiments. So, too, were the factors thought to be responsible specifically for variation in lateralization of letter identification. These include typeface (Bryden & Allard, 1976), the position of unilateral stimuli in the visual field (e.g., Heron, 1975), and whether stimuli are unilaterally or bilaterally presented (e.g., Bryden & Rainey, 1963; Heron, 1957; Hines, 1975; McKeever, 1971; White, 1972). Typeface was not a variable, and, moreover, the font was of a kind that has been shown to produce a consistent right-field advantage (Bryden & Allard, 1976). In some studies, a relatively small angular separation between the visual fields that results in presentation in parafoveal regions has tended to eliminate the mean right-field advantage (see White, 1969) without producing the bimodal distribution of visual-field advantages observed in the first two experiments. Finally, bilateral presentation of single letters has tended not to produce a right-visual-field advantage. Either no field difference has been observed (Heron, 1957), or a left-field advantage has actually resulted (Bryden & Rainey, 1963). What is at issue here, however, is a failure to find a consistent right-visual-field advantage when the unilateral R and L trials were compared.

Exploring the possibility that the trial-to-trial patterning of events in the first two experiments contributed to the bimodality in visual-field advantage is, therefore, worthwhile. There is some evidence that letters may be equally well identified in the right and left visual fields if R and L trials are presented

Table 10
Nonzero Values of η_{ij} for the RVF and LVF Groups
(Experiment 2)

Letter Pair	RVF	Letter Pair	LVF
M-W	.14	O-Q	.33
M-N	.13	M-W	.23
O-Q	.12	C-G	.22
C-G	.11	G-Q	.21
E-F	.10	M-N	.19
D-O	.10	B-D	.10
G-O	.09	C-O	.08
H-N	.09	B-O	.07
D-G	.08	G-O	.07
G-Q	.07	A-K	.06
N-W	.07	X-Y	.06
V-Y	.07	A-W	.04
P-R	.05	A-X	.04
V-W	.05	B-W	.04
A-K	.04	D-G	.04
D-P	.04	D-P	.04
F-R	.03	I-L	.04
X-Y	.03	U-V	.04
I-L	.03	B-K	.03
P-T	.03	E-F	.03
		E-L	.02
		L-Z	.02
		S-Z	.02
		U-W	.02

Table 11
Values of $\Sigma(O-E)^2$ for Each Model Summed Across the
37 Subjects in Experiments 1 and 2

	Models				
	1	2	3	4	5
$\Sigma(O-E)^2$	21.29	3.08	5.61	30.41	3.02
Relative Fit	7.05	1.02	1.86	10.07	1.00

in blocks rather than randomly intermingled (e.g., Jones, 1980a). This result suggests that the general context in which subjects make R and L judgments influences lateral advantages (cf. Kinsbourne, 1970). Some findings by Taylor (1976) suggest a hypothesis. Using a "same"- "different" paradigm, he found evidence for analytical component-by-component processing when pairs of letters were different and for holistic processing when the letters were the same. Conceivably, bilateral presentation of "same" pairs on one-third of the trials may induce a more holistic approach in some subjects, although, in others, this tendency would not be sufficient to counteract the visual reliance upon left-hemisphere specialization in letter identification. This hypothesis is obviously congruent with Kinsbourne's (1970) attentional model of lateralization. He has argued that lateral advantage may not be found if a mix of verbal and nonverbal stimuli is used over trials, since no differential activation of the hemispheres is produced (see, also, Cohen, 1975).

Method

In Experiment 3, the procedure of the first two experiments was repeated, but with the variation that, on RL trials, the pairs

of letters were different. If "different" pairs tend to be processed analytically, the sequence of events should reinforce normal left-hemisphere specialization and result in a consistent right-visual-field advantage.

Accordingly, the procedure of Experiment 1 was repeated with seven right-handed male undergraduates as subjects, with the difference that, on the 52 RL trials, the bilateral stimuli were pairs of different letters. Each letter of the alphabet appeared once in each visual field paired with a randomly chosen letter in the contralateral field. On RL trials, subjects were required to report a letter from both visual fields.

Results and Discussion

Mean values of P_R and P_L for the unilateral and bilateral conditions are shown in Table 12. The results were clear-cut. All subjects showed a right-visual-field advantage in both conditions, and all subjects showed a decrement in the bilateral condition. Analysis of variance showed significant main effects of visual field [$F(1,6) = 5.72$, $p < .05$], unilateral vs. bilateral presentation [$F(1,6) = 25.37$, $p < .002$], and the absence of a two-way interaction [$F(1,6) > 1$].

On the face of it, the right-visual-field advantage for identification of letters in the bilateral condition appears contrary to the results obtained by Bryden and Rainey (1963) and Heron (1957). The variable that appears to distinguish this experiment from the other two is the angular separation of the visual fields. Bryden and Rainey obtained a left-visual-field advantage with the stimuli centered at 2 deg 52 min, and Heron obtained no significant differences between the fields with an angular separation of 4 deg. Since the result here is a right-field advantage with presentation at 7.5 deg right or left of the midline, the three experiments, taken together, support the proposition that lateralization shifts from left to right as the distance between the visual fields is increased. A left-to-right scanning pattern based upon reading habits may be a more important determinant of lateralization, given bilateral presentation, when the visual fields are separated by a small angular distance (cf. Heron, 1957; Jones & Santi, 1978).

The demonstration that bilateral performance is less efficient is also of interest. Duncan (1980) has recently reviewed a number of experiments using different procedures and different dependent measures in which subjects have been required to identify simultaneously presented stimuli. He concludes that some effect of "divided attention" (i.e., a performance decrement) is almost invariably found. The decrement across both visual fields in the bilateral

Table 12
Means and Standard Deviations for P_R and P_L under Unilateral
and Bilateral Conditions (Experiment 3)

	Unilateral		Bilateral	
	P_R	P_L	P_R	P_L
Mean	.723	.643	.684	.610
SD	.059	.048	.063	.041

condition suggests in Duncan's (1980) terms that both stimuli pass through an early limited-capacity system in parallel. In principle, it would have been possible for subjects to have maintained bilateral right-visual-field accuracy at the unilateral level by attending only to right-visual-field events.

EXPERIMENT 4

The first three experiments have emphasized the role of processing strategies in structuring the pattern of lateral advantages. The randomization of unilateral and bilateral "same" trials may reverse the usual right-field advantage in about half the subjects. All subjects showed a right-field advantage when unilateral trials were intermingled with bilaterally presented "different" pairs. Given such effects when unilateral and bilateral trials are randomized over trials, it seems desirable to determine the fit of the five equations using a different procedure.

Method

In this experiment, bilateral and unilateral trials were blocked such that 26 bilateral trials were followed by 104 unilateral R and L trials, followed finally by 26 bilateral trials. Otherwise, the procedure of Experiment 1 was followed with 12 right-handed male subjects.

Results and Discussion

Probabilities for the R, L, and RL conditions are shown in Table 13. The methodology resulted in a consistent right-field advantage for the unilateral trials. Analysis of variance demonstrated a significant difference between the three conditions [$F(2,22) = 41.80$]. R and L conditions were significantly different, as were L and RL conditions ($p < .01$, Newman-Keuls).

Values of ϕ are shown in Table 14, and the observed and expected values of d'_{RL} for the five models are shown in Table 15. The data conform closely to those obtained for the RVF group in Experiment 1. The correlational model was the best fit, and the redundancy model was, as expected, given the ϕ values, also reasonably efficient.

GENERAL DISCUSSION

The results of Experiments 1, 2, and 4 are closely analogous to those obtained in auditory-visual recognition and detection experiments (e.g., Craig et al., 1976; Dougherty et al., 1971; Eijkman & Vendrik, 1965; Loveless et al., 1970). When both hemispheres

Table 13
Mean Values of P_R , P_L , and P_{RL} for Experiment 4

	P_R	P_L	P_{RL}
Mean	.782	.673	.791
SD	.068	.066	.060

Table 14
Values of ϕ^* for Each Subject in Experiment 4

Subject	ϕ
1	.7308
2	.6731
3	.7308
4	.6346
5	.5192
6	.6923
7	.7500
8	.6538
9	.7885
10	.7115
11	.8077
12	.8269

*All values are significant beyond $p < .05$.

Table 15
Observed and Expected Values of d'_{RL} in Experiment 4

S	Observed	Expected				
		Models				
		1	2	3	4	5
1	3.03	3.59	2.79	2.65	3.76	2.85*
2	2.72	3.50	2.65*	2.58	3.66	2.61
3	2.94	3.86	2.94*	2.72	4.05	3.06
4	3.03	3.56	2.86	2.62	3.71	2.90*
5	2.94	3.54	2.65	2.62	3.70	2.97*
6	2.58	3.43	2.79	2.49*	3.57	2.76
7	2.72	3.43	2.65	2.52	3.58	2.70*
8	2.65	3.42	2.72*	2.50	3.57	2.78
9	2.58	3.33	2.58*	2.44	3.46	2.60
10	2.86	3.36	2.72*	2.44	3.49	2.69
11	3.22	4.11	3.39	2.96	4.30	3.19*
12	3.39	4.45	3.69	3.19	4.58	3.44*
$\Sigma(O-E)^2$		7.37	.37	.86	10.01	.16
Relative Fit		46.29	2.31	5.39	62.91	1.00

Note—S = Subjects. *Denotes best fit for each subject.

were simultaneously stimulated, performance tended to be better than or equal to performance when the more specialized hemisphere was stimulated. The two models predicting the most efficient performance (statistical summation and vector summation of d'_R and d'_L) could be clearly rejected. These models also tend to overpredict performance in bisensory experiments, a fact that suggests that the complete independence of two equivalent sources of information may be generally implausible.

In general, a probability model that incorporates a covariance component, Equation 5, predicted RL performance most efficiently whether unilateral and bilateral trials were randomly intermingled or presented in distinct blocks. For all subjects in Experiments 1, 2, and 3, there was significant agreement between the R and L decisions indexed by the ϕ coefficient. Significant values of ϕ are necessary to support the proposition that the hemispheres are not independent, although, of course, it may be argued that the presence of a correlation is not sufficient.

Both hemispheres could be subject to the same transience in the level of internal noise, which would result in correlated output (cf. Craig et al., 1976; Eijkman & Vendrik, 1965). Any bilateral representation of function would also result in correlated decisions with respect to the two sets of visual-field observations, although the two hemispheres could function independently. Yet the failure of the complete independence assumption (Equation 1) is striking, and is explained, at least in part, by the assumption of a correlation between the right and left hemispheres (cf. Craig et al., 1976).

The two hemispheres may in principle function independently at levels of processing earlier than the production of the final judgment (cf. Dimond, 1972). Bilateral representation of function would then allow provision, to a central decision maker, of information that would be to some extent redundant. However, the implication of Equation 4 (vector summation of d'_R and d'_L) is that the system makes initially independent decisions about R and L events before combining information in a joint space. The almost complete failure of this model is, therefore, at least suggestive of an alternative hypothesis. The two hemispheres may constitute an integrated system at all levels of processing. Identification of information presented to one visual field would then depend upon the continuous activity of both hemispheres.²

In relative terms, the redundancy model also proved a reasonably efficient predictor of d'_{RL} or P_{RL} . I have already noted that Equations 2 and 5 may be difficult to distinguish. Although Equation 2 provided the best fit for an individual, the predictions of Equations 2 and 5 tended to be fairly close and the correlations between R and L responses were fairly substantial. The relative efficiency of Equation 2 need not, therefore, imply independent functioning of the hemispheres.

Another possible interpretation of Equation 2 is to regard it as the formally limiting case of a weighted averaging model in which no weight is given to the smaller of P_R or P_L . A model of the form

$$P_{RL} = w_R P_R + w_L P_L, \quad (6)$$

where w_R and w_L are weight parameters such that $w_R + w_L = 1$, will provide a fit for $P_{RL} \leq \max P$, since there are no constraints in the data on the value of the weights. In principle, we can regard Equation 3 as a special case of weighted averaging, where $w_R = w_L$. Equation 6, although trivial in the present context, is not implausible, since it may be taken to imply an averaging process in which greater weight is given to the more specialized hemisphere. In a study of integration of haptic extent between the hands, I obtained evidence for greater weighting of the left hand. This is consistent with the proposition that the right hemisphere is specialized for the spatial

extension task and is therefore accorded greater weight in the integrated judgment (Jones, Note 1).

Averaging models are consistent with feature-matching processes. Information from multiple "observations" in the two visual fields is assembled piecemeal, and the final decision represents an average across observations. There was some evidence in Experiments 1 and 2 for predominantly analytical processing on the part of some subjects and for holistic processing on the part of others. At least in Experiment 1, the complete dependence model (arithmetic mean of the unilateral probabilities) provided a reasonably good fit for subjects who showed a right-visual-field advantage and who may have relied upon a more analytical strategy. More detailed discussions of strategy differences between subjects would be premature. The all-or-none response, while appropriate for determining the efficiency of the five models, can provide only crude information about the degree to which a particular feature is taken into account. Ratings of the degree to which one letter resembles another (see Oden, 1979) may provide richer information about the details of strategy differences in relation to the left- and right-hemispheric specialization.

At a more global level, comparison of Experiments 1 and 2 on the one hand and Experiment 3 on the other hand does show something of the way in which lateral differences in letter identification can be shifted according to the context in which R and L trials are embedded. The direction of the advantage may reflect underlying cerebral specialization for a particular mode of information processing. The context, in this case of "same" or "different" letter pairs (cf. Taylor, 1976), either may be consistent with left-hemisphere analytical processing ("different" pairs) or may encourage a reliance upon more holistic strategies for which the right hemisphere is likely to be the more specialized.

Finally, the importance of quantitative models for the study of hemispheric processes should be underlined. Although it may sometimes be difficult to distinguish between quantitative equations (Equations 2 and 3, for example, are formally related, and Equations 2 and 5 may make identical predictions), writing such equations allows clearer tests of theory. Theories of hemispheric function have often been based upon more qualitative analogies. Dimond (1972) argues for a "division of labor" between the hemispheres in an integrated system. Such a division is said to lead to "facilitation." Either performance tends to be more efficient when the two hemispheres are stimulated, or the two hemispheres together have a greater capacity than the two hemispheres singly. Consideration of Equation 1 (statistical summation) is sufficient to show that more efficient performance when the two hemispheres are stimulated need not imply that the hemispheres produce an integrated decision. Similarly,

it is not enough to show only that functions tend to be bilaterally represented in the two hemispheres to prove that the "two-brain system," in Dimond's (1972) phrase, is interlocked. Bilateral representation need not be inconsistent with independent processing, and some form of partial bilateral representation may be consistent with ignoring information from the less specialized hemisphere.

There are evidently some differences in the representation of function between the hemispheres. However, lateralization is quite implausibly all or none, and asymmetrical representation of function need not imply that the hemispheres function independently. The present results indicate in a preliminary, descriptive way how the hemispheres may be integrated, and future work will concentrate on explanatory mechanisms.

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NOTES

1. Craig et al. (1976) fit bisensory data with $\phi = .5$. To fit the present data in this way involves no material change. For Equation 5, $\Sigma(O - E)^2$ would equal .35 for the LVF group and 1.70 for the RVF group.

2. This is not to suggest that the hemispheres cannot operate independently in other circumstances. Independence of the two

hemispheres may be essential for efficient performance of bi-manual skills (Dimond, 1972), although here the process of skill acquisition may be one in which an initially integrated system is "uncoupled."

(Manuscript received March 10, 1982;
accepted for publication May 24, 1982.)