Bisensory Stimulation: Inferring Decision-Related Processes from the P300 Component

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Three experiments were conducted to evaluate the P300 component of the human evoked response as an index of bisensory information processing. On different blocks of trials, subjects were presented with auditory stimuli alone, visual stimuli alone, or with audiovisual compounds. In each series there were two possible stimuli, one of which was presented less frequently than the other; the subjects' task was to count the infrequent stimuli. In the first two experiments the information in the two modalities was redundant, whereas in the third the modalities provided nonredundant information. With redundant information, the P300 latency indicated bisensory facilitation when the unimodal P300 latencies were similar; when the unimodal latencies were dissimilar, the bisensory P300 occurred at the latency of the earlier unimodal P300. Reaction times paralleled P300 latency. When the information in the two modalities was nonredundant, both P300 amplitude and reaction-time data indicated interference between the two modalities, regardless of which modality was task relevant. P300 latency and reaction time did not covary in this situation. These data suggest that P300 latency and amplitude do reflect bisensory interactions and that the P300 promises to be a valuable tool for assessing brain processes during complex decision making.

The P300 component of the event-related brain potential (ERP) that can be recorded from the human scalp seems to be a sensitive measure of information processing (see Price & Smith, 1974, for a bibliography). Since the P300 is a multifaceted measure whose amplitude, latency, and distribution over the scalp may be independently determined by different aspects of the

cognitive process, it might well prove to be a richer measure than such traditional indices of processing as reaction time (RT). For example, P300 latency may index the time of occurrence of a cognitive process (Kutas & Donchin, in press), its scalp distribution may index the nature of the task (Courchesne, Hillyard, & Galambos, 1975), and P300 amplitude may index expectancy for the eliciting event (Donchin, Kubovy, Kutas, Johnson, & Herning, 1973; Squires, Wickens, Squires, & Donchin, 1976). Of particular utility is the fact that the ERP can be used to assay ongoing cognitive processes without requiring an overt response by the subject. For example, Squires et al. (1976) demonstrated that P300 amplitude reflects rapid changes in a subject's "expectancies" that parallel the effects of sequential dependencies between reaction times (Falmagne, Cohen, & Dwivedi, 1975; Remington, 1969). The P300, however, revealed these expectancy fluctua-

tions during a task that required no overt responses.

Despite the potential utility of P300 and other ERP measures, few attempts have been made to utilize the growing body of knowledge about cognition in identifying the functional determinants of the various ERP components or to utilize P300 in clarifying issues of human information processing. The procedures and terminology of the two research areas have remained largely distinct. There is a clear need for experiments that use paradigms from the information-processing literature to evaluate the utility of the ERP as a measure of complex processes. Such experiments are also likely to help clarify the functional significance of P300.

Two issues are specifically addressed in the experiments reported here. The first concerns the ERP manifestations of the way in which subjects deal with multiple sources of information. Our work most clearly follows that of Garner and his co-workers (see Garner, 1974, for a review), who have shown, using multidimensional stimuli, that the nature of the dimensions or information channels, as well as their redundancy, determines the manner in which the subjects process the information. The second and third experiments are particularly relevant to this issue.

The second related area of interest is the relationship of P300 and the RT measure. Previous research suggests that P300 latency and RT sometimes covary, with longer RTs being associated with longer P300 latencies (e.g., Picton, Hillyard, & Galambos, 1974; Ritter, Simson, & Vaughan, 1972; Rohrbaugh, Donchin, & Eriksen, 1974). Other investigators report stable P300 latencies despite varying RTs (e.g., Karlin & Martz, 1973; Squires et al., 1976). Since RT appears to be multiply determined (Felfoldy, 1974), it may be the case that only some of the variables affecting RT also influence the P300 (e.g., Wilkinson & Spence, 1973). Experiment 3 is concerned with this problem.

As these studies required the simultaneous presentation of auditory and visual stimuli, the initial step was to determine the feasibility of analyzing the contribution of each element to the bisensory ERP. Previous studies have generally used simple nonsimultaneous sensory events, assuming that the simultaneous occurrences of more than one event would make interpretation of the ERP difficult, leading to serious restrictions on the procedures that can be examined via ERP techniques. The first experiment, then, investigated the dissociability of the effects of two simultaneously presented stimuli. To facilitate interpretation, only redundant information was used in this initial experiment.

Experiment 1

Method

Subjects. Six normal adults (ages 18–32, three females and three males), including the first and third authors, served as subjects. The volunteer subjects were paid for their participation. (The first and third authors appear as Subjects 1 and 2 in all figures and tables.)

Stimuli. The auditory stimuli were 80-db SPL tone bursts delivered binaurally through TDH-39 earphones against a continuous background of white noise at 55-db SPL at a rate of one every 1.3 sec. Two tone frequencies were used: 1,000 Hz and 1,500 Hz. Each tone burst was 60 msec in duration including 10-msec rise–fall times. The visual stimuli were presented via two fields of an Iconix Model 6137 four-field tachistoscope, and they were 50 msec in duration. A left-pointing and right-pointing arrow were outlined in black (visual angle of 1°) on a blank white field (visual angle of 6°). The luminance of these fields was 20 ftL. (68.52 cd/m²), measured with a Spectra brightness spot meter.

Recording system. The electroencephalogram was recorded from five electrode sites (Oz, Pz, Cz, Fz, and FPz according to the 10–20 system) referred to linked mastoids. The ground electrode was on the back of the right hand. Burden Neurological Institute silver-silver chloride electrodes affixed with collodion were used for scalp recording. Beckman Biopotential electrodes were used for the reference and ground electrodes. In addition, right supraorbital and canthal electrodes were used to record the electrooculogram. Subjects were instructed not to move their eyes excessively, and the averaged electrooculogram indicated that eye movement artifacts were indeed negligible.

The electroencephalogram was amplified with Grass 7P122 amplifiers (time constant was .8 sec, and upper-half amplitude frequency was 35 Hz) and was sampled for 768 msec beginning 100 msec prior to stimulus onset at a rate of one sample every 3 msec.

Data collection. Stimulus presentation and data collection were under the control of a Digital Equipment Corporation PDP 11/40 computer (see Donchin & Heffley, 1975). The data acquisition was monitored on line, and the averaged ERPs for each stimulus type for each block of trials were stored on digital magnetic tape for later analysis.

Procedure. Bernoulli trials were presented in blocks of 150. In each block, one of the two possible outcomes had a .10 probability of occurrence (the "rare" stimulus), and the other had a .90 probability of occurrence (the "frequent" stimulus). The subject, seated in a reclining chair, was asked to count the number of rare stimuli in each block, to be reported at the end of the block. In all experiments counting performance was virtually perfect.

There were seven different experimental conditions in which the stimuli were either unimodal or bimodal: (a) auditory stimuli with a frequent 1,000-Hz tone and a rare 1,500-Hz tone; (b) auditory stimuli with the probabilities of the two stimuli reversed; (c) visual stimuli with a frequent left-pointing arrow and a rare right-pointing arrow; (d) visual stimuli with the probabilities of the two stimuli reversed (Conditions 2 and 4 served only to confirm that the P300 was related to stimulus probability and will not be discussed further); (e) bimodal stimuli with the frequent stimulus being the simultaneous presentation of the 1,000-Hz tone and the left arrow and the rare stimulus being the compound of the 1,500-Hz tone and the left arrow ("variable auditory – constant visual"); (f) bimodal stimuli, with the frequent stimulus being the 1,000-Hz tone and left arrow and the rare stimulus being the 1,000-Hz tone and right arrow ("constant auditory – variable visual"); and (g) bimodal stimuli, with the frequent stimulus the 1,000-Hz tone and the left arrow and the rare stimulus the 1,500-Hz tone and the right arrow ("variable auditory – variable visual"). Thus in this last condition, the information supplied by the two modalities was redundant.

The subject was informed prior to each block of trials which stimuli would be presented. Each type of series was presented twice to each subject in the course of a 2-hour session so that each rare-stimulus ERP was the average of approximately 30 trials. The order of presentation was counterbalanced across subjects.

Results

P300s to unimodal stimuli. As in previous studies (e.g., Ritter & Vaughan, 1969; Ruchkin & Sutton, 1973; Squires, Squires, & Hillyard, 1975; Tueting, Sutton, & Zubin, 1971), the rare stimuli elicited large P300 components. This is shown in Figure 1 where the ERPs associated with the rare and frequent auditory stimuli are superimposed in the left column and the ERPs to the rare and frequent visual stimuli are
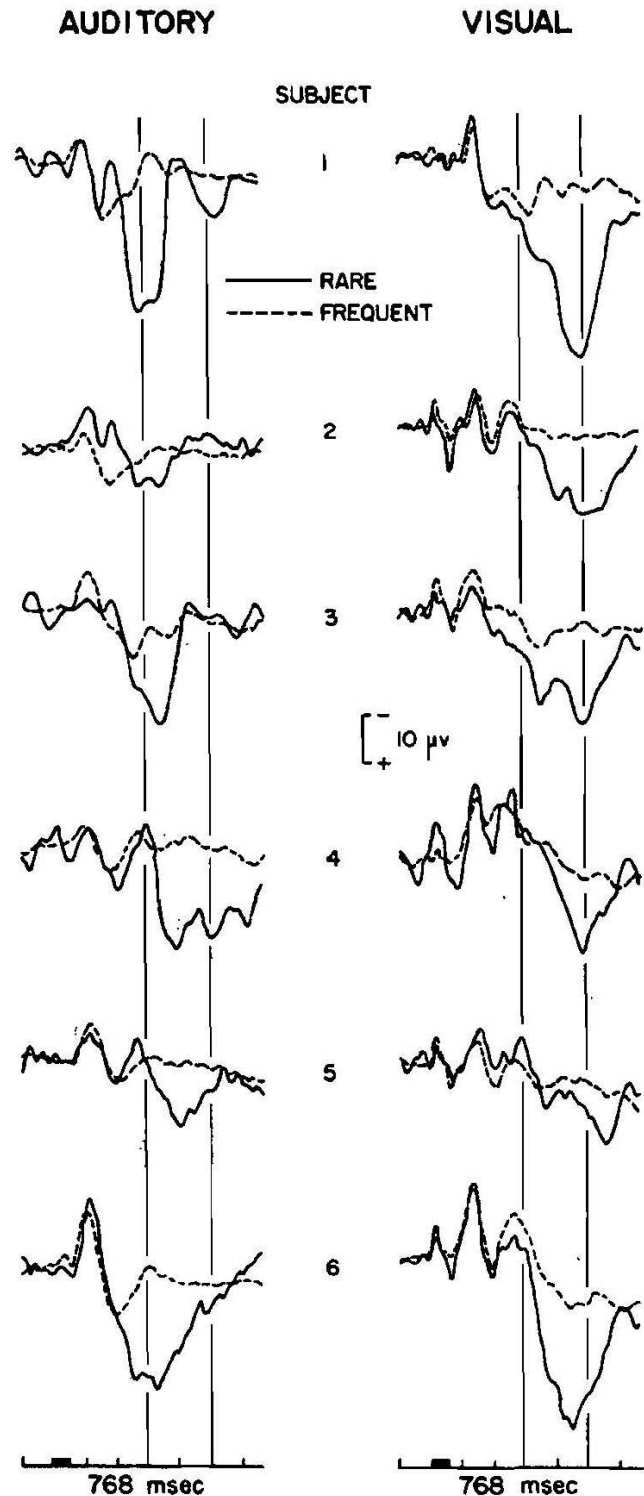
Figure 1. Experiment 1: Vertex evoked responses to the unimodal stimuli for each of the six subjects. (The responses to the rare stimuli [solid lines] are superimposed on the responses to the frequent stimuli [dotted lines] from the same condition.)

superimposed in the right column. For each subject the latency of the "visual P300" was much longer than that of the "auditory P300," $t(5) = 10.91$, $p < .001$. The mean peak latency of the auditory P300 was 360 msec, and the mean peak latency of the visual P300 was 500 msec. The two com-

Table 1
Mean Scalp-Amplitude Distributions of the P300 Component Associated with Rare Unimodal and Bimodal Events in Microvolts

Stimulus	Electrode site				
	Oz	Pz	Cz	Fz	FPz
Auditory rare	12	23	21	17	5
Visual rare	17	34	31	14	2
Auditory rare – visual frequent	17	27	22	14	1
Visual rare – auditory frequent	16	31	25	14	3
Auditory rare – visual rare	18	32	26	18	4

ponents, however, exhibited similar scalp-amplitude distributions. Table 1 shows the mean P300 amplitudes at each electrode site for the auditory and visual ERPs. The peak of the P300 component was chosen as the largest positive deflection within a latency range chosen by visual inspection of each ERP waveform, and its amplitude was measured relative to the 100-msec prestimulus baseline. The auditory P300 was of somewhat smaller amplitude than the visual P300, but for both modalities the largest P300 amplitudes were recorded at the parietal electrode, decreasing rapidly posteriorly and more slowly frontally. The variation in amplitude across electrode sites was statistically significant, $F(4, 20) = 12.19$, $p < .01$, whereas the effect of modality was not significant, $F(1, 5) = 3.28$, due to the U-shaped nature of the scalp distribution; the interaction of electrode site and modality was significant, $F(4, 20) = 6.25$, $p < .01$.

P300s to bimodal stimuli. When an unchanging stimulus in a second modality was presented simultaneously with the Bernoulli sequence in the first modality (Conditions 5 and 6), the rare stimulus evoked a P300 component that closely resembled the P300 elicited by that stimulus presented alone. The left column of Figure 2 presents the superimposed tracings of ERPs elicited by the rare auditory stimulus when presented alone (solid line) and when accompained by the frequent (unchanging) visual stimulus (dashed line). The analogous data

for the visual ERPs are shown on the right. There were no statistically significant differences in amplitude or latency of P300 due to the addition of an unchanging irrelevant stimulus in the other modality. The scalp distributions of P300 amplitude also remained unchanged (see Table 1), maintaining a parietal maximum.
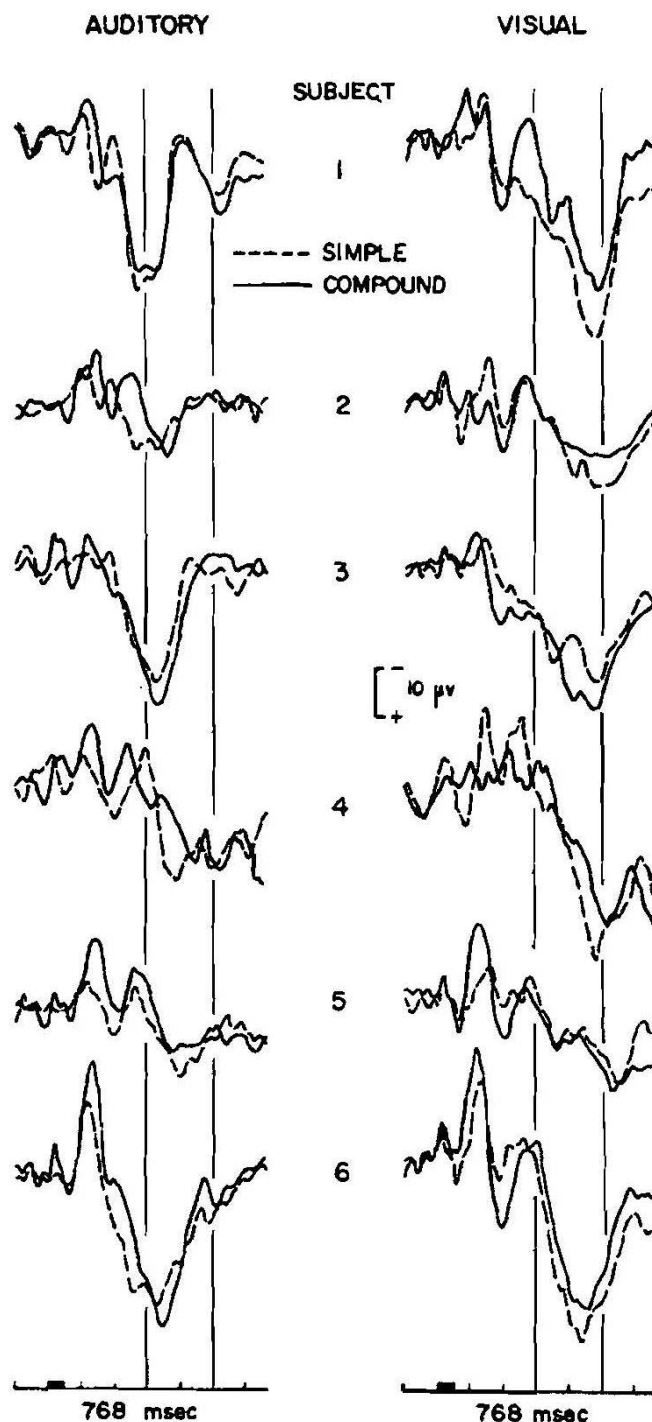
When rare stimuli occurred simultane-

Figure 2. Each subject's vertex evoked responses to the unimodal auditory and visual rare stimuli (solid lines) superimposed on the response evoked by that same stimulus when accompanied by a frequent stimulus in the other modality.

ously in the two modalities (Condition 7), the P300 mirrored the P300 elicited by the auditory element alone (Condition 5). This is demonstrated in Figure 3 where the ERPs to the rare-auditory–frequent-visual combinations are compared with the rare-auditory–rare-visual combinations. There were no statistically significant differences in amplitude or latency of the P300s thus compared. The similarity of these waveforms suggests that the rare visual stimulus was not contributing to the P300 in Condition 7.

Discussion

Apparently the contributions of the two modalities to the bisensory P300 can be readily determined. The auditory and visual P300s differed in latency by 140 msec, and when the two series were redundantly combined, the resulting P300 occurred at the latency of the auditory P300 and showed no effect (on latency or waveshape) of the visual stimulus. Choice RTs in analogous situations behave in much the same way; when the choice RTs to stimuli in each modality are widely disparate, the RT to the redundant bimodal stimulus equals that of the shorter unimodal RT (e.g., Hershenson, 1962; and see Loveless, Brebner, & Hamilton, 1970, for a review of bisensory stimulation).

The predominance of the auditory P300 might be attributed to a natural auditory predominance deriving from some inherent difference in the processing of auditory and visual stimuli. This interpretation is unlikely, however, in view of the data of Colavita (1974) showing a pronounced visual predominance in a RT task with somewhat different auditory and visual stimuli than were used here. Alternatively, the discrimination between the 1,000-Hz tone and the 1,500-Hz tone might have been easier than the discrimination between the right-pointing and left-pointing arrows, and the P300 associated with the easier task might predominate. The next experiment addressed this issue.
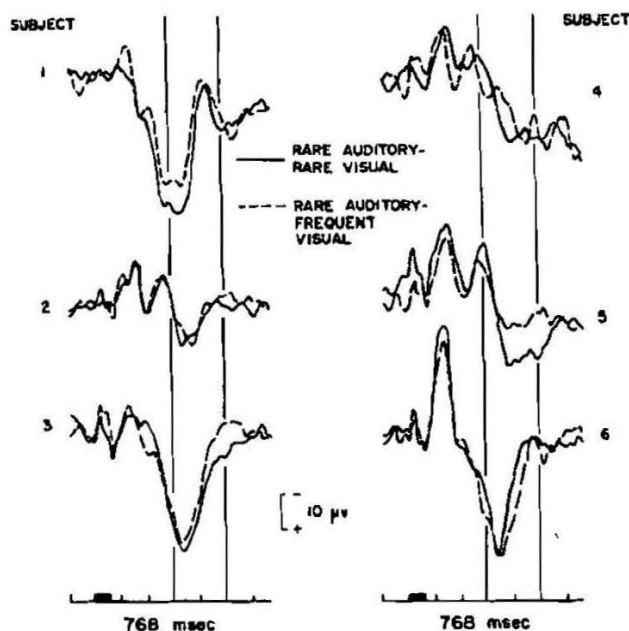

Figure 3. Vertex evoked responses to the rare auditory – rare visual compound (solid line) superimposed on the response to the rare auditory – frequent visual stimulus (dotted line) for each of the six subjects.

Experiment 2

A reasonable interpretation of the data in Experiment 1 is that P300 latency reflects the latency of the decision about the stimulus. It has been previously demonstrated in choice RT experiments (e.g., Biederman & Checkosky, 1970; Felfoldy, 1974; Thurmond & Alluisi, 1963) that decision latency varies with stimulus discriminability. Furthermore, the degree of facilitation of the bisensory RT depends upon the similarity of the RTs to the two component stimuli. In situations like the one in Experiment 1 in which the individual RTs are quite different, no bisensory interaction is found, but with similar component RTs, the RT to the compound is shorter than either of the unimodal RTs (e.g., Biederman & Checkosky, 1970; Wood, 1974). Experiment 2 therefore varied intramodality discriminability to determine whether the auditory predominance of Experiment 1 was reversible and whether bisensory facilitation is reflected in P300.

Method

Subjects. Six subjects (five females and one male) participated in the ERP section of this experiment,

Table 2

Reaction Times of Seven Subjects to Rare and Frequent Stimuli in all Eight Conditions of Experiment 2

Stimulus	Frequent		Rare	
	M	SD	M	SD
Easy auditory	279	43	387	68
Difficult auditory	374	66	532	101
Easy visual	276	28	392	56
Difficult visual	340	82	446	68
Easy auditory – easy visual	251	41	366	53
Easy auditory – difficult visual	260	32	384	67
Difficult auditory – easy visual	261	32	391	56
Difficult auditory – difficult visual	294	34	424	66

including three subjects from the previous experiment. (Subjects 1, 2, and 6 of that experiment are Subjects 1, 2, and 4 here.) Seven subjects (including Subjects 1 and 2) participated in the RT segment.

Stimuli. Two sets of auditory stimuli were used: 1,100–Hz versus 1,000-Hz tones (the easy auditory discrimination) and 1,100-Hz versus 1,060-Hz tones (the difficult auditory discrimination), with the 1,100-Hz tone as the rare ($p = .10$) stimulus in both cases. Similarly, there were two sets of visual stimuli, orange versus blue (the easy visual discrimination) and orange versus yellow (the difficult visual discrimination), with orange as the rare stimulus in both cases. The color stimuli were produced by filtering the tachistoscope flashes with opaque-projector filters of various hues.

The stimulus durations and repetition rates in the ERP experiment were the same as in Experiment 1. In the RT experiment each stimulus presentation followed the previous response after a random interval of 500–1,000 msec.

Procedure. There were eight conditions in this experiment. Four involved unimodal stimuli, and four involved bimodal stimuli. The four unimodal stimulus conditions were the easy auditory, difficult auditory, easy visual, and difficult visual discriminations. In the bimodal stimulus conditions, each auditory discrimination was paired with each visual discrimination, with the rare events in each modality occurring simultaneously as in the previous experiment.

During ERP recording, trials were presented in blocks of 150, with the instruction to count the rare stimuli. Each of the eight conditions was presented three times during the course of two 2-hour testing sessions, with the order of presentation balanced.

During the RT sessions, one of two buttons was pressed depending upon the stimulus presented. Stimuli appeared in blocks of 100. The RTs reported here are the means of two blocks of trials, one in

which the subjects responded with the left hand to rare stimuli and the right hand to frequent stimuli and one in which the association of hand and stimuli was reversed. Even though it would have been obviously advantageous to record the RTs at the same time that the ERPs were recorded (Donchin & Sutton, 1970), the likelihood that motor potentials (Kornhuber & Deecke, 1965) would contaminate the P300 argued for separate acquisition of these data. Also, the RT data were collected primarily to validate any bisensory interactions obtained here by comparing them with previous reports and not to make direct P300–RT comparisons.

Results

RT data. Mean RTs to the rare and frequent stimuli are shown in Table 2. The easy discriminations in the two modalities yielded virtually identical RTs. The RTs for the difficult discriminations were considerably longer. These data replicate previous findings on discriminability and RT (e.g., Thurmond & Alluisi, 1963). The bimodal stimuli whose elements gave widely different RTs (easy auditory – difficult visual and difficult auditory – easy visual) yielded RTs that were significantly less than the longer of the two unimodal RTs ($p < .05$ for each comparison) and approximately equaled the earlier of the two unimodal RTs. This was true for both the rare and frequent stimuli in each case. When the RTs to both elements of the compound were more similar (easy auditory – easy visual and difficult auditory – difficult visual), the mean RTs to the bimodal stimuli were shorter than either of the unimodal RTs. This result was statistically significant for the bimodal difficult condition, $F(2, 12)$

Table 3

Latencies of Six Subjects of the P300s to the Rare Stimulus in Each of the Eight Conditions of Experiment 2

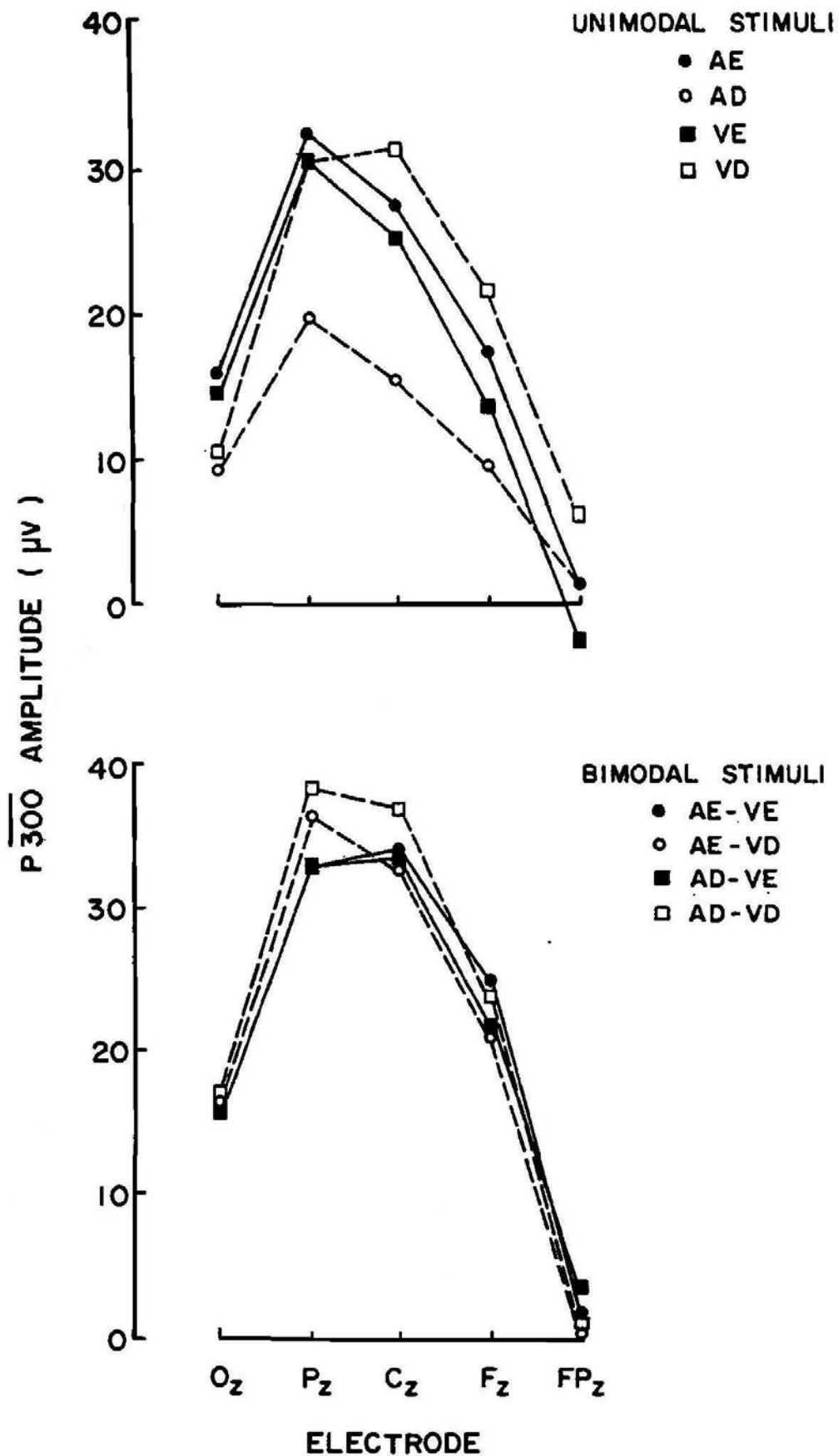| Stimulus	M	SD
Easy auditory	359	41
Difficult auditory	419	52
Easy visual	371	18
Difficult visual	420	16
Easy auditory – easy visual	349	35
Easy auditory – difficult visual	362	34
Difficult auditory – easy visual	370	16
Difficult auditory – difficult visual	403	34

Figure 4. Experiment 2: Mean baseline-to-peak amplitude of P300 at each of the five electrode sites, for each of the eight experimental conditions. (AE = auditory easy, AD = auditory difficult, VE = visual easy, and VD = visual difficult.)

Table 4
Amplitude (in microvolts) for Six Subjects of the Slow Wave Evoked by the Rare Stimulus in Each of the Eight Conditions of Experiment 2 for the Five Electrode Locations

Condition	Oz	Pz	Cz	Fz	FPz
Auditory easy	9	12	1	−14	−17
Auditory difficult	4	9	1	−8	−12
Visual easy	7	10	1	−12	−17
Visual difficult	3	13	5	−8	−12
Auditory easy – visual easy	4	6	−2	−14	−18
Auditory easy – visual difficult	6	9	−2	−14	−17
Auditory difficult – visual easy	3	7	−1	−16	−20
Auditory Difficult – visual difficult	9	14	5	−13	−14

$= 10.91$, $p < .01$, but not for the bimodal easy condition, $F(2, 12) = 3.58$, $p < .10$.

P300 latency. The latency data for the P300 at the vertex electrode are given in Table 3. (The vertex electrode was used for reasons that are discussed below.) In general, the relationships among the P300 latencies in the various conditions parallel the relationships between the RTs described above, with shorter P300 latencies corresponding to faster RTs. The main exception to this is the difficult auditory condition where the RTs were long compared to the difficult visual condition, whereas the P300 latencies in the difficult auditory and difficult visual conditions were almost equal. Since the data were collected with different groups of subjects, no clear interpretation can be made of this discrepancy.

P300 amplitude and scalp distribution. The scalp distributions of the P300s are shown in Figure 4. All of the P300 distributions are similar, with maximum amplitude at Pz. The bimodal P300s tended to be somewhat larger than the unimodal P300s.

Slow-wave amplitude and scalp distribution. The "slow wave" is another component that has been identified in the ERP to unexpected target stimuli (Squires, Donchin, Herning, & McCarthy, 1977; Squires et al., 1975). Slow-wave amplitude was measured as the mean base-to-peak amplitude over the last 150 msec of each waveform,

and these data are shown in Table 4. In agreement with earlier studies, the slow wave is positive at the parietal electrode and negative frontally. In addition, the present experiment provided data on the slow wave at Oz and FPz where it is positive and negative, respectively. The slow-wave distribution and amplitude were unaffected by stimulus modality, task difficulty, and the bimodal versus unimodal nature of the eliciting stimulus. The slow wave has its lowest absolute amplitude at the vertex; thus to the extent that P300 and slow-wave overlap temporally, the amount of contamination of base-to-peak measures of P300 by the slow wave is minimal at this site. For this reason all between-condition comparisons of P300 latency and amplitude in the present experiments were made at Cz.

Discussion

Experiment 1 raised the question of whether the predominance of the auditory element of the bisensory stimulus was due to differences in the discriminability of stimuli within each modality or whether the visual modality always plays a subordinate role in the elicitation of the bisensory P300. The results of Experiment 2 indicate that the discriminability of the stimuli within the modality is the factor determining which modality will predominate. Even though the auditory element predominated in the easy-auditory–difficult-visual condition, the opposite was true for the difficult-auditory–easy-visual condition. P300 appears to be dominated by whichever modality is associated with the earlier decision (as inferred from P300 latency and RT). When the decisions in the two modalities have approximately the same latencies, the bisensory P300 is earlier than either individual P300. These results are in agreement with the RT literature, where it has been suggested (e.g., Loveless et al., 1970; Raab, 1962; Wood, 1975) that redundancy gains can be explained by a statistical combination model, which assumes that processing of component dimensions proceeds simultaneously (in parallel) and that the RT on each trial is

determined by whichever component process is completed first. The amount of redundancy gain will be proportional to the overlap of the unimodal RT distributions. When such gains occur, the variance of the distribution of the bimodal RTs should also be reduced compared to the unimodal RT distributions. Assuming that P300 latency is correlated with the decision latency, this RT model predicts a decrease in the latency of P300 and an increase in its amplitude due to the decreased variability in the timing of the decision. Experiment 2 showed that the decreased latencies of the bimodal P300s were indeed associated with increased P300 amplitudes. (A similar prediction would of course be made by any model that accounted for decreased RT variance with decreased RT.)

One particularly important aspect of these data is the marked effect that stimulus discriminability had on the latency of the P300. The latency of the P300 to the 1,100-Hz tone, for example, was 60 msec later when paired with a 1,060-Hz tone than when paired with a 1,000-Hz tone, even though in both conditions the counting performance was nearly perfect. Although we have implicated the role of task "difficulty" by our use of the labels *easy* and *difficult*, explanations in terms of the salience of the target stimulus (Jenness, 1972) or the magnitude of the template mismatch (Squires, Hillyard, & Lindsay, 1973) may be equally suitable. It was not the purpose of the present experiments to test the adequacy of various hypotheses regarding the psychological correlates of the P300. The point here is that the sensitivity of P300 latency implies considerable variability across experiments and across subjects due to differences in the stimuli used and the difficulty of the task for the individual subject. The equivalence of late positive waves of varying latencies has sometimes been questioned. For example, Thatcher (1977) has observed a positive component with a 400-msec latency (P400), which he claims represents a component distinct from the component with a 300-msec latency, even though the two were recorded under simi-

lar circumstances. Our data suggest, as do others[1] (Kutas & Donchin, in press; Ritter et al., 1972), that the latency of the late positive component is determined by the latency or the duration of the endogenous process that it manifests (Donchin, 1975). A great deal of caution must therefore be used in identifying late components solely on the basis of peak latency. On the other hand, this same result provides encouraging evidence that P300 latency is indeed a sensitive measure of decision processes in its own right, although in the past the major emphasis has been placed instead on P300 amplitude variations.

Even though small differences in the scalp-amplitude distributions of the auditory and visual P300s were found in the first experiment, no such differences were found in Experiment 2 when the discriminability of the stimuli within the two modalities was equated. Thus it appears that the auditory and visual P300s can be considered to be equivalent components, provided that the conditions under which the auditory and visual P300s are elicited have been carefully equated.

Experiment 3

In the first two experiments, the two modalities always provided redundant information so that the appropriate response was always perfectly correlated with the stimulus. For a complete assessment of the degree to which P300 reflects the interactions known to occur between multiple channels of information, it is necessary also to examine the effects of nonredundant information. When subjects are asked to attend to only one of two orthogonally varying dimensions and to ignore the other, the task is called a "filtering" task (Posner,

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[1] Also, this method of data presentation probably underestimates the amount of facilitation or interference compared to more traditional measures due to the use of asymmetric probabilities of the various stimuli. Felfoldy (1974) found that the largest effect of going from one variable dimension to two was on the RTs to nonrepetitions of stimuli. Since the use of asymmetric probabilities produces fewer nonrepetitions, the averaged effect would be diminished.

1964). Here stimulus changes occur with and without a change in response. Felfoldy (1974) measured RTs in a filtering task and demonstrated that both stimulus and response variables influence the total RT. Experiment 3 looked at whether this is also true of P300 latency.

An analysis of filtering tasks, however, must take into account the nature of the stimulus dimensions used. Garner (1974) classified pairs of dimensions as "integral" or "separable." For visual stimuli, for example, value and chroma are integral dimensions, whereas size and lightness are separable, perceptually independent dimensions. Several converging operations have been used to support this distinction including similarity judgments, perceptual classification tasks, RT, and speed classification (card-sorting) tasks (Garner, 1974). With speed measures of performance, redundant integral dimensions facilitate performance, but redundant separable dimensions do not (Garner & Felfoldy, 1970; Wood, 1974). With nonredundant dimensions, on the other hand, filtering tasks are completed faster with separable than with integral dimensions (Gottwald & Garner, 1975). Although one might expect auditory and visual dimensions to be independent or separable (see Garner, 1974, p. 170), both the P300 latency and RT data of Experiment 2 meet the first criterion for integrality: facilitiation under conditions of redundant information. However, as Garner (1974, p. 132) has pointed out, in circumstances such as those in Experiment 2, it is to the subject's advantage to attend to both dimensions even when they are by nature separable. A more critical test of the integrality or separability of dimensions comes from procedures in which the information provided by the two dimensions is not redundant and attention to both dimensions would interfere with performance. If the subject cannot exclude the irrelevant dimension, the dimensions are integral; if no interference is found, the dimensions are separable. Experiment 3 therefore investigated P300 and RT measures of information processing with the elements of the bisensory stimuli providing nonredundant information.

Method

Subjects. Five subjects (four females and one male) participated in the ERP section of Experiment
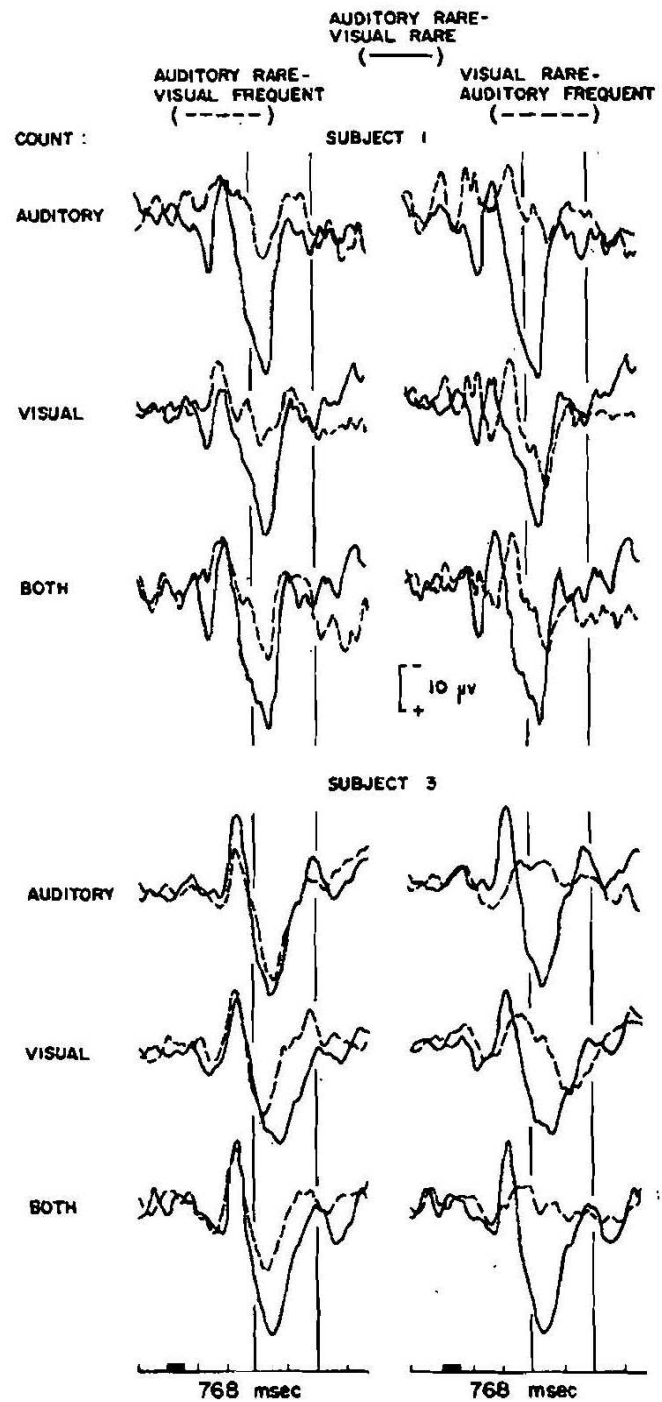

Figure 5. Experiment 3: Subtracted waveforms of two subjects for double (solid lines) and single (dotted lines) rares for each counting condition. (The ERP to the double rare [auditory rare – visual rare] is shown once in the left column superimposed on the response to the auditory rare – visual frequent stimulus and once on the right superimposed on the response to the visual rare – auditory frequent stimulus.)

3, including two (Subjects 1 and 2) who had participated in both previous experiments. RTs were taken from the same seven subjects who participated in the RT section of Experiment 2.

Stimuli. All stimuli in this experiment were bisensory audiovisual compounds. The two auditory stimuli were a 1,000-Hz tone and a 1,100-Hz tone, the easy auditory discrimination of the last experiment. The two visual stimuli were an orange flash and a blue flash, the "easy visual" discrimination. Four types of bisensory stimuli could occur in each block of trials: 1,000 Hz–orange ($p = .85$), 1,000 Hz–blue ($p = .05$), 1,100 Hz–orange ($p = .05$), and 1,100 Hz–blue ($p = .05$). Thus there were three equiprobable types of rare stimuli, two of which had a rare stimulus in one modality and one had rare stimuli in both modalities. The stimuli were the same on every block of trials; only the task differed.

Procedure. The subject was assigned one of three tasks at the beginning of a block of trials: (a) count all rare (1,100-Hz) tones; (b) count all rare (blue) flashes; or (c) count both rare tones and rare flashes, counting a double rare as one. There were 150 stimuli per block, and five blocks were presented in each counting condition in counterbalanced order over the course of two 2-hour sessions. In addition, three control conditions were presented in which each of the combinations of auditory and visual stimuli was the frequent, noncounted stimulus, with the exception of the 1,000 Hz–orange combination, which had been the frequent stimulus in all other blocks. RTs were collected in the same manner as in the previous experiment.

Results

Waveforms. The ERPs for two subjects are shown in Figure 5. The data for these subjects were chosen as the most representative of the experimental effects. Each waveform is the difference between the averaged ERP to a particular rare compound and the corresponding ERP to that compound when it was frequent. These subtractions were made to show the isolated effects of the various rare events, without any stimulus-specific effects. The solid lines are the waveforms associated with the double-rare stimulus; this same waveform is shown twice, once on the left superimposed on the ERP to the auditory-rare–visual-frequent stimulus and once on the right with the ERP to the auditory-frequent–visual-rare stimulus. The three counting conditions are represented in the three rows. The amplitude and latency of the double-rare P300 remained approximately the same across counting conditions, whereas the amplitudes of the single-rare P300s varied with the instructions.

P300 amplitude and latency. The latencies of the P300s to the double-rare stimuli and to the auditory rare (visual frequent) stimulus were about the same, 350–355 msec in every counting condition (Table 5). The latency of the visual-rare (auditory-frequent) P300 was 40–50 msec longer. These latencies were all unaffected by the counting task.

The amplitude of the P300 to the double-rare stimulus was consistently greater than that of either single-rare P300 and was unaffected by the counting condition. For the single-rare P300s, the maximum amplitude occurred when only rares in that modality were being counted, the amplitude

Table 5

Mean P300 Latencies and Amplitudes for the Three Experimental Conditions for the Three Types of Rare Stimuli

Count	Auditory rare – visual rare		Auditory rare – visual frequent		Auditory frequent – visual rare	
	M	SD	M	SD	M	SD
Latencies						
Auditory	356	16	354	19	400	23
Visual	350	20	356	38	394	23
Both	352	17	351	23	398	23
Amplitudes						
Auditory	25	10	18	6	5	3
Visual	23	4	11	2	13	4
Both	24	7	14	4	10	6

Table 6
Mean Reaction Times to Rare and Frequent Stimuli for the Seven Subjects in Experiment 3

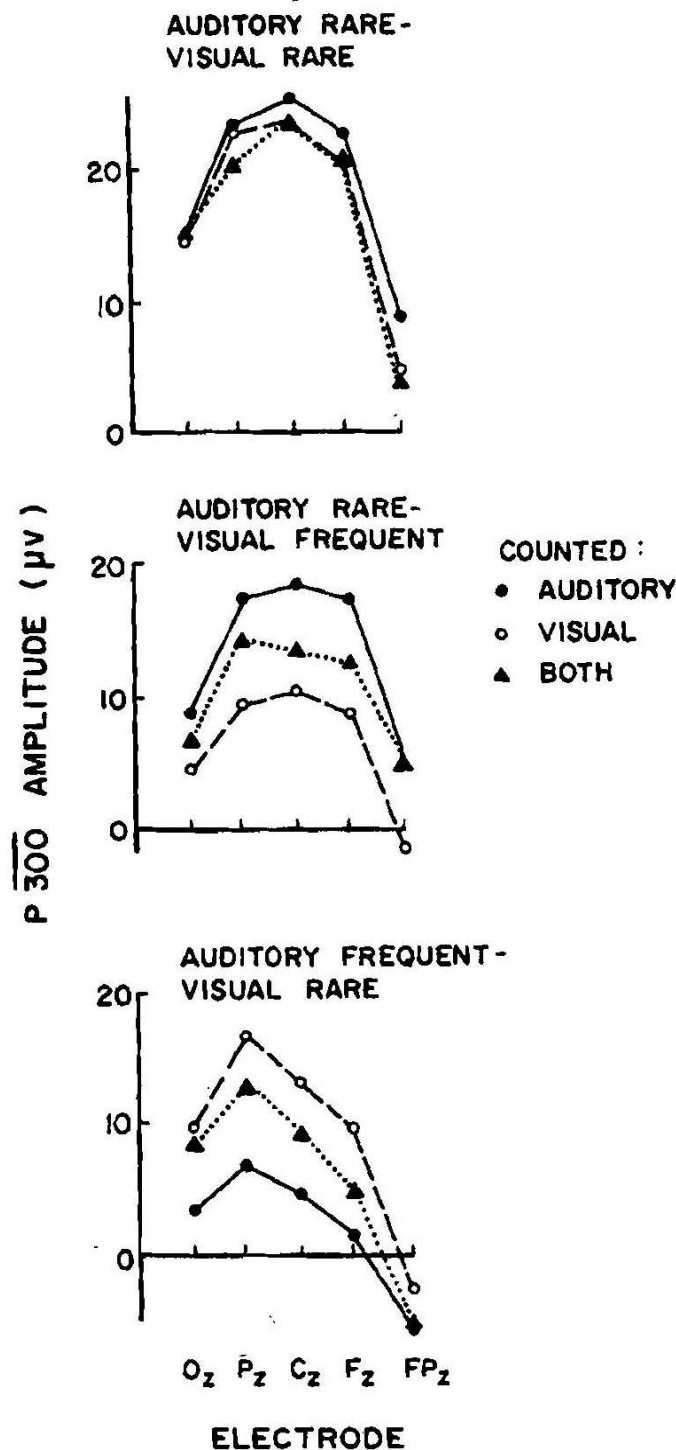| Auditory/visual	Auditory		Visual		Both	
	M	SD	M	SD	M	SD
Rare	401	67	384	55	409	69
Rare/frequent	426	69	342	62	485	90
Frequent/rare	340	80	399	60	467	99
Frequent/frequent	298	40	276	24	317	42

Figure 6. Mean P300 scalp-amplitude distribution for each stimulus in each counting condition.

was minimal when stimuli in the other modality were counted, and it was intermediate when both were counted.

RTs. The mean RTs to all four stimuli in each of the three conditions are shown in Table 6. RTs to rare stimuli in the task-relevant modality combined with a frequent stimulus in the irrelevant modality were much longer than those to the double-frequent stimuli, for both auditory and visual modalities (a difference of 128 msec for the auditory in the "attend-auditory" condition, $p < .001$, and 123 msec for the visual in the "attend-visual" condition, $p < .001$). A rare stimulus in the irrelevant modality also lengthened the RT but by a smaller amount (42 msec for irrelevant visual in the attend-auditory condition, $p < .05$, and 66 msec for the irrelevant auditory in the attend-visual condition, $p < .01$). The RT to the double-rare stimulus was significantly shorter than to the single auditory rare in the auditory condition (25 msec, $p < .01$) but not significantly shorter in the attend-visual condition (15 msec). When subjects were instructed to attend to both modalities, the RTs to all stimuli were lengthened over the single-modality conditions (e.g., the mean RT for double-frequent stimuli in the attend-both condition was 19 msec longer than in the attend-auditory condition and 41 msec longer than in attend-visual condition).

P300 scalp distribution. The scalp-amplitude distributions of P300 are given in Figure 6 for each of the three types of rare stimuli. The P300 to the auditory-frequent–visual-rare stimulus (bottom frame) had a parietal maximum and re-

sembled the distribution in the easy-visual task of Experiment 2. However, the distributions for the auditory-rare–visual-frequent stimulus (middle frame) and the double-rare P300 (top frame) were more equipotential than those shown before (Figure 4). The mean ratios of Fz to Pz were .96, .93, and .42 for the double-rare, the auditory-rare, and visual-rare P300s, respectively. An analysis of variance on the base-to-peak amplitudes of the auditory and visual P300s showed a significant interaction between the effects of stimulus and electrode position, $F(4, 16) = 4.82$, $p < .01$, whereas a similar analysis of the P300s to the same stimuli in Experiment 2 gave a nonsignificant interaction, $F(4, 20) = .19$. This comparison is particularly meaningful in view of the fact that the topographical differences in Experiment 3 were found within the same series of stimulus presentations, whereas the identical distributions in Experiment 2 represent comparison across blocks of trials.

Slow wave. The slow wave was measured, as before, as the mean difference in voltage from the prestimulus baseline to the last 150 msec of each waveform. These values are shown in Table 7. Even though the amplitudes and amplitude variations across electrodes differ somewhat across conditions, particularly for the auditory-frequent–visual-rare stimulus, the variations are unsystematic and do not correlate with the distributional variations of the P300. Thus the distributional differences found for the auditory and visual P300s cannot be attributed to variations in the slow wave elicited by the different stimuli. The distributional differences can be accounted for by the differential overlap of slow wave with the early and late P300s. Subjects with large slow waves and large latency differences between auditory and visual P300s also showed large distributional differences. Those with small slow waves and small latency differences had little or no distributional difference. The size of the distributional differences between the auditory and visual P300s (auditory Fz/Pz ratio minus the visual Fz/Pz ratio) had a .75 correlation with the size of the slow wave across the five subjects and a correlation of .86 with the difference in the peak latencies of the auditory and visual P300s.

Discussion

For a simplified comparison of the present data with traditional measures of bisensory interaction, RTs to all stimuli in a condition were averaged for the relevant conditions of Experiment 2 and 3 (Table 8). As discussed previously, Experiment 2 showed a gain in performance with redundant dimensions. In Experiment 3 dimensional interference was found in the filtering tasks (cf. "filtering," with the corresponding unimodal results). Even greater interference was found in the condensation task. Although these effects are

Table 7

Mean Amplitude (in microvolts) of Five Subjects of the Slow Wave Evoked by Each of the Three Types of Rare Stimuli in Each Experimental Condition of Experiment 3

| Eliciting stimulus | Counted stimulus | Electrode | | | | |
		Oz	Pz	Cz	Fz	FPz
Auditory rare – visual rare	Auditory	6.2	5.9	.0	−5.4	−6.5
	Visual	4.5	1.8	−3.5	−9.0	−7.7
	Both	5.2	2.8	−1.0	−5.0	−1.0
Auditory rare – visual frequent	Auditory	2.4	3.4	−2.8	−7.8	−11.2
	Visual	2.6	2.6	−.2	−4.8	−7.1
	Both	5.1	6.2	.4	−5.8	−9.6
Auditory frequent – visual rare	Auditory	1.5	4.5	2.6	−.2	−4.2
	Visual	1.6	2.7	−5.1	−12.3	−13.4
	Both	6.2	7.6	2.0	−3.9	−8.8

Table 8
Mean Reaction Times in Unimodal Auditory Easy and Visual Easy Conditions (Experiment 2), the Redundant Compounds (Auditory Easy – Visual Easy, Experiment 2), and the Nonredundant Compounds Under Different Instructional Conditions (Experiment 3)

	Stimulus		
Task	Uni-modal	Redun-dant	Nonredundant
Auditory	290 (2)	—	312 (3: filtering)
Visual	288 (2)	—	291 (3: filtering)
Auditory/ visual	—	262 (2)	338 (3: condensation)

Note. Number in parentheses refer to experiment number.

not large, they are comparable to the effects previously reported (e.g., Felfoldy, 1974; Garner, 1974).[2] Furthermore, interference between the dimensions in Experiment 3 can also be inferred from an analysis of the RTs to the individual types of rare events (Table 6). Irrelevant rare events delayed the "frequent" response and facilitated the "rare" response, confirming that the "irrelevant" dimension was in fact not ignored. The ERP data also support this conclusion, since the irrelevant rare stimulis did elicit a small P300. By Garner's criteria, then, the pitch and color dimensions used in these experiments would be considered "integral" dimensions. That this is the case with dimensions in two different sensory modalities is perhaps surprising. One possibility is that with further training the subjects might have been able to separate the dimensions more completely; however, the data of the two subjects who had already participated in the previous two experiments indicate that this is unlikely. Another important factor might be the difficulty of the discriminations involved; according to Long (1975), who used auditory frequency and visual intensity dimensions, interference is observed when the intramodality discriminations are difficult, but no interference is observed with easy discriminations.[3] A third possibility is that alternating between tasks, as was done here, interferes

with the subjects' separation of the modalities. Whatever the explanation, it appears that the integrality concept must be interpreted more broadly than it has been previously. The close agreement found here between the physiological and performance data nevertheless supports the distinctions Garner has made about stimulus dimensions and also the utility of the P300 component of the evoked response as a measure of these variables.

The RT data of Experiment 3 agree with those of Felfoldy (1974); the shortest RTs were to the double-frequent stimuli; a rare stimulus that required a frequent response (i.e., an irrelevant rare) produced some delay in RT, whereas a rare stimulus requiring a rare response (a relevant rare) delayed the response even further. The present RT data, along with those of Felfoldy, support the idea that RT reflects at least two stages of processing, evaluation of the stimulus and initiation of the appropriate motor response. On the other hand, the latency of P300 did not vary with the counting response required. It is clear from Experiments 1 and 2 that P300 latency can vary widely in counting tasks. There, P300 latency varied with the discriminability of the relevant stimuli; the more difficult it was to identify the stimuli, the later was the P300. In Experiment 3 the discriminability of the two stimuli was constant, and so was the P300 latency. So although there are evident differences between RT and

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[2] Long's (1975) measure of interference was a decrease in the percentage correct. With easy discriminations performance may be asymptotically 100% correct and interactions between the dimensions may be obscured. Thus the relevance of this variable to other types of measures is not yet clear.

[3] Felfoldy (1974) performed a trial-by-trial analysis of his data, looking at the effects of repetitions and nonrepetitions of the stimulus and response conditions from the last trial. Thus the analysis is not directly comparable to the one performed here. However, with the probabilities used in Experiment 3, it can be safely assumed that the "double-frequent" stimuli mainly represent repetitions of stimuli and responses and that the rare stimuli represent nonrepetitions of stimuli, and either repetitions or nonrepetitions of responses, depending on the particular condition, so that the comparison between the results of the two experiments is straightforward.

counting tasks, the data of Experiments 2 and 3, when taken together, present an instance in which an independent variable (stimulus discriminality) affects both P300 latency and RT and another instance in which an independent variable (choice of target stimulus) affects RT and P300 amplitude but has no effect on P300 latency. A plausible interpretation of these data is that the process manifested by P300 is involved with stimulus evaluation rather than with response selection. Acceptance of this tentative conclusion must be tempered with caution pending a more direct comparison between the RT and counting tasks. A preliminary comparison, however, has been reported by Kutas and Donchin (in press), and their results are consistent with the present view.

The amplitude of the P300, unlike its latency, did vary with the task in Experiment 3. An irrelevant rare stimulus produced a small P300, a rare stimulus in the relevant modality evoked a larger P300, and the largest P300 was associated with the double-rare stimuli. Thus P300 amplitude appears to increase with the discrepancy between the stimulus expected (the double-frequent stimulus) and that which actually occurs. This effect has been called "equivocation" by Ruchkin and Sutton (in press) and has been supported by several investigations (e.g., Adams & Benson, 1973; Ford, Roth, & Kopell, 1976; Hillyard, Squires, & Squires, Note 1; Johnson & Donchin, Note 2).

The scalp distribution of P300 varied in yet a third manner; auditory-rare and double-rare stimuli both evoked P300s that were basically equipotential over Pz, Cz, and Fz, whereas the P300s to the visual-rare stimuli were larger at Pz than at Fz. These relationships were independent of the counting condition. This result is of particular importance in view of the recent trend in the P300 literature to identify a variety of different kinds of P300s mainly on the basis of their different scalp topographies. (See Tueting, in press, for a discussion of this trend.) Although we have tentatively attributed the effect reported here to the differential

overlap of P300 and slow wave, it is certainly not clear at this point whether such an explanation would account for other reported differences in scalp topography, for example, those of Courchesne (1975), who reported that novel, irrelevant visual stimuli inserted into a Bernoulli series of visual stimuli elicited a P300 with a frontal distribution, whereas the relevant rare targets elicited a P300 with a more parietal distribution.

Since it appears that speed measures of information processing provide a combined measure of several stages of processing while P300 is influenced by only a particular subset of those variables, P300 emerges as a useful adjunct to more traditional means of evaluating cognitive events. This is particularly true in that P300 appears to be a multifaceted index whose various characteristics are functionally independent. P300 latency reflects the discriminability of stimuli along the relevant dimension and presumably the speed of identification and decision making (Experiments 1 and 2); P300 amplitude increases when the jitter in its latency is reduced (Experiment 2; Ruchkin & Sutton, in press) and with increased discrepancy between what is expected and what occurs (Experiment 3); and finally, P300 scalp distribution also varies with differences in processing, although the nature of this variation is as yet not well defined. Although the functional and neurophysiological nature of P300 and other ERP components remain to be determined, the experiments reported here affirm their status as important indices of cognitive processes, and perhaps more importantly emphasize the multifaceted nature of P300 and the independence of its various characteristics.

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2. Johnson, R., Jr., & Donchin, E. *Intensity discrimination effects on the auditory event-related potential.* Manuscript submitted for publication, 1977.

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