hav. **4**, 414 (1965); T. Bever, J. Lackner, R. Kirk, *Percept. Psychophys.* **5**, 4 (1969).

3. R. Barker and H. Wright, *The Midwest and Its Children* (Harper & Row, New York, 1955); H. Dickman, in *The Stream of Behavior*, R. Barker, Ed. (Appleton-Century-Crofts, New York, 1963), pp. 23–41; C. Metz, *Film Language: A Semiotics of the Cinema* (Oxford Univ. Press, New York, 1974); J. Carroll, in *Studies in Structural Aesthetics*, T. Bever, Ed. (Erlbaum, Hillsdale, N.J., in press).
4. K. Reisz and G. Millar, *The Technique of Film Editing* (Hastings House, New York, 1968).
5. This is analogous to the fact that a probe word from the second clause of a sentence is recognized faster than one from the first clause of the sentence [D. Caplan, *Percept. Psychophys.* **12**, 73 (1972); J. Kornfeld, thesis, Massachusetts Institute of Technology (1973); L. Shedletsky, thesis, University of Illinois (1974); see also G. Suci, P. Ammon, P. Gamlin [*Lang. Speech* **10**, 69 (1967)].
6. The segments of the type E sequences were linked by mise-en-scène devices other than cuts, such as, pans, tilts, dollies. The devices linking the segments were designed not to be phenomenally obtrusive (for example, so-called jump cuts or expressive montage) nor were they invisible in the sense of Hollywood "hidden" cuts. Subjects did not report afterwards that their attention had been drawn to the cuts and other devices, but many were aware that there had been cuts in the sequences. The devices seemed to be similar with respect to phenomenal obtrusiveness, but we have no way of precisely quantifying their relative strengths.
7. Black-and-white motion picture sequences were rear projected by an L & W Data Analyzer (model 224A). The film sequences were projected at 16 frames per second. The film sequences ranged from 75 frames to 100 frames in length (from 4.7 to 6.3 seconds in duration). Viewers watched the back-projection screen at a distance of 3.5 feet. The image was 10.5 inches by 8.5 inches; it subtended a visual angle of 11.5° by 14°.
8. By subject, $P < .003$ (one-tailed, Wilcoxon matched pairs signed ranks) and by item, $P < .05$ (one-tailed, Wilcoxon rank sums).
9. By subject, $P < .01$ and $P < .02$ (one-tailed). We have too few items in each subcategory to perform statistics by item in the internal analyses.
10. By subject, $P < .01$ and $P < .01$ (one-tailed).
11. The mean distance from the end of the probe site to the end of the test sequence in the second-segment probe items is 49 frames. For first-segment probe items the mean distance is 29 frames (a difference of 1.25 seconds).
12. Across subjects, $r = -.12$, $t = 0.37$, d.f. $= 10$.
13. Second-sequence probe cases, across subjects, $r = +.82$; first-sequence probe cases, across subjects, $r = +.51$.
14. M. Potter and E. Levy, *J. Exp. Psychol.* **81**, 10 (1969).
15. J. Fodor, T. Bever, M. Garrett, *The Psychology of Language* (McGraw-Hill, New York, 1974); J. Carroll and T. Bever, in *Handbook of Perception*, E. Carterette and J. Friedman, Eds. (Academic Press, New York, in press), vol. 7.

16. We gratefully acknowledge advice we received from J. Hochberg and L. Gellman.

9 June 1975; revised 24 October 1975

Brain Wave Components of the Contingent Negative Variation in Humans

Abstract. *In a contingent negative variation paradigm with two stimuli paired at an interstimulus interval of 4 seconds, two distinct waveforms having functional and topographic differences are observed. An early wave is maximal over the frontal cortex and is elicited by the warning stimulus. A later wave, maximal over the motor cortex, precedes the imperative stimulus and is identified with preparation for motor response.*

Slow brain potential shifts are recorded from the human scalp during periods of preparation or active mental involvement. The most familiar of these potentials, the contingent negative variation (CNV), first described by Walter *et al.* (*1*), occurs during the interval between a warning stimulus and a subsequent imperative stimulus that requires a mental or motor response. The CNV has proven sensitive to a number of psychological variables, none of which can yet be singled out as a definitive or exclusive correlate (*2*). This lack of consensus as to the underlying variables reflects a growing belief that the CNV may comprise two or more separate processes, combining in unrecognized proportion (*3–5*). Here we distinguish two component processes on the basis of latency, topography, and functional properties. An early component is maximal over the frontal cortex and appears in response to the warning stimulus—whether or not it is paired with a subsequent imperative stimulus. A second, later component shares critical features with the readiness potential, first described by Kornhuber and Deecke (*6*) as a negative shift preceding voluntary movement, in that it has a more central distribution over motor areas of the cortex and is related to the dynamics of the motor response.

This research led from our previous findings that the distribution of the CNV over the scalp varied in accordance with different perceptual and motor tasks (*7*). In one condition, in which the word "left" or "right" served as a warning stimulus and designated the hand to be used in the response, the bilaterally recorded CNV became progressively asymmetrical throughout the 1.5-second interstimulus interval, being greater over the contralateral hemisphere. The increasing asymmetry before the signal to respond suggested some contribution from the readiness potential, which has been observed to lateralize in a similar manner and over a similar time course (*8*). However, this contribution has been difficult to assess, especially in view of reports that CNV characteristics sometimes have little to do with specific response requirements (*9*).

A means whereby the readiness potential might be observed separately from other negative waves was suggested to us by recent reports by Loveless and Sanford (*4*, *5*) and Weerts and Lang (*10*), who have shown that the CNV assumes two distinct and nonoverlapping phases when the interstimulus interval is extended beyond the typical range of 1 or 2 seconds. The first phase is a broad negative wave that peaks within a second or so after the warning stimulus. Under conditions in which the interstimulus interval is constant and responding speed is emphasized, a second negative shift appears before the imperative stimulus.

We were able to observe clearly both these waves in a reaction time task employing tone bursts paired with flashes, separated by a relatively long interstimulus interval of 4 seconds. Subjects were required to respond to the light flashes as quickly as possible, but not prematurely, by fully depressing a telegraph key beneath the index finger. Complete depression of the key (3-mm throw) required a force equivalent to 450*g*; however, reaction times were measured from the earliest key displacement. Identical keys were located under each hand, and the appropriate hand on each trial was designated both by the pitch of the warning tone, which was either 1000 or 1500 hertz, and by the shape of the corresponding flash, which was either a square or a diamond (square rotated 45°). The paired stimuli were presented in random order. Subjects reported that the two pitches were easily discriminable and enabled unimanual response preparation during the interstimulus interval. The different combinations of high or low tone pitch, square or diamond flash shape, and left or right responding hand were balanced over subjects.

The tone bursts were rectangularly gated for a duration of 20 msec and delivered over binaural insert earphones at an intensity of 85 db. The flash patterns were formed by masking the milk-glass faces of two Grass PS-2 photostimulators, mounted in different channels of a three-field tachistoscope. The third channel was dark except for a dim fixation cross. At a viewing distance of 175 cm, the square and diamond each subtended a visual angle of 2.3° by 2.3°. The original intensity, at a setting of 4, was reduced approximately 80 percent through the optics of the tachistoscope.

Fourteen right-handed psychology students (nine male) served as subjects. During a single 2-hour session they received two identical blocks of 80 paired tones and flashes, half requiring a right-hand response and half a left-hand response. The interval between the key press and the warning tone for the next trial varied randomly from 3.5 to 7.5 seconds.

The blocks of paired stimuli were preceded by a condition in which subjects listened attentively but without responding to 30 unpaired tone bursts, varying randomly between the high and low pitches and separated by random intervals of 3.5 to 7.5 seconds. In an additional condition interposed between the two blocks of paired stimuli, subjects made 80 uncued key presses at an approximate rate of one per 4 seconds, alternating between left and right hands. Subjects were asked not to move or blink their eyes except between trials. The experimental room was darkened and isolated from outside sounds with continuous white noise delivered over a speaker at moderate intensity.

The electroencephalogram (EEG) was recorded from Beckman miniature silver–silver chloride electrodes arrayed along the midline at frontal (Fz), vertex (Cz), and parietal (Pz) sites, as well as from left (C3) and right (C4) motor area sites, all referenced to linked earlobes. The EEG was amplified with Grass 6A1B amplifiers modified to yield a 12-second time constant, with an upper cutoff of 40 hertz. The electrooculogram (EOG) was recorded similarly from electrodes above and below the left eye. The amplified EEG and EOG were recorded on FM tape for off-line analysis on a PDP-12 computer (digitized at a rate of 42.5 samples per second). All trials on which there were EOG deviations or premature or erroneous responses were excluded from analyses.

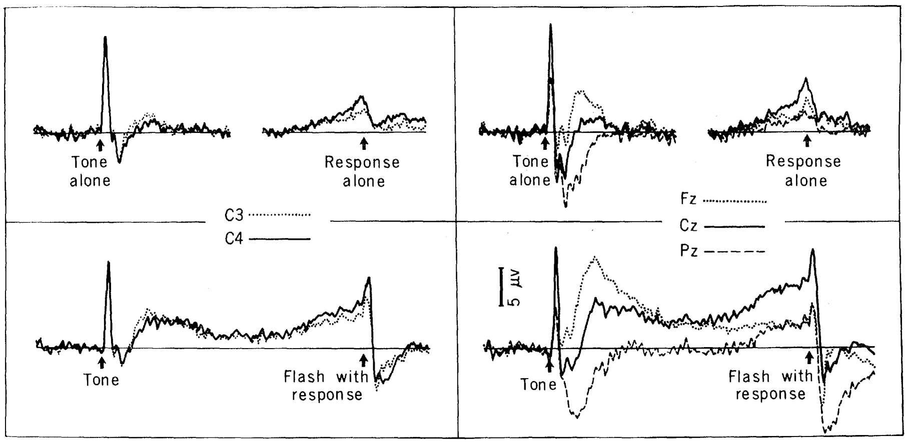

Fig. 1. Contingent negative variations elicited by paired stimuli (bottom) compared with potentials elicited by unpaired tones and uncued responses (top). Comparisons for midline frontal (Fz), motor (Cz), and parietal (Pz) sites are shown in the right panels, and for bilateral left (C3) and right (C4) motor sites in the left panels. The interstimulus interval for paired stimuli is 4 seconds. The time and amplitude scales are the same for all averages; negativity is upward. Uncued response averages are time-locked to the key press, and averages for the uncued response and paired stimuli conditions are based only on those trials requiring a left-hand response. Waveforms are averaged over all 14 subjects.

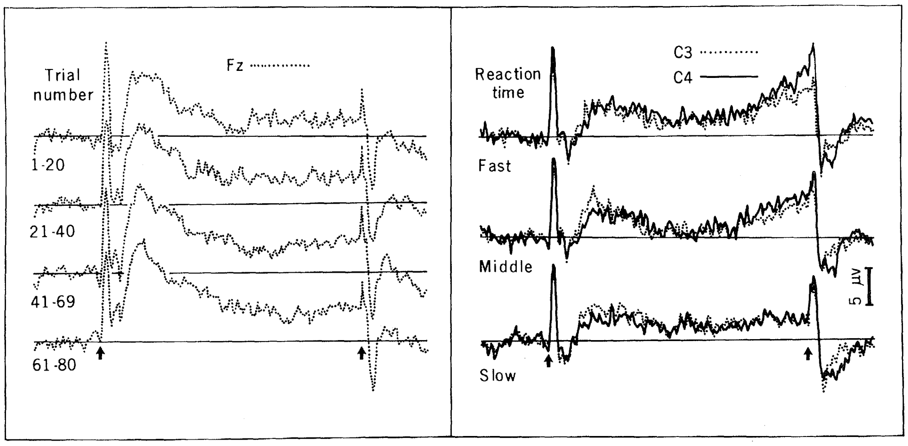

Fig. 2. Averaged CNV's as a function of trial number during the first block of paired stimuli (left panel) and as a function of reaction time during the second block of paired stimuli (right panel). Averages in the left panel are from the midline frontal (Fz) site, and those on the right are from the left (C3) and right (C4) motor area sites. The first and second arrows indicate the tone warning stimulus and the flash imperative stimulus, respectively. For each subject, potentials were averaged separately for fast, middle, and slow thirds of the reaction time distributions associated with left- and right-hand responses. The averages shown in the right panel are for left-hand responses only and are combined over all 14 subjects. The associated median reaction time values (averaged over all subjects) for fast, middle, and slow thirds are 140, 168, and 229 msec, respectively. The larger response-related asymmetries apparent for fast reaction times reversed correspondingly for right-hand responses. The interstimulus interval is 4 seconds. Time and amplitude scales are the same in both panels; negativity is upward.

The CNV's in response to the paired stimuli, plotted in Fig. 1, bottom, include two distinct long-duration negative waves. The first attains peak amplitude about 0.5 second after the primary components of the potential evoked by the warning stimulus (tone), and the second begins about 1.5 seconds before the imperative stimulus (flash). In comparison, Fig. 1, top, shows the negative afterwave elicited by unpaired tones, and the readiness potential preceding the uncued key-press responses.

As shown in Fig. 1, right, the midline distribution of the early CNV wave is comparable to that for the afterwave elicited by the unpaired tones: maximum at Fz, reduced substantially at Cz, and absent or somewhat positive at Pz. This is in contrast to the midline distribution of the late CNV wave preceding the flash and the readiness potential preceding the uncued responses, which share a more central focus at Cz and have smaller amplitudes at Fz and Pz (*11*).

Differences between CNV's from C3 and C4, as illustrated in Fig. 1, bottom left, provide further grounds for distinguishing separate early and late CNV waves and for identifying them with the negative afterwave and the readiness potential shown in Fig. 1, top left. There are significant bilateral asymmetries in both the late CNV wave and the readiness potential, and the direction of asymmetry depends strongly on the responding hand. The greater amplitude in all cases was recorded over the hemisphere contralateral to the responding hand; the relative enhancement at C4 for the left-hand responses shown in Fig. 1 reverses for the right-hand responses. This reversal is of comparable magnitude during the uncued response condition and both blocks of paired stimuli (*12*). In contrast, the early negative afterwave elicited by the tone shows no relationship with the responding hand. For both left- and right-hand responses there is a small trend (statistically nonsignificant) for this wave to be larger at C3 than C4.

As Fig. 2 indicates, early and late CNV waves differ not only in their scalp topography but also functionally; the early wave grows in amplitude throughout a series of trials while the late wave is related to reaction time. The early frontal wave manifested similar patterns of orderly growth (Fig. 2, left) during both blocks of paired stimuli, beginning at comparable amplitude values in both blocks (*13*). There was a similar (although statistically nonsignificant) growth during the unpaired tone condition (not illustrated); by the last five unpaired tones, the amplitude of the negative afterwave was nearly the same as during the first 20 trials of the following block of paired stimuli. In contrast, the late wave revealed no systematic or significant growth as a function of trial position at any electrode site. When the averages were computed on the basis of reaction time (Fig. 2, right), however, the late CNV wave showed a significant inverse relationship to reaction time (*14*), while the early wave was not related to reaction time.

We believe these data delineate and confirm the functional separation of two component processes in the CNV, one a negative afterwave associated with the warning stimulus and the second identified with the readiness potential. We have been able to distinguish these elements by minimizing the temporal overlap between the two at an interstimulus interval of 4 seconds. Additional processes may well become involved at shorter interstimulus intervals or under different conditions. However, the two waves described here would be sufficient, when temporally overlapped and coalesced, to form CNV's resembling those often obtained at short interstimulus intervals. Any such mixture of the two negative waves would mutually dilute individual relationships between the respective waves and the experimental variables associated with each, for instance, the relationship we observed between reaction time and amplitude of the late CNV wave.

Our results suggest that the more important effects of the pairing of stimuli lie in the temporal conjunction of these two waves. A connection or contingency between the stimuli may not be directly or uniquely responsible for the production of the individual negative variations we have studied. Frontal waves having similar features were elicited by the tone whether or not it was paired with a subsequent imperative stimulus. These observations indicate that pairing a given stimulus with another may be but one manipulation that causes a stimulus to elicit a negative afterwave. Other manipulations might include requiring close attention to the stimulus (as in the unpaired tone condition of the present study), raising stimulus intensity (*4*), or assigning to it some experimental importance by requiring a discrimination or by making it rare or novel (*15, 16*). Others (*4, 5, 10*) have speculated that the effect common to these manipulations is an orienting response—an interpretation we cannot easily reconcile with our finding that the negative afterwave grows in amplitude over repeated trials.

Likewise, the late CNV wave appears not to be strictly contingent on the pairing of stimuli, in that it reflects a process of response preparation rather than stimulus anticipation. If, as we believe, the late CNV wave is primarily a readiness potential, then the study of the readiness potential can be extended beyond the scope of repetitive stereotyped movements. In addition to the present variable of response speed, it may be possible to examine the readiness potential within the context of heretofore inaccessible variables, such as the degree to which the eventual response is specified and its susceptibility to distraction by competing timed mental or motor processes.

JOHN W. ROHRBAUGH
Department of Psychology, University of California, Los Angeles 90024
KARL SYNDULKO
Gateways Hospital, Los Angeles 90026,
and *Department of Psychology, University of California, Los Angeles*
DONALD B. LINDSLEY
Departments of Psychology, Physiology,
and *Psychiatry,* and *Brain Research Institute, University of California, Los Angeles*

References and Notes

1. W. G. Walter, R. Cooper, V. J. Aldridge, W. C. McCallum, A. L. Winter, *Nature* **203**, 380 (1964).
2. W. C. McCallum and J. R. Knott, Eds., *Event-Related Slow Potentials of the Brain* (Elsevier, New York, 1973).
3. R. P. Borda, *Electroencephalogr. Clin. Neurophysiol.* **29**, 173 (1970); T. Järvilehto and H. Fruhstorfer, *Exp. Brain Res.* **11**, 309 (1970).
4. N. E. Loveless and A. J. Sanford, *Biol. Psychol.* **2**, 217 (1975).
5. ——, *ibid.* **1**, 303 (1974); *J. Gerontol.* **29**, 52 (1974).
6. H. H. Kornhuber and L. Deecke, *Pfluegers Arch. Gesamte Physiol. Menschen Tiere* **284**, 1 (1965).
7. K. Syndulko, thesis, University of California, Los Angeles (1972); —— and D. B. Lindsley, in *Proceedings of International Symposium on Cerebral Evoked Potentials in Man, Bruxelles, 1974*, J. Desmedt, Ed. (in press).
8. L. K. Gerbrandt, W. R. Goff, D. B. Smith, *Electroencephalogr. Clin. Neurophysiol.* **34**, 461 (1973); M. Kutas and E. Donchin, *Science* **186**, 545 (1974); H. G. Vaughan, Jr., L. D. Costa, W. Ritter, *Electroencephalogr. Clin. Neurophysiol.* **25**, 1 (1968).
9. J. Cohen, in *Averaged Evoked Potentials: Methods, Results and Evaluations*, E. Donchin and D. B. Lindsley, Eds. (Government Printing Office, Washington, D.C., 1969), pp. 143–198; E. Donchin, L. K. Gerbrandt, L. Leifer, L. Tucker, *Psychophysiology* **9**, 168 (1972).
10. T. C. Weerts and P. J. Lang, *Biol. Psychol.* **1**, 1 (1973).
11. Statistical tests were based, in the case of the early wave, on the single most negative point within 400 to 1000 msec after the tone burst. The late wave was measured as the average amplitude over the last 500 msec preceding the flash or, in the case of the uncued responses, before the response. Analyses of variance revealed that the midline differences were significant for the early wave during the unpaired tones ($F = 13.18$; d.f. = 2, 26; $P < .005$) and both blocks of paired stimuli ($F = 39.11$; d.f. = 2, 26; $P < .001$; and $F = 73.70$; d.f. = 2, 26; $P < .001$). The midline differences were also significant for the late wave during the uncued responses ($F = 8.18$; d.f. = 2, 26; $P < .005$) and both blocks of paired stimuli ($F = 9.22$; d.f. = 2, 26; $P < 001$; and $F = 8.39$; d.f. = 2, 26; $P < .005$).
12. The interaction of responding hand with lateral electrode site was significant for the late wave in the uncued response condition ($F = 18.59$; d.f. = 1, 13; $P < .001$) and both blocks of paired stimuli ($F = 10.40$; d.f. = 1, 13; $P < .01$; and $F = 5.84$; d.f. = 1, 13; $P < .05$). The late CNV wave averaged 5.3 μv for the contralateral hemisphere versus 4.1 μv for the ipsilateral hemisphere during the first block of paired stimuli, 4.4 μv versus 3.4 μv during the second block of paired stimuli, and 2.8 μv versus 1.4 μv for the readiness potential. Over all 14 subjects the contralateral-ipsilateral differences in the readiness potential correlated significantly with differences in the late CNV wave during the second block of paired stimuli ($r = +.56$, $P < .05$).
13. The early wave differed significantly in amplitude between the first and last 20 trials for both blocks of paired stimuli, measured at Fz ($F = 7.56$; d.f. = 1, 13; $P < .025$; and $F = 7.29$; d.f. = 1, 13; $P < .025$).
14. Differences in the late wave at Cz were significant over the three reaction time categories, measured during the second block of paired stimuli ($F = 4.97$; d.f. = 2, 26; $P < .025$). The late CNV waves from the bilateral (C3 and C4) electrode sites, as plotted in Fig. 2, had the following values during the second block of paired stimuli: for the fast reaction times the contralateral value averaged 6.4 μv versus 4.9 μv from the ipsilateral electrode, 3.8 μv versus 3.0 μv for the middle reaction times, and 2.5 μv versus 2.1 μv for the slow reaction times.
15. M. Haider, E. Groll-Knapp, G. Studynka, *Exp. Brain Res.* **5**, 45 (1968); N. K. Squires, K. C. Squires, S. A. Hillyard, *Electroencephalogr. Clin. Neurophysiol.* **12**, 74 (1975); D. Symmes and M. A. Eisengart, *Psychophysiology* **8**, 769 (1971).
16. Prior work in our laboratory (J. W. Rohrbaugh, K. Syndulko, D. B. Lindsley, in preparation), as well as studies by Loveless and Sanford (*4, 5*) and Weerts and Lang (*10*), has established that the early CNV wave cannot be attributed solely to the fact that the warning stimulus required a discrimination. In our prior work 12 subjects each received four reaction time conditions given in the same order. In the first three of these conditions (using simple, go or no-go, and choice reaction time) the warning stimulus was a nondiscriminative tone of the same pitch on every trial. The fourth condition was similar to the one used here, with a discriminative tone of either 1000 or 1500 hertz. In all conditions the warning stimulus elicited a negative afterwave that peaked at about 8 μv (at Cz) and differed by no more than 1 μv from one condition to another.
17. Supported by PHS grant NS 8552 to D.B.L. and by PHS fellowship 1 F22 MH00736 to J.W.R.

7 July 1975; revised 17 October 1975

Photochemical Smog Systems: Heterogeneous Decay of Ozone

Fox *et al.* (*1*) describe the results of two experiments from which they conclude that "dilution as opposed to static experimental conditions may prove to be more important if smog chamber data are to be used as guides in developing certain future control strategies." Although the above suggestion may be correct, the evidence presented by Fox *et al.* (*1*) is incomplete in at least one serious aspect. At the low dilution rates associated with their reported smog chamber experiments, the heterogeneous decay of O_3 (*2, 3*) could well be the dominant mechanism by which O_3 is lost from the gas phase. Since Fox *et al.* neither mention the material from which the chamber is made nor state the results of pertinent auxiliary experiments, the reader has no way of assessing the influence of the mechanism of heterogeneous decomposition upon the concentration of O_3.

The following approximate calculation, involving the model of a well-mixed chemical reaction with flow, demonstrates my main concern. In this case the mass balance for O_3 can be expressed as

$$V\frac{dc}{dt} = qc_{\text{in}} - qc + \sum_{i} \text{sources} - \sum_{j} \text{sinks}$$