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PRIMARY TASK EVENT-RELATED POTENTIALS RELATED TO DIFFERENT ASPECTS OF INFORMATION PROCESSING¹

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ABSTRACT

This paper reviews the results of two studies which investigated the relationships between cognitive processing and components of transient event-related potentials (ERPs) in a task in which mental workload was manipulated. The task involved the monitoring of an array of discrete readouts for values that went "out-of-bounds," and was somewhat analogous to tasks performed in cockpits. The ERPs elicited by the changing readouts varied with the number of readouts being monitored, the number of monitored readouts that were close to going out-of-bounds, and whether or not the change took a monitored readout out-of-bounds. Moreover, different regions of the waveform differentially reflected these effects. The results confirm the sensitivity of scalp-recorded ERPs to the cognitive processes affected by mental workload and suggest the possibility of extracting useful ERP indices of primary task performance in a wide range of man-machine settings.

INTRODUCTION

There is by now a vast literature relating scalp-recorded brain electrical activity to various cognitive processes. Other talks in this session have focused on studies which related behavioral performance to either steady-state evoked potentials, elicited by a rapidly oscillating stimulus, or probe evoked potentials, elicited by discrete stimuli that were irrelevant to the mental processing task the subject was given. In contrast, the data presented in this paper relate to the use of the transient evoked potential (or event-related potential, i.e. ERP) elicited by task-relevant stimuli. In particular, we examined the scalp-recorded responses to discrete visual stimuli that were presented in the context of a monitoring task as the mental workload of that task was systematically manipulated.

Most previous investigations that have addressed the relationship between ERPs and mental workload have focused on responses elicited in dual-task paradigms. Typically the waveshape of the ERP elicited by secondary task stimuli has been related to changing levels of difficulty of the primary task and has been interpreted as reflecting the spare cognitive capacity that remains after the demands of the primary task have been met. While the results of these studies have revealed important insights regarding the influence of cognitive processes on ERPs, it is not clear how widely applicable this methodology will be in evaluating the workload of human operators in real-world

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systems.

The secondary tasks used in most laboratory studies of mental workload have been relatively simplistic and contrived. They have been chosen for the convenience with which their stimuli elicit the responses of interest, whether physiological or behavioral. Although such tasks offer a conceptual similarity to operational systems in which human operators must time-share between tasks and process stimuli which compete for attention, they do not lend themselves readily to use in operational or simulated systems. In most operational systems in which mental workload is a concern, the operator is already over-burdened. To further burden him with contrived stimuli and tasks, in order to assess the workload of existing tasks, is impractical at best and invalid at worst. Even if certain existing tasks offer stimuli to which ERPs, and reaction times can be time-locked, it is unlikely that they will be functionally equivalent to the contrived secondary tasks used in the laboratory. Such "secondary" tasks will likely be performed in conjunction with differing configurations of other existing tasks, and it is difficult to ensure that these other "primary" tasks are given priority, as implicitly assumed if one is to interpret secondary task measures as reflecting spare cognitive capacity.

Because of these considerations, we examined ERPs that were elicited by stimuli presented in a single (primary) task as the difficulty of that task was varied. Workload-related effects obtained in such a paradigm would suggest the usefulness of ERP measures of cognition, both for systems in which processing resources can be devoted to a single task, as well as those in which the ERP-eliciting task must be time-shared with others. The present paper summarizes the results of two studies for which more detailed accounts of methods and results have already been published (refs 1, 2, 3). Our intent here is to discuss these studies, both the reasoning behind them and the interpretation of results, in terms of their implications for eventual applications in man-machine systems.

WORKLOAD EFFECTS ON TRANSIENT ERPS

Transient ERPs are usually extracted from the ongoing EEG by signal averaging over numerous occurrences of the eliciting stimulus. The ERP waveform is comprised of various "components", each having a characteristic scalp topography, latency range, and polarity. It is assumed that these components reflect the electrical activity from numerous generators within the brain, the activity of which overlaps in both space and time. For our purposes, it is not critical to understand the brain loci and generator mechanisms underlying these scalp-recorded components. Instead the focus is on how these components vary differentially with experimental manipulations and what these systematic variations suggest about the mental operations that these manipulations call into play. The components of most interest here are those which have been shown by previous work to be related, not to the physical characteristics of the stimuli to which an ERP was time-locked, but to the cognitive processing which was required by the task within which these stimuli were presented. Differential scalp topography and differential response to manipulations of the cognitive task are the primary means for disentangling the functional components of these waveforms.

Studies relating ERP components to mental workload grew out of previous findings which showed consistent attention-related effects on the amplitude of

the P300 component. P300s are elicited by stimuli that are attended (i.e. task relevant) and, in some sense, unpredictable (see e.g., reviews in refs 4, 5). The basic hypothesis underlying most studies of P300 and workload has been that P300 amplitude would be modulated by the amount of attention, or the amount of central processing resources, that could be devoted to processing the ERP-eliciting stimuli. Thus, in dual-task situations, when the attentional demands of the primary task are increased, there is less of the limited pool of attention that can be devoted to secondary task stimuli, and hence the amplitude of the P300 elicited by such secondary task stimuli should decrease. Much of this work has been performed by Donchin, Wickens, and their colleagues, at the University of Illinois (see review in ref. 5). In the early studies, tracking a computer-driven cursor was used as the primary task. The secondary task involved the presentation of discrete stimuli which required either an overt response to which choice reaction time was measured, or a covert updating of a running count of the occurrence of some subset of the stimuli.

The initial results were somewhat discouraging. The amplitude of the P300 elicited by low probability auditory stimuli in a counting task was markedly reduced when the counting was performed concurrently with a visual-motor tracking task; however, there were no further systematic decreases in the P300 amplitude as the difficulty of the tracking task was increased, either by requiring that tracking be performed in two dimensions (ref. 6) or by increasing the bandwidth of the cursor in a one-dimensional tracking task (ref. 7).

More encouraging results were obtained when the auditory counting task was time-shared with a visual monitoring task in which subjects detected directional changes in a simulated air traffic control display. In this situation, the P300 elicited by auditory stimuli decreased in amplitude as a function of the number of elements which subjects monitored (ref. 8). The interpretation of these findings was consistent with the viewpoint which was emerging from behavioral studies at the time (e.g., ref. 9) which posited that processing resources were segregated into multiple "pools." Thus P300 amplitude elicited by secondary task stimuli may have been modulated by the demands of the primary task when it involved visual monitoring, because the perceptual demands of these two tasks may have tapped the same pool of processing resources. On the other hand, the P300 amplitude elicited by secondary task auditory stimuli may not have reflected the workload dynamics of the tracking tasks, because the visual-motor demands of tracking tapped a different pool of resources.

Further evidence that P300 amplitude is related to available processing resources was sought by examining the reciprocity between the amplitudes of the P300 elicited in the context of primary versus secondary task stimuli in dual task paradigms. In order to elicit ERPs related to primary task processing, a task was developed which involved compensatory tracking with the cursor moving in discrete steps, rather than moving continuously as before. When subjects tracked these step changes in conjunction with a secondary task that consisted of counting occurrences of certain auditory stimuli, the amplitude of the P300 elicited by the secondary task stimuli decreased as the difficulty of the tracking task increased. However, when subjects were instructed to count occurrences of the cursor step changes in a given direction (i.e., the secondary task stimuli were "embedded" in the primary task), the P300 elicited by the step changes increased in amplitude as the tracking task was made more difficult (ref. 10).

These studies provided valuable insights into the way in which cognitive resources are allocated in complex tasks. In addition, they established P300 amplitude as a sensitive index of the amount of processing resources, in a sense the degree of attention, that is devoted to particular classes of stimuli in complex tasks. However, possible practical applications of these results are subject to the previously discussed limitations of secondary task methodologies. Granted, the fact that measures of attention allocation can be extracted from ERPs elicited by stimuli being covertly counted, offers the possibility of applying a secondary task methodology without the need to burden the subject with additional manual response requirements (ref. 5). However, even when the stimuli being counted are embedded in the primary task, as was the case when subjects counted step changes in a cursor being tracked (ref. 10), the cognitive demands of the counting task are superfluous to the otherwise existent task demands. The question addressed by the present work was to what extent ERPs elicited by stimuli in a single, complex task, as they are processed naturalistically, will reflect the cognitive workload demands of the situation.

THE PRESENT READOUT MONITORING TASK

We designed a laboratory task which provided discrete stimuli to elicit ERPs and allowed for the manipulation of mental workload, but yet was analogous, in many ways, to the types of monitoring activities which are performed in operational environments. The richness of this task afforded the opportunity to relate the waveforms elicited by similar physical stimuli to a variety of information-processing constructs, but without requiring subjects to concentrate on more than one task at a time. Our interest was in determining the extent to which graded effects on ERP amplitude as a function of mental workload could be observed within the context of this single task. Positive results will suggest the usefulness of ERPs as indicants of certain mental processes in any setting which offers the ability to time-lock recordings to a discrete eliciting stimulus, regardless of whether or not other tasks are being performed concurrently.

The Task. The subject's task was to monitor successive CRT displays of a circular array of six two-digit readouts. On each presentation of the display, termed a trial, one of the six readouts changed from its value on the previous trial. The values of the readouts changed, either increasing or decreasing, in large (30) or small (10) steps, within the range from 00 to 99. Large step changes were less frequent than small step changes. Presentations of the array of readouts lasted 500 msec and were separated by intervals which varied randomly from 1800 to 1900 msec.

Subjects were instructed to monitor a subset of the readouts to determine which of these readouts reached 90 or above or fell to 10 or below. Readouts which met or exceeded these target values were referred to as having gone "out-of-bounds." Workload was manipulated by instructing subjects to monitor one (low workload), two (medium workload), or three (high workload) of the six readouts. After passively monitoring a "run" of twenty trials, subjects reported the positions and sequence of occurrence of targets, i.e. attended readouts that went out-of-bounds. A given subset of readouts was designated as the targets for a sequence of six successive runs. The order of these workload conditions and the arrangement of the target readouts were counterbalanced.

In the first experiment, there was an equiprobable chance that each of the

six readouts would change on a given trial. Thus the probability of a monitored readout changing was dependent on the number of readouts being monitored. In the second experiment, monitored and non-monitored readouts changed with equiprobability, regardless of the number of readouts being monitored. Other details of the stimulus generation rules are presented in references 1, 2 and 3. A typical sequence of trials is shown in Figure 1. ERP recordings were obtained from an array of scalp electrodes with conventional methodologies (also detailed in references 1, 2, and 3).

Rationale. In the present monitoring task, the way in which the stimuli varied from observation to observation was different from the method used in most studies in the literature. Typically, the sequence of stimuli in ERP studies consists of a Bernoulli series; i.e., the particular stimulus presented on each trial is independent of that presented on previous trials. Our goal in designing the present experiments was to construct a monitoring task which called into play the same cognitive processes that are invoked in real-world monitoring tasks. In operational settings, the likelihood of a particular meter reading or display state is determined by those of the recent past; drastic changes from the last reading are less likely than relatively small changes; readings which require an overt response, e.g. because they reflect a system with some parameters "out-of-bounds," are preceded by readings in the "danger" zone.

In reflecting these features, the monitoring task used here was analogous to a wide variety of real-world challenges. A pilot's in-flight interaction with engine performance and environmental system displays or a process control operator's monitoring of plant status are fairly obvious examples of such circumstances. However, in terms of the cognitive processes invoked, the present task was also analogous, in perhaps less obvious ways, to other applied tasks. For example, an air traffic control display of planes moving about an airspace also presents information which, while not entirely predictable, is nevertheless dependent on trends. Monitoring such displays as planes move towards or away from "danger zones" and, at times, enter "out-of-bounds" conditions, such as impinging on another plane's circumscribed airspace, presents many of the same mental challenges as the present laboratory task.

This monitoring task afforded the opportunity to investigate a number of cognitive influences on ERPs. Selective attention effects on ERPs could be distinguished by comparing responses to changes in a readout being monitored as opposed to changes in a readout for which there was no such task requirement. Similarly, processing which specifically reflected the occurrence of a "target" stimulus, could be distinguished by comparing the responses elicited by attended readouts that went out-of-bounds to those elicited by attended readouts that stayed or went in-bounds, or those elicited by unattended readouts which changed in any manner. In addition, we were interested in the ERP effects related to both "tonic" changes in information processing workload, imposed by the number of readouts being monitored throughout a run of trials, and the more "phasic," dynamic influences imposed by the number of attended readouts that were close to, i.e. in "danger" of going out-of-bounds.

It is interesting to consider how the pattern of effects related to these variables, aside from demonstrating the sensitivity of ERPs to these cognitive influences, can reveal specific aspects of subjects' performance in the task. For example, the extent to which the ERPs reflect the influence of attention, the differences between targets and non-targets, or effects related to number

of monitored readouts that are "in danger" might change with the level of "tonic" workload. Will the need to monitor more readouts cause a focusing of attention, and thus perhaps greater differences between responses to monitored and non-monitored readouts? Might increasing task demands cause target stimuli to be processed differently? Might the number of readouts "in danger" be more readily noticed when workload is high, because this information could be used by the subject to distinguish which of the readouts being monitored are most likely to become targets in the near future, or will this information be disregarded when workload is high, due to the fact that there are fewer central processing resources available to devote to this additional processing?

FINDINGS

There were several aspects of the averaged ERP waveforms obtained here which showed systematic variations in response to one or more of the factors of interest. These features were designated and quantified as follows: 1) the "peak positivity" (the mean amplitude over a 200 msec epoch centered about the most positive peak between 500 and 900 msec post-stimulus onset); 2) the "slow positivity" (the mean amplitude between 900 and 1050 msec post-stimulus onset); 3) the N250 (the mean amplitude between 200 and 300 msec post-stimulus onset); and 4) the N450 (the mean amplitude between 400-500 msec post-stimulus onset). Although ERP waveshapes were generally similar across subjects, there was considerable inter-subject variability in the latency of the peak positivity. These measurement epochs were selected after inspection of across-subject, grand-average waveforms and were chosen to accommodate the systematic differences in the waveforms despite this latency variability. All of the effects discussed here were statistically significant (see refs 1, 2, and 3 for details) and were consistent between the two experiments, unless otherwise noted.

Figure 2 presents across-subject grand-average waveforms from Experiment 1 obtained from the Cz electrode. The waveforms in the two rows were sorted depending on whether they were elicited by changes in readouts being monitored or by changes in non-monitored readouts. The responses to changes that took a readout out-of-bounds are superimposed on the responses to changes that took or left a readout in-bounds. The differences among responses as a function of tonic workload can be ascertained by comparing the waveforms across columns, which present the ERPs elicited when one, two or three readouts are being monitored. The waveforms elicited by target stimuli, that is, monitored readouts that moved out-of-bounds, are presented as the dashed and dot-dashed traces in this figure.

Figure 3 presents a somewhat similar breakdown, but different layout, of the comparable data from Experiment 2. Here, the ERPs elicited under the low and high workload conditions are superimposed. In the different rows are responses recorded from different electrodes, moving from back to front of the head along the mid-line for waveforms going down the page. In the different columns are the responses elicited by changes in monitored and non-monitored readouts, both changes that took the readout out-of-bounds and those which took or left the readout in-bounds. Responses to target stimuli here are shown in the right-most column.

One other view of these data proved revealing. In Figure 4 are presented difference waveforms calculated by subtracting the ERPs obtained under the low workload condition (one readout being monitored) from those obtained under the

high workload condition (three readouts being monitored). The layout of these waveforms across the other conditions corresponds to that in Figure 3.

Target Effects. As is apparent in Figures 2 and 3, there were pronounced differences between the ERPs elicited on target trials and those elicited on non-target trials. First, responses elicited by monitored readouts as they went out-of-bounds had a much larger peak positivity than either changes in the monitored readouts that did not take the readout out-of-bounds or changes of any kind in non-monitored readouts. This effect was limited to the region of the peak positivity and probably reflects a modulation of P300 amplitude that has been reported numerous times in the past (e.g., refs 11 and 12). Interestingly, this aspect of the response to targets was present to the same extent no matter what the workload.

Second, there was an additional target effect, this one related to workload, that was evident in the difference waveforms. Figure 4 shows a negative-going wave in the 400-500 msec latency region that was present only when the responses to target stimuli elicited under low workload were subtracted from the responses to target stimuli elicited under high workload. Whether this waveform component should be seen as a negativity that enters in as the result of increased workload or a positivity that enters in as workload is reduced, cannot be resolved. However, the present results provide strong evidence that the workload manipulation added or enhanced a new component in the waveform, rather than simply modulating a peak, or peaks, that were otherwise there. Peaks in a difference waveform that are due to either increases or decreases in amplitude, or to shifts in latency, of peaks that are evident in the raw average waveforms, should have the same scalp distributions as those raw average peaks. Instead, Figure 4 indicates that the ERP peak in the 400-500 msec region of the difference waveforms had a more posterior distribution than either of the peaks in this vicinity of the raw average waveforms seen in Figure 3. This impression was confirmed by statistically showing that the profile of amplitudes across the scalp in this time region was different for the raw average waveforms elicited under low workload than for those elicited under high workload (ref. 3). Past references to endogenous ERP negativities in this latency region (e.g., ref. 13) provide a preliminary basis for interpreting this effect as an N450 component that is enhanced as the result of increased workload.

Selective Attention Effects. As can be seen in Figures 2 and 3, there was, at least at the low workload levels, a systematic difference between the ERPs elicited by changes in monitored and non-monitored readouts. The amplitude of the peak positivity was larger in response to changes in monitored readouts as compared to changes in non-monitored readouts. This difference is best seen by comparing the responses elicited by in-bounds changes in the monitored and non-monitored readouts. Interestingly, the attention-related effect diminished with increasing workload, apparently due more to increasing peak positivities in the responses elicited by non-monitored readouts than to those elicited by monitored readouts. This same pattern of results was found in Experiment 2, when changes in monitored and non-monitored readouts occurred with equal probabilities, and in Experiment 1, when probabilities varied with the number of readouts being monitored. The differences between ERPs elicited by monitored and non-monitored readouts at low workload may be related to selective attention differences that have been interpreted as reflecting the activation of different sensory channels (refs. 14, 15); however, the polarity and timing of this effect, and its modulation by workload, is difficult to

interpret. Further investigation of this effect is needed.

Tonic Workload Effects. Of primary concern in these data was whether there were differences in the ERP as a function of the level of workload imposed by requiring subjects to monitor different numbers of readouts. Two interactions with workload have already been noted -- with increasing workload, an N450 component emerged in the responses to target stimuli and the peak positivity increased in the responses to all changes in non-monitored readouts. In addition, two main effects of the tonic workload manipulation are evident in Figures 2, 3 and 4. First, as the subject was required to monitor an increasing number of readouts, the ERPs elicited by all stimuli showed an increased slow positivity. This slow positivity was manifest in the latency region following the peak positivity (note that the waveforms in Figure 2, which were derived from Experiment 1, span a shorter epoch than the waveforms in Figures 3 and 4, which were derived from Experiment 2) and can be seen as a slow return to baseline, but with a more posterior scalp distribution than the peak positivity itself. It is likely, although not entirely clear, that this slow positivity is the Slow Wave component which has been distinguished from the P300 on the basis of both scalp distribution and relationship to experimental manipulations (e.g., ref. 16).

A second main effect of tonic workload was apparent in the difference waveforms. When responses to readout changes from the low workload condition were subtracted from the corresponding responses from the high workload condition (Figure 4), a negative-going peak appeared in the 200-300 msec latency region. This N250 occurred in the responses to both changes in monitored and non-monitored readouts, regardless of whether these changes took the readout out-of-bounds or took or left it in-bounds. As with the N450, which was only present in the responses to target stimuli, we interpreted this effect as a negative-going component which entered or was enhanced as the result of increasing workload. This interpretation was based on the fact that the scalp distribution of this wave differed from that of the corresponding activity in the raw average waveforms and the fact that processing negativities related to selective attention have been reported in this latency region of ERP waveforms (ref. 17). Statistical tests confirmed that the amplitude profile across the scalp in the 200-300 msec latency region differed between the low and high workload conditions. To our knowledge, this workload-related effect had not been reported prior to our paper (ref. 3).

It is possible that the standing requirement to monitor a given number of readouts for minutes at a time may have caused differential DC-shifts in the EEG. The transient ERPs elicited by readout changes might then have been superimposed on different baselines, and the apparent main effects of workload on post-stimulus ERP components could have resulted from a confound of, or interaction with such differential baselines. To determine whether or not such differential pre-stimulus activity could have influenced the present findings, we did the recordings for Experiment 2 in a manner which allowed us to quantify the DC level of the pre-stimulus baselines. There were no systematic differences in the pre-stimulus baselines of the ERPs elicited under different workload conditions.

Phasic Effects of the Number of Readouts in Danger. As mentioned previously, the specific value of the readout presented on a given trial was dependent on its value on the previous trials; namely, it increased or decreased by a large or small increment from its value on the previous trial. Therefore, at any

given time, only those readouts that were within a large increment of going out-of-bounds were "in danger" of becoming targets on the next presentation. Although it was not part of the subject's defined task to attend to this aspect of the situation, and no mention was made of it in the instructions, subjects could have facilitated their performance on the task by attending to this information. Therefore, we sorted the ERPs that were elicited with different numbers of readouts "in danger," to see if the waveforms showed evidence of this factor having influenced the processing of the readouts.

Figure 5 presents the data from Cz for Experiment 1 with the responses superimposed that were elicited when 0, 1 or 2 monitored readouts were "in danger." In the two rows of waveforms are presented the ERPs elicited by monitored and non-monitored readouts. In the three columns within each half of the figure are presented the data as a function of the number of readouts being monitored -- i.e., level of tonic workload. These waveforms showed an enhanced positivity in the long latency regions with increasing numbers of monitored readouts in danger. Statistical tests (see ref. 2) confirmed this effect on the peak positivity, with the slow positivity showing the same trend but not reaching statistical significance. This increased positivity was present in both the responses to monitored and non-monitored readouts and was found to the same extent at all levels of tonic workload. When the waveforms were sorted according to the number of non-monitored readouts in danger, no systematic ERP differences were found.

These data clearly suggest that subjects processed the readouts differently depending on the number of monitored readouts that were close to going out-of-bounds, even though they were not explicitly instructed to do so. It is not clear whether this differential processing should be seen as an additional, albeit self-imposed, workload demand of the task, or whether subject's chose to assume this additional processing as a means of coping with the primary task of detecting target readouts. A number of further manipulations are necessary in order to arrive at a convincing interpretation of this effect. However, the fact that this effect occurred, suggests the value of looking more closely at subjects' strategies when dealing with non-Bernoulli sequences of stimuli.

DISCUSSION

Obviously, the monitoring task that we designed provided a rich environment for eliciting cognition-related effects on scalp-recorded ERPs. To summarize, we found:

1. An N250 wave, possibly a Processing Negativity (e.g., ref. 17), that emerged with increasing workload, in the responses to all readouts
2. An N450 wave, possibly related to the N2 complex (e.g., ref. 13), that emerged with increasing workload, in responses to the target stimuli only
3. A peak positivity, probably related to the P300 (e.g., ref. 5), which dramatically increased in amplitude when a target stimulus occurred, increased in amplitude as a function of the number of monitored readouts "in danger," and showed an interaction with tonic workload and selective attention, such that the differences between responses to monitored and non-monitored readouts which were found at low workload levels diminished with the requirement to monitor more readouts.
4. A slow positivity, possibly related to the Slow Wave (ref. 16), which increased in amplitude with workload, in the responses to all readouts.

More work is required to determine the functional significance of the waveform changes we observed and to relate them convincingly to ERP components that have been identified in other paradigms. Nevertheless, the present findings warrant several important general conclusions. Workload-related ERP effects can be derived in single task paradigms without burdening the subject with competing task demands, the effects of different cognitive variables are specific to circumscribed regions of the waveforms, and some regions of the waveforms are affected by multiple information-processing manipulations. These relationships confirm the exquisite sensitivity of scalp-recorded ERPs to the cognitive milieu in demanding tasks and suggest the possibility of eventually indexing specific cognitive processes with specific waveform components or with the activity in specific latency regions of ERPs.

It is interesting to note, however, that even prior to attaining a thorough understanding of the functional significance of specific ERP components, one can infer, from the pattern of results, a number of indications about how subjects performed the present task. Consider the fact that changes in monitored readouts that went out-of-bounds (i.e. targets) elicited a markedly different response from changes in monitored readouts that stayed in-bounds, whereas responses to changes in non-monitored readouts did not distinguish between in-bounds and out-of-bounds changes. These results suggest that subjects did indeed selectively attend to the readout positions that they were instructed to monitor. Likewise, the fact that the ERPs showed a significant effect related to the number of monitored readouts "in danger," but no effect of the number of non-monitored readouts "in danger," suggests that subjects noticed the former but not the latter. Both of these findings are consistent with the conclusion that subjects did not process the value of non-monitored readouts despite the fact that only one readout changed on a given presentation and subjects did not know whether a monitored or non-monitored readout was about to change.

On the other hand, this conclusion must be reconciled with the fact that both the workload effect on the N250 and slow positivity, and the effect of number of monitored readouts "in danger" on the peak positivity, were found in the responses to changes in both monitored and non-monitored readouts. This finding suggests that these ERP effects reflect differential processing due to the distributing of attention among the readouts being monitored, and that this processing, in essence, is related to determining which readout changed, rather than to determining the specific value of the readout that changed. Therefore, the present ERP results can be used to infer that subjects selectively attended to the readouts that they were to monitor, that they noticed the number of monitored readouts that were "in danger" of going out-of-bounds, and that workload modified some aspects of the processing of all stimuli, whether monitored or not.

Such information would be useful to know in a number of practical applications. Design issues such as configuring display formats which minimize workload, maximizing the effectiveness of warning messages, and increasing the salience of task-critical information often hinge on reliable measures of which stimuli are being attended, whether extraneous information is intrusive, whether subjects are taking advantage of useful information that is available, and which of several alternative designs entail less mental workload. The present results point towards the possibility of using ERPs to address such issues, in situations where one can not rely on, or it is difficult to acquire, subjective and behavioral measures. Moreover, in addition to playing a

confirmatory or surrogate role, ERPs may serve a diagnostic function. When overt performance has been observed to fail, one may be able to glean information from ERP effects like those obtained here in order to indicate the particular aspects of information-processing, and by inference the particular aspects of system design, that were deficient. Beyond the design arena, such ERP measures may also be helpful for monitoring the progress of training on demanding tasks or for selecting personnel who are particularly capable of functioning in various tasks.

Of course, many of the ERP effects obtained here were small and required extensive data analysis based on average waveforms. For some engineering applications, one would have the luxury of collecting as much data and analyzing it to the extent that we did here, but in other applications one would be more constrained. Nonetheless, the present results may point the way towards other manipulations or measures that would better emphasize the effects of interest. It will be interesting to see, as studies like the present ones are recast in the operational systems or simulators whose task demands have been approximated in the laboratory, to what extent the cognitive-related patterns of ERP results become more pronounced.

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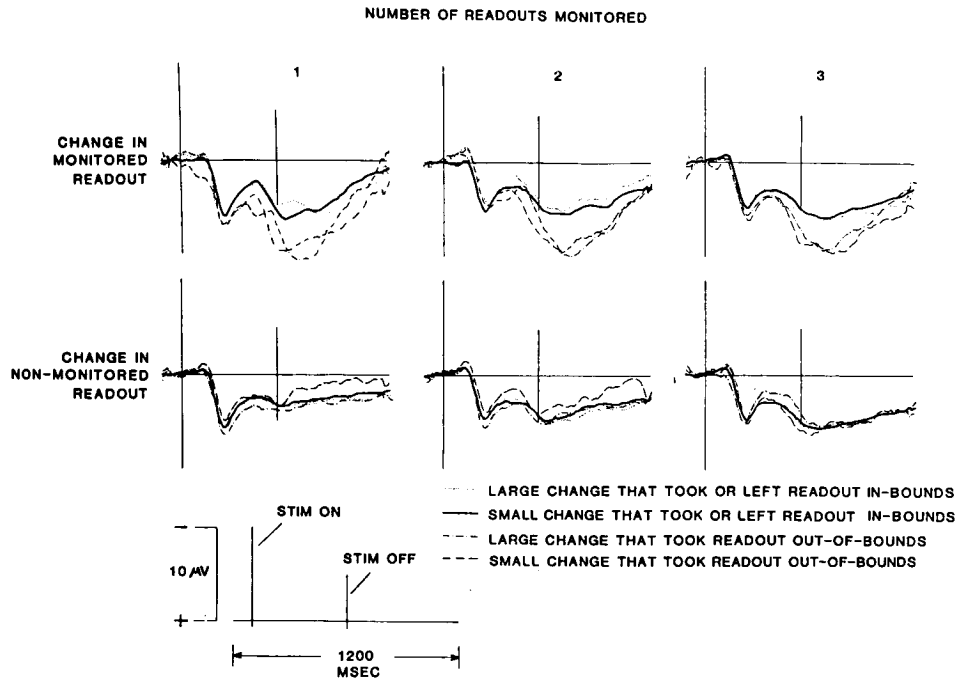


Figure 2 — Across-subject average waveforms from Experiment 1 at Cz, with responses to changes that took a readout "out-of-bounds" superimposed on responses that took or left a readout "in-bounds." Responses are sorted according to whether the eliciting change occurred in a monitored or non-monitored readout and according to the number of readouts being monitored (tonic workload).

C-3

Raw Average Waveforms

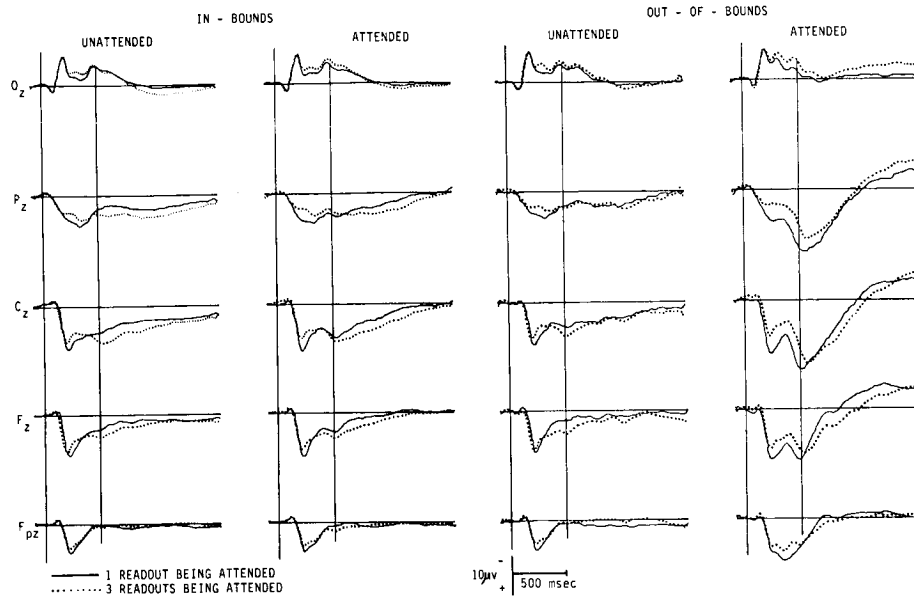


Figure 3 — Across-subject average waveforms from Experiment 2 at a range of mid-line scalp sites. Responses elicited under low workload (one readout being monitored) are superimposed on those elicited under high workload (three readouts being monitored). Responses are sorted according to whether the eliciting change occurred in a monitored or non-monitored readout and whether or not the eliciting change took the readout out-of-bounds. (Reprinted from Ref. 3)

Difference Waveforms

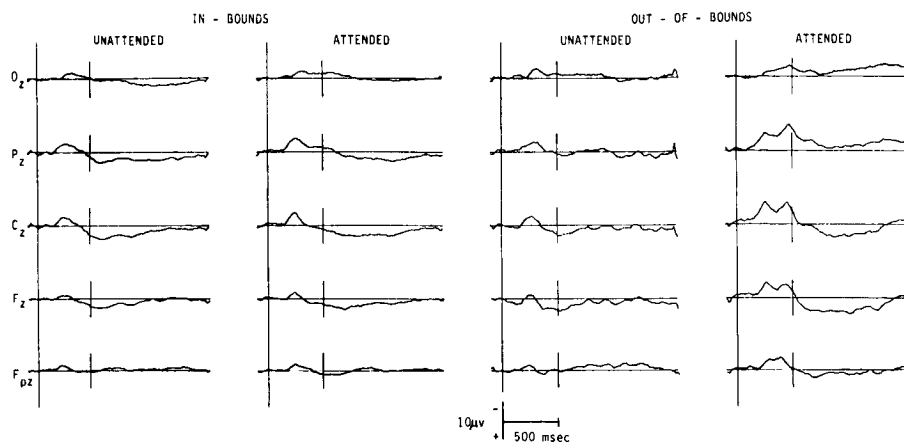


Figure 4 — Difference waveforms corresponding to the data in Figure 3, with the responses elicited under low workload subtracted from the responses elicited under high workload. (Reprinted from Ref. 3)

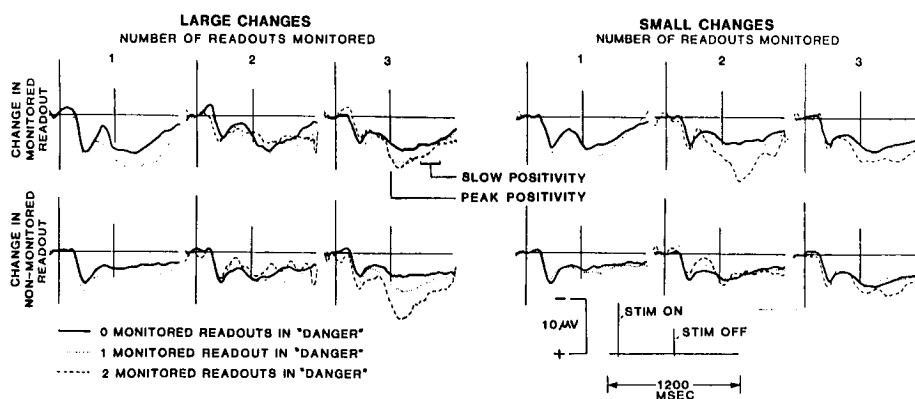


Figure 5 — Across-subject average waveforms from Experiment 1 at Cz, with responses elicited when different numbers of monitored readouts were "in danger," i.e., within an incremental value of going "out-of-bounds." The responses are sorted according to whether the eliciting change occurred in a monitored or non-monitored readout, the number of readouts being monitored at the time, and whether the eliciting change was a large or small increment. (Reprinted from Ref. 2)