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AUTHOR	Wiener, E. L.
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ABSTRACT

Research investigated the utility of an alternative technique for the study of vigilance performance. The usual approach has been to study how well subjects responded to a signal of given difficulty; this technique altered the difficulty of the task to ensure a fixed level of performance. A computer-based, self-adjusting program presented background stimuli--a pair of dots 4.25 inches apart displayed on a cathode ray tube--and special stimuli--a pair of dots with wider spacing. The amount by which the latter width exceeded 4.25 inches was raised if subjects failed to discriminate it and lowered as they succeeded, to maintain a fixed discrimination rate. Results indicated that the adaptive variable behaved in a manner consistent with the usual measures of vigilance decrement--i.e., that vigilance dropped sharply at first and then levelled off. Thus, increased widths for the special stimuli were required over time. It was concluded that this technique could be used as a research tool in vigilance studies and that it has practical applications for the training of human monitors of equipment in military, industrial, health and computer fields. (Author/PB)

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Adaptive Measurement of Vigilance Decrement

By E. L. WIENER

University of Miami, P.O. Box 8294, Coral Gables, Florida, U.S.A.

This paper describes a computer-based monitoring task which is adaptive, or self-adjusting, with the size of the signal stimulus (compared to a fixed non-signal stimulus) being mediated by the detection score of the subject, so as to maintain a constant detection rate. Data are presented which indicate that in order to maintain a fixed detection criterion over a 48-min vigil, the adaptive variable (separation distance of a pair of dots presented simultaneously) behaved in a manner consistent with the usual measures of vigilance decrement. Several adaptive strategies are discussed.

1. Introduction

In the classical vigilance task, subjects are presented occasional signals, stimuli which are abnormal along some dimension compared to a train of normal stimuli, or a blank display. The usual performance measure is whether the subjects respond to the signal or not, though reaction time is used by some experimenters and commissive errors (false alarms) may also be recorded. This paper suggests an alternative technique for the study of vigilance performance, particularly the familiar time decrement reported by Mackworth (1950) and innumerable other authors.

Adaptive, or self-adjusting, tasks are those in which some aspect of the task, usually its difficulty level, is mediated by some measure of quality of task performance in such a way that as the subject masters the task to a preset criterion the task is made more difficult. If his performance drops below some specified lower limit, the task is made easier. Thus the task is essentially a closed-loop control system which is performance-adjusted. In this study we have followed essentially the logic advocated by Kelley (1969), wherein adjustments in task difficulty are made so as to ensure a fixed level of system performance: thus the measure of proficiency at any given time is not the output of the system, but the difficulty level at which it is operating.

Specifically in the vigilance task employed here the difficulty level of the task, or ' adaptive variable ' to use Kelley's terminology, was the extent to which the signal was larger than the background, or normal, stimulus. This was mediated by the hit rate of the subject—as his detection performance increased beyond a preset upper limit the difference between the signal and the non-signal was decreased, and a contrary adjustment was made when his performance descended below the lower limit. The adaptive logic for making these adjustments will be described in detail shortly. If results using this technique were consistent with most monitoring studies, vigilance decrement would be observed as an increasing signal size, necessary to maintain a fixed detection rate, as the vigil progressed. Such a procedure could be employed manually, with an experimenter keeping track of the performance scores, adjusting the size of the next signal according to some set of decision rules, and recording the setting. Experimenter error under such a heavy workload would seem very likely, especially if more than one subject were run simultaneously. Experiments using adaptive techniques have been made practical by the appearance of small, stored-program digital computers.

At this point it may be worthwhile to review the difference between vigilance tasks and traditional psychophysical methods, as the technique described above may sound very much like the up-and-down method of threshold determination (Kappauf 1969). The essential difference is in the effect of time. In psychophysical measurement the subject is highly alert and expects the presentation of a signal upon which he will pass judgement. In vigilance, the subject awaits a signal which he may or may not detect when it is presented. But in any psychophysical sense the signal is very much above threshold—that is, if he were alerted and were presented with a two-alternative, forced choice of signal and non-signal his discrimination would be correct every time. Thus, in vigilance studies, the subject fails to detect a signal for reasons which authors of various theoretical persuasions would dispute, but certainly not because the signal is psychophysically indistinguishable to an alerted operator.

The adaptive technique as reported here must also not be confused with vigilance experiments in which the signal strength (or effective threshold) was increased until the subject responded, as in the studies of Elliott (1957) and Adams (1956). These would more resemble the ' up ' portion of the up-and-down method. Signal magnitude in these cases was mediated only by the subject's failure to respond to the presently displayed signal, not his scored past performance.

Since we believe this to be a first attempt to use adaptive techniques in vigilance, and since as Kelley and others point out (see McGrath and Harris 1971) that these techniques are still very much of an art and not a science, we will share with the reader some of our early, unsuccessful attempts, on the road to what we consider a successful self-adjusting task.

2. Method

2.1. *The Basic Vigilance Task*

The entire experiment was run under the control of a Digital Equipment Corporation PDP-12 computer. This included the scheduling and timing of stimuli, signal and non-signal stimulus generation, and response recording and scoring, as well as adaptive adjustments. Subjects viewed a 6·5 by 9 in. cathode ray tube display located at the end of a table approximately 4 ft from their seated position at approximately 12 in. below eye level. Once every second a stimulus consisting of two dots appeared on the scope at mid-scope vertically but separated horizontally by 4·25 in. symmetrical about the centre of the scope. The dots were illuminated for the first 0·15 sec of each sec. The signal was a presentation of two dots slightly more separated horizontally. The adaptive variable was the width (W) or separation of these two signal dots. The two non-signal dots were always displayed in the same location. Thus the subject viewed a steady train of brief flashes of two horizontally separated dots, with an occasional presentation of two dots slightly further separated. The task resembles somewhat that used by Jerison and Pickett (1964).

The horizontal position of the stimulus dots was determined by setting a digital value into a register. When a display instruction was encountered in the timing loop, this value was converted to an analog voltage determining its actual position on the scope. The horizontal widt of the scope was 512 points. The width of the signal will be expressed from this point on in terms of these points, with 1 in. equal to 60 points. The non-signal value of W (4·25 in.) was 256. The reader familiar with computers of this type will be accustomed to expressing scope positions in octal notation (the total scope width being 000 to 777 octal), but for clarity and statistical analysis, all scope values in this paper are expressed in decimal.

2.2. *Signal Schedule*

The signal schedule was the same as that previously used by the author (Wiener 1968), a 48-min run with 32 signals randomly inserted during the run, with the restriction that eight signals occurred during each 12-min block, and no two signals occurred closer than 0.3 min apart. With these constraints, the inter-signal intervals were drawn from a random uniform distribution with a mean of 1.5 min.

2.3. *Initial Calibration*

As this display had not been employed before, the author having previously used a voltmeter display, initial calibration runs were performed to find a suitable signal value of W. With the non-signal W set at 256, various larger values of W were tried until a satisfactory value was determined; this being 316 (5·25 in.). This was considered acceptable in the sense that it yielded mean detection rates under fixed, non-adaptive 48-min runs which were consistent with previous work done by the author: approximately 80% in the first 12-min block, with rapid decreases to below 60% in the final block. The signal/non-signal relationship could be described in terms of Weber's function,

$$\frac{\Delta I}{I} = \frac{316-256}{256}, \text{ or } 0{\cdot}23$$

2.4. *Subjects*

Subjects were undergraduate students in elementary psychology classes. They were recruited by posted ' signup ' sheets and were not screened, except to exclude anyone who had previously served in the experiment.

2.5. *Non-Adaptive Procedure*

After initial calibration, a new group of 21 subjects was run under non-adaptive conditions to establish baseline data, with the signal value of 316. Two subjects were run simultaneously in separate booths. Each had his own scope which was independently programmable, though under non-adaptive conditions the stimuli displayed to the two subjects were identical throughout. Subjects were seated in their booths, the computer started so that a train of non-signals was presented as tape-recorded instructions were read to the subjects. After the basic task was explained, six signals, appearing as every 10th stimulus, were displayed. The experimenter asked each subject to point out at least one signal to be sure that the instructions were understood and the signals were clearly discriminable. No problem occurred with this. At the end of these signals further taped instructions cautioned the subjects that the signals would be less frequent, and would be irregularly spaced during the actual run. The subjects had an opportunity to ask questions (there were seldom any) and the computer was halted and restarted for the beginning of the run. No knowledge of results was offered, other than the confirmation during the instructions that the subject had correctly pointed out a signal to the experimenter. Subjects had their watches removed. Subjects responded by pressing a normally open push-button switch mounted in front of them on their table. They had 2·5 secs in which to respond, and could thus observe up to two more non-signals before responding. Any response not preceded within 2·5 secs by a signal was counted as a commissive error.

2.6. *Adaptive Procedure*

The procedure for running adaptive subjects was identical to the non-adaptive, except that one additional sentence in the instructions pointed out that the width of the signal pair of dots might vary, but would always be larger than the non-signal pairs.

2.7. *Adaptive Control*

In an experiment of this type a huge variety of adaptive schemes would be possible. First there is the question of how often to adapt—before each signal, or each *K* signals. Next there is the measure of performance to be used for determining the adaptation, and finally, the logic, a set of decision rules, by which the adjustment is made to *W* as a function of the performance measure. Guidelines for selecting the adaptive strategy are given by various authors (see Kelley and Kelley 1970), but each task is novel, and one is at a loss to come up with ready answers on adaptive logic (McGrath and Harris 1971). Therefore we groped our way through a series of adaptive strategies with pilot subjects until developing what we considered a satisfactory program. We now shall briefly describe four of the strategies.

The general routine followed in all programs is shown in the flowchart in Figure 1. Prior to the presentation of each signal, the program tested whether it would be an ' adaptive signal ', that is one on which an adjustment might be made. For example, in the final version every odd-numbered signal (except the first) was an adaptive signal. Depending on the subjects' immediate past performance an adjustment might be made on the value of *W* prior to the presentation of an odd-numbered signal. The next signal to appear would not be adaptive: it would be displayed at the same value of *W* as the last. Recall that the two subjects' displays were independent; each might have a different value of *W*, beginning with the first adaptive signal.

Thus, as the flowchart illustrates, prior to the time the next signal in the schedule is to be delivered, the program first determines whether it is a signal on which an adjustment might be made. If not, the entire adaptive process is bypassed. If it is an adaptive signal, the program then tests whether or not an adjustment is warranted by each subject's score, and if so, the adjustment is made in signal magnitude (*W*) before the signal is displayed.

One further check was performed to be sure that the limits of the scope and the task were not exceeded. If adaptation to a larger *W* (easier task) were called for, a check was made that *W* would not exceed the scope limits. If the

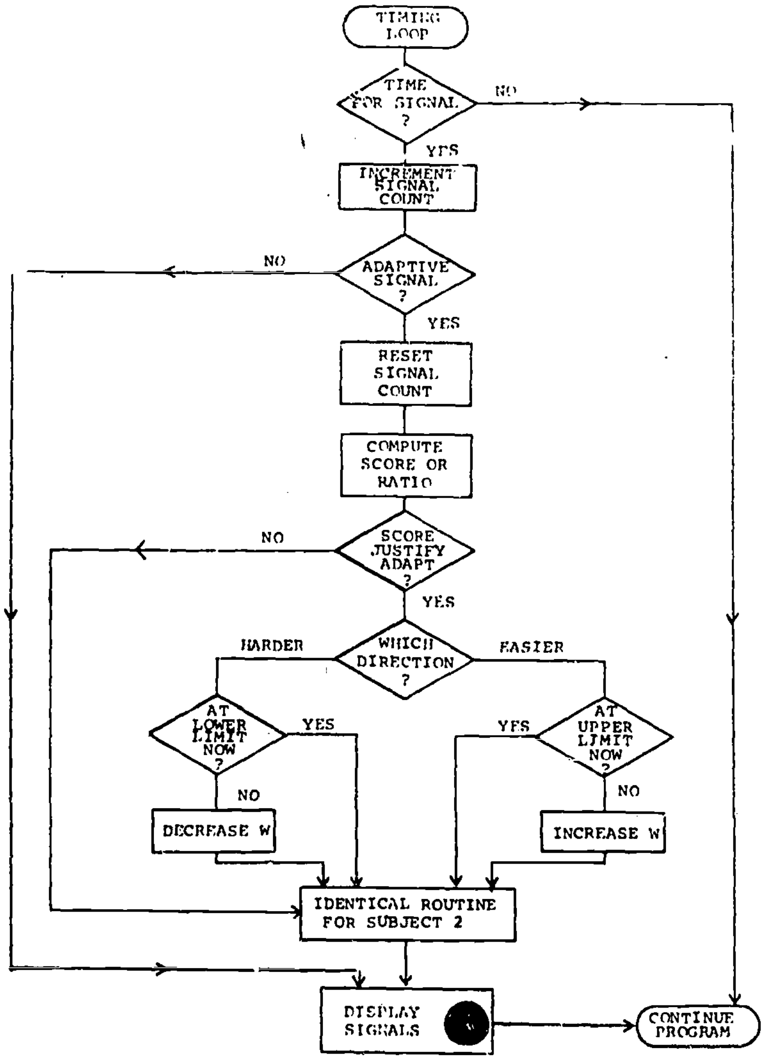

Figure 1. Flow chart of portion of computer program for adaptive adjustment of signal size. The lower portion is repeated for Subject 2.

subject were performing so badly as to be at the outer limit, *W* simply remained at that value until his score improved to the point where an inward adjustment was required. Similarly, a check was made on the lower limit, so that the signal *W* could not become reduced to a level that was not at least four points larger than the non-signal *W*. Having passed all of these tests, adaptation by an amount Δ being added to, in the case of low performance, or being subtracted from, in the case of a high score, the previous value of *W*. This value signal was then displayed.

2.8. *The Adaptive Strategies*

The first program, ADAPT-1, was a fast-adapting system. Prior to each odd-numbered signal (except the first), the score on the previous two was noted. If the subject had scored two detections, *W* was decreased (usually five points), and if no detections, W was increased the same amount. For a score of one out of two detections, there was no change in W. According to Kelley, this would result in an oscillating value of W, with hit rates stabilized near 50%. In practice, it worked very poorly, with very low detection rates, resulting in continual increases in W, but failure to bring the hit rate up. We believe this strategy scored too small a sample of past performance.

In ADAPT-2 we attempted to take a larger sample on which to base the performance measure, and to adjust with a Δ which varied with the score. This time the adaptive signal followed each four signals (number 5, 9, etc.), the score being the number of signals detected out of the previous four. For detection scores of 4 out of 4, W decreased; for 3, remained the same; for 2, 1 and 0, increased by various amounts, with a rather sizable increase for 0 hits. This program was also quite unsuccessful. causing severe oscillations, though an improved control of the hit rate. The basic problem with this scheme was that adaptation was too slow, with only seven opportunities for adjustments. The use of a variety of values of Δ related to the score, rather than just a single plus-and-minus value, still has some allure, and may be investigated later, but at this point we abandoned the procedure.

ADAPT-3 was designed to utilize the entire detection history as a performance measure, in hopes of locking in on a predetermined detection rate. Again the adaptive signal was every odd one, and the score was the total percentage of signals detected to date. A register counted the number of signals delivered to date, and a register for each subject counted his number of hits. Before each adaptive signal, the ratio was computed, and W was decreased if the ratio exceeded the upper limit (75%); if the ratio equaled or was less than the lower limit (70%), W was increased. Otherwise no adjustment was made.

This program was very nearly satisfactory, in that there was no large oscillations in W, but it contained one defect. In some cases subjects might have a run of missed signals, and soon develop ratios that were so low there was no possible recovery during the run. W continued to increase, and in many cases subjects responded to the signals, but could not pull their scores above the 75% upper adjustment threshold, so W remained stationary or continued downward, even in the face of high recent scores. We might mention in passing that though ADAPT-3 was considered unsatisfactory as an experimental program even its flaw represents a class of real-world adaptive systems: those with long lags in which an operator gets off to a bad start, and in spite of adjustive mechanisms which cause his performance to improve, can never recover. The author is struck by the parallel to the engineering student who does poorly in difficult courses early in his career, finds himself with an unsatisfactory grade point average and threat of suspension, and then makes an adaptive adjustment by taking easier courses to 'pull his average up'. But often he is so far down by the time he adapts that the best he can do is approach a satisfactory average asymptotically from below. There are probably many other adaptive systems which contain this quirk.

ADAPT-4 modified the previous program by evaluating only the last eight signals. The first eight were scored as in ADAPT-3, but after the eighth signal, the score was measured by looking at the hit ratio only of the last eight presented. Thus all earlier performance was expunged and the subject's mastery was determined from a recent history of performance, overcoming the previous defect. Since the same limits were used, W increased if fewer than six out of the last eight signals were detected, and decreased if seven or eight were detected, with no change in the case of six detections. Again the adaptive signal was every odd one, and Δ was [redacted]. 16. A group of 13 subjects was run under this strategy.

3. Results

3.1. *Non-Adaptive Performance*

The non-adaptive or fixed W group represents a typical vigilance task. The data recorded were detections, expressed in Figure 2 in terms of percentages, and commissive errors, recorded by 12-min blocks. This figure displays what

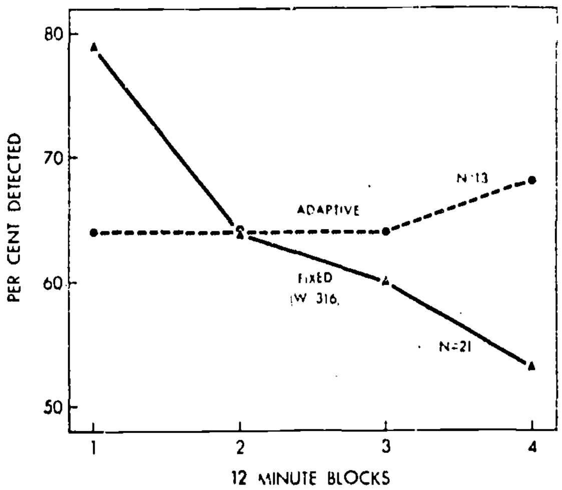

Figure 2. Percent signals detected by non-adaptive and adaptive groups.

is generally regarded as the typical vigilance decrement function, with the most rapid drop in detection rate occurring early in the vigil. Statistical analysis of these data seems unnecessary. The number of commissive errors by time blocks is shown in Table 1. As the author has written before (Wiener 1967), the distribution of commissive errors by subjects is highly positively skewed, with most subjects making few such errors, and a small number of subjects contributing heavily to the total. There remains the

Table 1. Commissive errors by time blocks

	Block				
Fixed	1	2	3	4	Total
Errors	258	178	168	160	764
No. > Md.	8	5	5	5	
No. ≤ Md.	5	8	8	8	
Cell Md. = 2, $\chi^2 = 2{\cdot}1$					
Adaptive					
Errors	208	179	118	103	608
No. > Md.	14	9	7	8	
No. ≤ Md.	7	12	14	13	
Cell Md. = 1, $\chi^2 = 5{\cdot}6$					

interesting question of whether the subjects who made large numbers of commissive errors have high detection rates: that is, do they simply have a relaxed criterion for responding which allows them to detect more signals at the cost of more false alarms, as statistical decision theory predicts. To examine this, we have computed the median number of commissive errors per subject (15) and the median number of hits per subject (19), and tallied the frequency of subjects whose total places them above or below each median, casting these frequencies into a 2-by-2 contingency table (Table 2). A χ^2 test for row and column independence yields a value, corrected for continuity, of 0·4,

Table 2. Frequency count of subjects above and below the median on detections and commissive errors. Fixed *W* group

	Detections No. < Md.	Detections No. > Md.
Commissive Errors		
No. ≤ Md.	4	7
No. > Md.	6	4

Md. Detections = 19
Md. Commissive errors = 15
$\chi^2 = 0{\cdot}41$

which is non-significant. Indeed, the table indicates that a preponderance of those with high false alarm scores had low detection scores, and vice versa. Another median test was performed on commissive errors across time blocks, by tallying the number of subjects in each time block above and below or equal to the cell (subject-by-block) median, which was two. This analysis resulted in a χ^2 of 2·1 with df = 3, a non-significant value. This median test is also summarized in Table 1.

3.2. *Adaptive Performance*

The performance of the adaptive group, expressed in terms of mean, the width of the signal stimulus, is displayed in Figure 3. The detection rate is

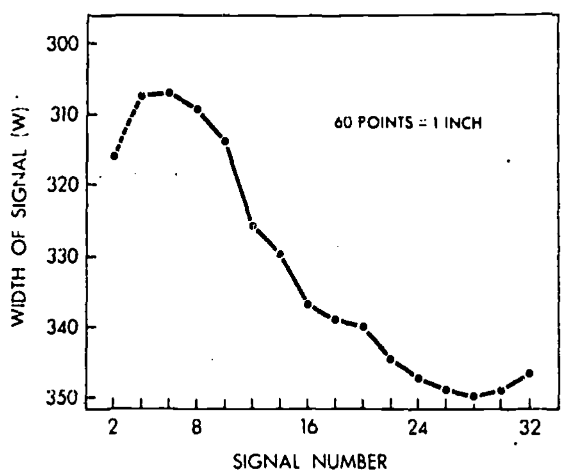

Figure 3. The adaptive variable W, the width of the separation between the two signal stimulus dots, plotted against signals. W is expressed in oscilloscope points, with 60 points equal to one inch.

shown in Figure 2, indicating the system output (percent detected) was held at a very constant level. The curve displayed in Figure 3 is clearly typical of vigilance functions. In fact it looks rather similar to that of Jerison and Wallis (1957) who plotted signal-by-signal detection rates instead of the usual block means. Near the end of the vigil, W reached a maximum value of 350 (5·85 in.), yielding a $\Delta I/I$ of $(350-256)/256=0{\cdot}37$. Therefore this value, the increase in W necessary to hold a constant system output in terms of percent detection rate, represents a novel view of vigilance decrement. It is interesting that the figure even shows a slight upswing (reduction of W) at the end, which is a familiar finding in vigilance literature, for reasons unknown. This phenomenon has often been carelessly referred to as an 'end spurt' effect, without sufficient empirical support, in view of the fact that subjects usually have their watches removed and generally underestimate the time they have been on watch.

The number of commissive errors by time blocks is shown in Table 1, and a median test resulted in a non-significant χ^2. Also a 2-by-2 table was formed by counting the number of subjects above and below (or equal to) the median of commissive errors (10) and the median number of detections (21). Of the 13 subjects, three each were tallied in three of the cells and four were in one cell. Obviously detections and false alarms are not correlated in this group either.

To test whether this apparent decrement was statistically significant, the value of W for each subject (row) was ranked from 1 to 15 (the first value, $W=316$, at signal No. 2 was not used, as it was not a random variable, but a fixed starting point). Then the sum of the ranks for each column was computed. Under the null hypothesis that the mean value of W did not change over columns (adaptive signals; in effect, time), the column rank sums should be stochastically equal. This hypothesis was tested by Friedman's χ^2 of the ranks test, with a computed value of 54·5, significant at the 0·001 level with $df=14$. A median test of the same hypothesis was performed. The grand median for all values of W was found to be 328, and the number of values of W above and below was computed and cast into a 2-by-15 contingency table. A χ^2 of 35·6 was computed, with 14 degrees of freedom, significant at the 0·002 level.

4. Discussion

This study reports a novel methodology for measuring vigilance decrement, seen as an increasing level of signal intensity or magnitude necessary to guarantee a stationary detection rate. This is in distinction to the usual dependent variable which shows decreasing detection rates for signals of equal dimensions. We believe that adaptive techniques have high promise as research tools in vigilance work, especially in those situations, such as transfer designs, where the experimenter may wish to run various conditions in which subjects may have different performance levels, but a similar exposure to detected signals.

There may be practical applications of these techniques as well, in those industrial, military or perhaps health settings in which monitors can be trained to some preset criterion by adjusting the parameters of a signal. This would particularly be feasible in elaborate systems, such as power plants or air-defence installations, where computer-driven displays are monitored, and false signals of known characteristics can be inserted. The purpose of such insertions would be training the watchkeeper, keeping his alertness at a high level by elevating the apparent signal rate, or providing a running check on his performance (monitoring the monitor).

To be sure, the adaptive program employed here might be improved upon. The signal detection rate, while extremely stable and within the preset limits, tended to be near the lower limit, slightly above the level of five out of eight signals detected. This may be corrected by some fine tuning of the program parameters: probably changing the values of Δ by using a larger value for increasing W than for decreasing, as suggested by Kelley and Kelley (1970). Another avenue which we have not explored in these strategies, but which we think might have high potential for adaptive control of vigilance tasks, would be to include commissive errors in the scoring criterion. In one such strategy, a composite score could be formed from a weighted sum of detections and false alarms. The weights, ideally, would be based on a utility analysis of the costs to the system of the two types of errors.

Alternatively, adaptive adjustment could hinge on either of the two criteria independently, with adjustment in W being ordered if either measure is out of limits. For example, the ADAPT-4 program could have an additional check to adapt outward if the number of commissive errors exceeded a certain value. Most reasonably, though not necessary, this would be an asymmetric limit test, adapting only in the case of high error rates, since a lower limit at or near zero would be expected.

This suggests the intriguing possibility of a conflict in adaptive criteria; i.e., a high detection rate and high false alarm rate, which would prompt opposing adaptive commands. This is exactly what the theory of signal detection suggests: that some subjects set a very loose criterion for responding, thus obtaining high hit rates at the cost of high false alarm rates. Though the author is not inclined toward such an interpretation of vigilance results, as the data from both this and previous experiments indicate that this is simply not the case, an instance of this sort would have to be covered in the adaptive decision rules.

Until now the author has carefully avoided using the term ' adaptive training ', which is often erroneously interchanged with adaptive measurement, when no training is involved. But the author's past studies of training for vigilance (Wiener 1967, 1968, Attwood and Wiener 1969) and the apparent success of adaptive measurement as reported here, convince him that adaptive methods could be used in transfer of training designs to enhance vigilance performance. With the proper management of training variables, subjects may be trained to maintain a constant W throughout a vigil, or even decrease the W requisite to insuring a preset detection rate. We intend to investigate this shortly.

Finally, a word of caution may be needed. Vigilance tasks are altogether different from tracking tasks, where adaptive techniques have achieved their most conspicuous success. In vigilance, responses are discrete, spaced far apart, and a time lag exists between the last response to be scored and the delivery of the next adaptive signal. Thus there is a considerable ' phase lag ' between past performance, however scored, and the next adjusted stimulus. Furthermore, there are few opportunities for adaptive adjustment during a run, as most experimenters choose to keep their signal rate low. Therefore, while adaptive techniques are attractive for vigilance research, they must be employed with a fair measure of caution and scepticism. The highly alert subject will continue to detect signals until they are adjusted downward to seeming psychophysical limits, if not the limits of resolution of the apparatus; and likewise, drowsy, inattentive, or poorly motivated subjects will overlook signals which have been adjusted to a level of conspicuity that no operator should be able to miss. In short, the author recommends further research in self-adjusting vigilance tasks, but with the caveat that experimental results may be far from perfect. Investigators who possess a highly developed servo-mechanistic view of the world are likely to be disappointed in their data.

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Cet article décrit une tâche de surveillance gérée par un ordinateur et qui est adaptative, c'est-à-dire auto-ajustable dans ce sens que la dimension du stimulus-signal (en comparaison avec un stimulus ordinaire constant) varie en fonction du taux de détections du sujet, en maintenant ce taux constant. Les données issues de cette étude montrent que pour maintenir un critère de détections constant pendant une période d'observation de 48 mn, la variable adaptative (distance qui sépare un couple de points présentés simultanément) doit être ajustée de manière à suivre la détérioration de la vigilance habituellement décrite. La discussion porte sur les diverses stratégies adaptatives possibles.

Die Arbeit beschreibt eine Computer-gesteuerte Überwachungsaufgabe, die adaptiv oder selbststeuernd (durch Vergleich mit einem fixierten Nicht-Signal-Reiz) die Stärke des Signalreizes an die Entdeckungs-Häufigkeit so anpasst, dass diese konstant bleibt. Ergebnisse zeigen, dass zur Einhaltung einer fixiertrn Entdeckungsrate in 48 Minuten Wachzeit die adaptibe Variable (Trennungsdistanz eines gleichzeitig präsentierten Punktepaares) sich in einer Weise verhielt, die mit der üblichen Grösse der Wachsamkeitsabnahme übereinstimmte. Verschiedene Strategien der Anpassung werden diskitiert.

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