Memory Load and Event Rate Control Sensitivity Decrements in Sustained Attention

Abstract. *The capacity to sustain attention at an efficient level deteriorates over time in discrimination and monitoring tasks. This "vigilance decrement" results from a decrement in perceptual sensitivity only if (i) target discrimination loads memory and (ii) stimulus events occur rapidly; otherwise, the decrement reflects temporal changes in response criteria. These results provide a basis for distinguishing between the perceptual and response processes underlying the vigilance decrement that may be generalized across a range of tasks.*

Most people find it difficult to sustain attention at an efficient level for a prolonged period. Since Mackworth first noted in the 1940's that radar operators detect fewer targets after about 30 minutes on continuous watch (*1*), many investigators have shown that detection efficiency in various discrimination and monitoring tasks declines with time (*2*). Less well understood, however, is whether this "vigilance decrement" results from a decline in the observer's perceptual sensitivity or from changes in response criterion, two fundamental parameters of signal detection theory (*3*). As the decrement in the target detection rate is normally accompanied by a decline in the false detection rate, the vigilance decrement may be due either to a deterioration in the observer's ability to discriminate targets from nontargets (*4*), or to a response process in which the observer becomes more cautious about reporting a target with time (*5*).

I now report that the vigilance decrement results from a decrement in perceptual sensitivity only when the observer has to discriminate a target from a nontarget represented in memory and when stimulus events are presented rapidly. In contrast, if the discrimination does not load memory, or if the event rate is low, the decrement results from changes in response criteria. The results provide a conceptual basis for distinguishing between perceptual and response processes underlying the vigilance decrement that is relevant both to the development of a theory of sustained attention (*6*, *7*) and to performance evaluation in such areas of application as radar monitoring, industrial inspection, and the impact of environmental stressors (*8*, *9*).

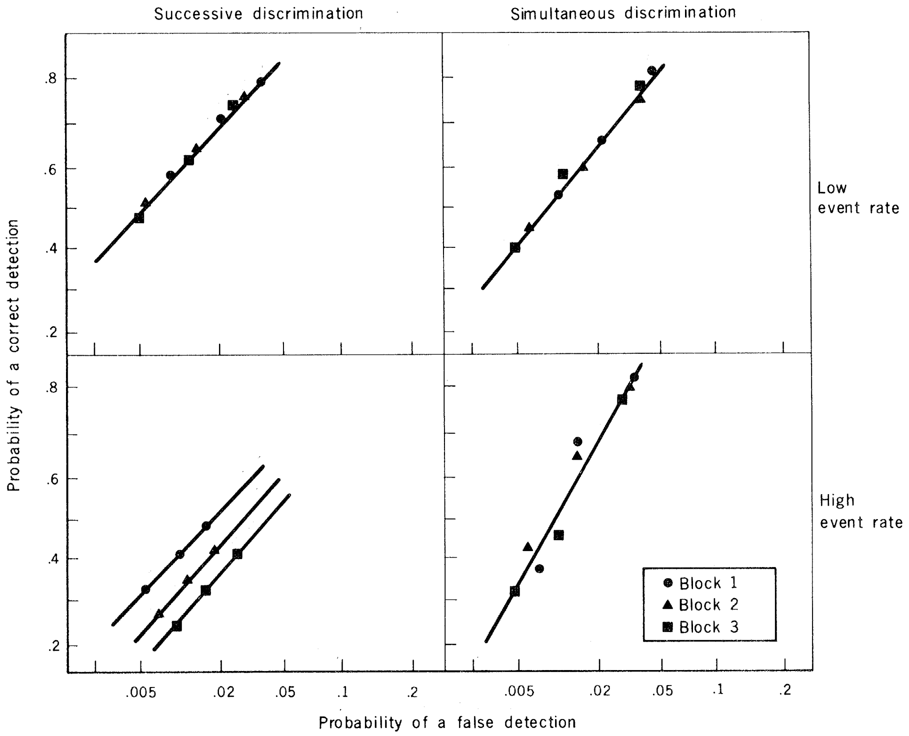

Fig. 1. Normalized group receiver operating characteristics (ROC's) in consecutive 15-minute time blocks of each vigilance session, and for each target type (successive- or simultaneous-discrimination) and event rate condition. Each ROC point is the mean of the normalized correct detection and false detection probabilities for the ten subjects in each group. In normalized (double probability) plots, each straight line represents a given level of detectability across different response criteria.

The analysis of perceptual and response processes in vigilance is commonly based on the signal detection parameters d' (sensitivity) and β (response criterion), respectively (*3*). Although the use of these measures has been criticized (*10*), analyses based on nonparametric measures and the receiver operating characteristic (ROC), which avoid some of the parametric assumptions of signal detection theory (*3*), also suggest that the vigilance decrement reflects one of two underlying and independent processes (*6*, *11*). Yet the limiting conditions associated with each of these underlying processes are not well defined. One view holds that sensitivity decrements occur only for visual displays, especially those demanding a high rate of observation (*7*). There are, however, examples of auditory tasks showing sensitivity decrements and tasks with high event rates that do not show such decrements (*11*, *12*).

A closer examination of the discrimination tasks used in studies of sustained attention suggests a division of these tasks into two general categories. In the first category are tasks in which the target is specified as a change in some feature of a repetitive standard stimulus, the standard value being absent when the nonstandard value is presented; examples include the discrimination of an increase in the brightness of a flashing light or a decrease in the duration of a tone. In tasks belonging to the second category, the target is specified fully within a stimulus event, as in the detection of a disk of different hue in a display of disks, or of a pure tone in a noise burst (*6*, *12*). I will refer to these two tasks as successive discrimination and simultaneous discrimination (*13*). The distinction is that the successive-discrimination target imposes a memory load, since the target and nontarget features are not present at the same time (*6*, *14*). Both intramodal and cross-modal correlations in performance are large within but not across these task categories (*12*, *15*), further testifying to the validity of this dichotomy, which is critical to the specification of sensitivity decrements. A second critical factor is the event rate, or the rate of presentation of nontarget stimulus events. Following the seminal study by Jerison and Pickett (*16*), several investigators have shown that a high event rate has a detrimental effect on the detection rate (*17*), and two studies have reported sensitivity decrements for visual vigilance tasks at high event rates (*18*).

To determine the conditions under

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Table 1. Mean values of sensitivity and hit rate (of target detections) for each target type and event rate in consecutive 15-minute time blocks of each vigilance session. Sensitivity is indexed by d_a in experiment 1 and by d' in experiment 2. In experiment 1, the hit rate refers to responses of high or intermediate confidence.

Target type	Event rate	Sensitivity 1	Sensitivity 2	Sensitivity 3	Hit rate 1	Hit rate 2	Hit rate 3
		Experiment 1					
Successive	Low	2.57	2.58	2.55	.71	.66	.62
Successive	High	2.15	1.85	1.78	.42	.37	.32
Simultaneous	Low	2.44	2.50	2.48	.67	.63	.58
Simultaneous	High	2.54	2.47	2.54	.65	.63	.54
		Experiment 2					
Successive		2.42	2.11	1.81	.68	.45	.36
Simultaneous (a)		2.30	2.37	2.37	.64	.59	.58
Simultaneous (b)		2.34	2.34	2.37	.63	.63	.58

which sensitivity decrements occur, the influences of target type and event rate were examined in two experiments conducted with visual and auditory displays. Forty paid volunteers participated in experiment 1, in which two auditory tasks were compared at low and high event rates. In the successive-discrimination task, the target was a 2.1-dB increase in the intensity of an intermittent 1000-Hz tone. In the simultaneous-discrimination task, a 1000-Hz tone had to be detected within an intermittent noise burst. The two types of task were matched for difficulty so as to give approximately equal values of sensitivity under short-term detection conditions. Each task lasted 45 minutes, and the event rate was either 15 or 30 events per minute. Targets were presented irregularly at a mean rate of one target per minute in the low event rate condition. Since the effects of event rate may be confounded with changes in conditional target probability, the latter was kept constant across event rates by doubling the target rate in the high event rate condition (*19*). Subjects used a four-category confidence rating scale in responding to targets and nontargets. Four groups of subjects were formed, each being assigned to a different task and event rate condition. The training and practice sessions included a 10-minute "expectancy-matching" (*20*) task that accurately sampled the main task features. A digital computer controlled the presentation of stimuli and the acquisition of responses in all phases of the experiment.

Figure 1 displays the group ROC plots (*21*) of the probability of correct versus false detections for each 15-minute block of the vigilance session. For the group performing the successive-discrimination task at a high event rate, the ROC's show a progressive reduction in detectability in consecutive time blocks. For each of the other groups, however, the ROC points cluster about a line of fixed detectability, indicating that in these conditions the vigilance decrement resulted primarily from changes in the response criteria, with no change in detectability.

The group ROC's in Fig. 1 were fitted by eye and are shown for illustrative purposes only. Parameter estimation was based on the individual ROC's, which were fitted through the use of a maximum-likelihood solution under the assumption of normal distributions of signal and noise (*22*). In most cases these ROC's were well formed and proper (*23*) and did not vary greatly in the amount of skew (*24*). Sensitivity was indexed by d_a, a relatively more robust measure than d' (*25*). Table 1 gives the mean values of d_a for each time block and for each target type and event rate condition. An analysis of variance (target type by event rate by time block) and a test for simple effects confirmed that a sensitivity decrement occurred only for the successive-discrimination task at a high event rate [F (2, 72) = 44.06, $P < .001$].

Table 1 also gives the mean detection or hit rates for targets reported with high or medium confidence. A vigilance decrement was obtained in all conditions [F (2, 72) = 77.41, $P < .001$]. In addition, event rate depressed the overall detection rate [F (1, 36) = 56.92, $P < .001$], but principally for the successive-discrimination task [F (1, 36) = 44.74, $P < .001$]. The response criterion for high or medium confidence reports (log β) showed little change in the sensitivity decrement condition, the mean values in successive time blocks being 1.09, 0.98, and 0.98. However, the three-way interaction term that would have distinguished this trend from the overall significant [F (2, 72) = 9.66, $P < .001$] increase in log β (*26*) was not significant [F (2, 72) = 2.94, $.05 < P < .10$].

These results indicate that performance deteriorates sharply over time when a target has to be discriminated from previously presented nontargets in a rapidly changing display. This may be due to the memory load involved in this type of discrimination. However, the simultaneous-discrimination task studied involved the detection of a pure tone in noise, whereas the successive-discrimination task required the discrimination of a tone increment. The lack of a sensitivity decrement for the former task may thus be due either to the absence of a memory load or to the need to detect a stimulus in noise. In order to clarify the nature of the factor controlling the sensitivity decrement, therefore, a second experiment compared three visual vigilance tasks at a high event rate.

Two adjacent sources of visual stimulation were used in each of these tasks, for the following reasons. Consider a single-source successive-discrimination task with the target specified as a decrease in the intensity of a flashing light. If an identical second source is added, with the target defined as a decrease in the intensity of both light sources, it remains a successive-discrimination task. However, if the task is modified so that the target (dimmer flash) is presented on only one source, simultaneous discrimination is now possible since the two sources may be compared within a stimulus event. This task is referred to as simultaneous-discrimination task (a) (Table 1). A second simultaneous-discrimination task (b), in which the target was a small circle appearing at the center of one of the two light sources, was also examined. A memory load hypothesis would predict that under a high event rate only the successive-discrimination task will show a sensitivity decrement.

The visual display used in each task consisted of two circular light sources separated by 35 cm, each subtending 2° of visual angle. The decrease in intensity that defined a target in the intensity discrimination was 9.2 cd/m^2. Targets were presented irregularly at a mean rate of two targets per minute, the event rate was 30 events per minute, and task duration was 45 minutes. Subjects used a single response key to signal target detection (*27*). Training and practice sessions were the same as in experiment 1. The 36 paid volunteers were divided into three groups, each assigned to a different task. Tasks were matched for difficulty under alerted conditions.

Table 1 summarizes the main findings of this study. An analysis of variance (tasks by time blocks) and tests for

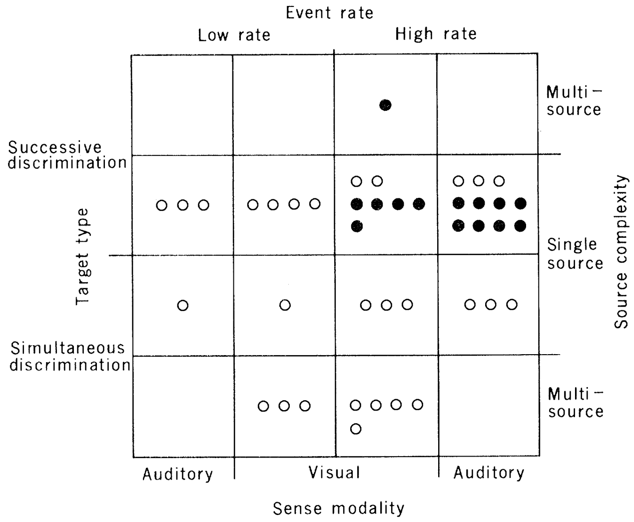

Fig. 2. A classification of vigilance tasks according to the presence (filled circles) or absence (open circles) of a reliable decrement in perceptual sensitivity over time. Each circle represents a task used in a study of sustained attention reporting data according to d' or a related index.

simple effects showed that sensitivity declined reliably in the successive-discrimination task [$F\ (2, 66) = 57.20$, $P < .001$], but not in the two simultaneous-discrimination tasks ($F < 1$). The hit rate showed a decrement in all three tasks [$F\ (2, 66) = 95.16$, $P < .001$].

These results confirm those of experiment 1 and show that memory load and event rate are the two critical factors that control temporal changes in sensitivity in vigilance tasks. Given the modality-specific nature of many vigilance phenomena (*2*), the congruence of the findings between visual and auditory stimulation provides impressive empirical support for the distinction between successive and simultaneous discrimination in the context of vigilance (*12*).

As a further test of the generality of the results, I compared them with the findings of 27 previous studies reporting sensitivity data using d' or a related index (*6, 12*). Each study was classified according to target type (successive or simultaneous discrimination), event rate (lower or higher than 24 events per minute), modality (visual or auditory), and whether a sensitivity decrement was obtained or not. This taxonomic analysis reveals an orderly pattern of results (Fig. 2). A sensitivity decrement can be obtained for either a visual or an auditory task, but only for successive-discrimination tasks combined with a high event rate. Not all such combinations showed a reliable decrement, but in general this analysis provides strong support for the experimental findings and suggests that they may be generalized across a range of vigilance tasks.

The cognitive processes involved in target discrimination in these tasks may be characterized as data-limited (*28*), or processes for which performance cannot be improved beyond a certain level by increasing processing resources, because the data are of relatively poor quality. This limitation may result either from signal-data or memory-data limits on processing (*28*). Signal-data limits refer to situations in which performance depends more on the quality of the input, as in the detection of a weak signal in noise; when there are memory-data limits, performance is affected by the quality of the stored representation of input data, as in delayed-comparison memory tasks and successive-discrimination vigilance tasks (*29*). Tasks which combine both limitations with the demands of a high processing rate will be likely to yield sensitivity decrements over time. In terms of an "effort" theory of attention (*30*), such tasks demand a high level of effort for their execution; time pressure, which may be associated with both a high event rate and a high memory load, will increase this demand, such that the level of effort needed to sustain performance cannot be maintained, and a sensitivity decrement occurs.

For tasks that do not demand this sustained level of effort, sensitivity remains stable over time, and the vigilance decrement results from an increase in the response criterion, which may be due to changes in subjective probability of the occurrence of a target or to related changes in response strategy (*6, 11*). Training subjects to adopt more optimal response strategies may reduce or eliminate the vigilance decrement in these cases (*6*). When sensitivity decrements occur, however, the only way to control the decrement may be to redesign the task. Apart from their implications for training and design, these results provide a basis for incorporating the perceptual and response processes underlying the vigilance decrement into a composite theory of sustained attention (*6*). More generally, the results indicate that the ability to sustain attention depends both on the required stimulus processing rate and on the nature of the cognitive processes involved in target discrimination.

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Emergence of Interoceptive and Exteroceptive Control of Behavior in Rats

Abstract. *The role of exteroceptive and interoceptive aversive stimuli in rats 2 to 14 days old was investigated according to an odor aversion paradigm. Amyl acetate odor was paired with either peripheral shock, intraperitoneal shock, or lithium chloride poisoning. Intraperitoneal shock was an effective unconditioned stimulus at all ages and produced odor aversions comparable to lithium chloride poisoning; peripheral shock, however, was effective only in rats 10 days of age or older. Interoceptive control of aversively motivated behaviors thus seems to develop before exteroceptive control, and the failure of previous studies to find reliable learning and retention of shock-motivated behaviors before 8 to 10 days of age may be attributable to the site to which shock was applied rather than to insensitivity to shock per se.*

To date, attempts to show learning and retention of responses motivated by electric shock or other noxious exteroceptive stimuli have been unsuccessful in rats younger than 8 to 10 days of age (*1*). For example, little evidence has been found for either acquisition or long-term retention of escape or avoidance learning motivated by electric shock (*2, 3*) or cold air (*4*) in rats less than 1 week old. Conversely, young rats can learn odor aversions or simple discrimination for food reinforcement as early as 1 or 2 days of age (*5*). Moreover, long-term retention of odor aversions, lasting a week or more, has been demonstrated in 2-day-old rats (*6*).

Before odor aversion learning by 2-day-old pups was demonstrated, it was possible to entertain the notion that appetitively motivated behaviors were acquired earlier in developmental sequence than aversively motivated behaviors. The odor aversion data reported by Rudy and Cheatle (*6, 7*), however, suggest that such a distinction is inappropriate. Since rats as young as 2 days of age can learn and retain a toxicosis-induced odor aversion response, the difficulty in demonstrating learning and retention of responses motivated by electric shock in rats younger than 8 or 9 days of age remains to be explained. The distinguishing feature of the studies of Rudy and Cheatle (*6, 7*) versus those of Misanin *et al.* (*2*) and Nagy (*1*), and other studies using electric shock, may lie in the nature of the unconditioned stimulus (US) and experimental paradigms. Although it is clear that rats, even when newborn, react to exteroceptively applied shock, the neural mechanisms responsible for the association of peripheral pain and peripheral cues may not mature until later.

In contrast, odor aversion studies suggest that the mechanisms responsible for the association of internal malaise and odor cues are functional by 2 days of age (*6, 7*). In this research we explored the role of interoceptively versus exteroceptively applied aversive stimuli in the learning of odor aversions and addressed the more general issue of the development of exteroceptive control of behavior.

Sprague-Dawley rats ($N = 320$) were used in these experiments. The general design was to condition rats of various ages by pairing an odor conditioned stimulus (CS) with either peripheral shock (PS) or intraperitoneal shock (IPS) and to test for odor aversion on the following day. For the groups receiving interoceptive shock, two copper wire-insulated electrodes with 2-mm exposed tips were inserted into the peritoneal cavity on either side of the stomach (easily visible through the skin). The site of entry of the electrodes was covered with petroleum jelly to prevent leakage of body fluids, and the electrodes were fastened in place with adhesive tape. A subcutaneous indifferent electrode (a wound clip) was implanted in the nape of the neck of each rat that was to receive PS. After the electrode was implanted, the rats were kept in an incubator (34°C, 54 percent relative humidity) and were allowed at least 30 minutes to recover from light ether anesthesia.

The rats were conditioned in a Plexiglas chamber (24 by 15 by 15 cm) containing six compartments separated by nylon mesh cloth. The floor and walls of two of the compartments were made of copper wire mesh, through which the PS was delivered. The rats were placed in the conditioning chamber with one rat per compartment for a period of 30 minutes. Each conditioning session was started by introducing humidified air into the chamber for 40 seconds; odorized air [13 ml of air (per minute) bubbled through amyl acetate mixed with 167 ml of humidified air (per minute)] followed for the next 20 seconds (*8*). The rats receiving shock as the US received a 1-second shock pulse, delivered by constant-current shock generators that terminated with the amyl acetate phase of the cycle. Thus, by the end of the conditioning session, each rat had been exposed to 30 20-second amyl acetate pulses, each ending in shock.

On the conditioning day, the rats were 2, 7, 10, or 14 days old. Five levels and two loci of shock were investigated at each age. The rats received either IPS or PS at 0, 0.1, 0.5, 1.0, or 2.0 mA.

Testing occurred 24 hours later for all but the 2-day-old groups, which were tested when 8 days old to allow them to develop adequate locomotor capabilities. The test chamber consisted of a Plexiglas tray (30 by 20 by 3 cm) and a chamber (30 by 20 by 10 cm) with a copper mesh floor mounted on top of the tray. The tray was divided into two equal

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