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Computerized Assessment of Sustained Attention: A Review of Factors Affecting Vigilance Performance*

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ABSTRACT

Results of empirical studies using computerized tests of sustained attention are summarized. Factors that affect vigilance performance fall into three broad categories: task parameters, environmental or situational factors, and subject characteristics. Complex interactions of factors from each category affect performance further. Such interactions may help to explain inconsistencies in the literature regarding effects on vigilance. Implications for both research and clinical practice are discussed.

The ability to sustain attention, also known as "vigilance" or "watchkeeping" behavior (Mackworth, 1970; Warm, 1984), is the subject of research in a variety of psychology fields, including human factors, cognitive, developmental, educational, clinical, and neuropsychology (Mirsky, Anthony, Duncan, Ahearn, & Kellam, 1991; Parasuraman & Davies, 1984). In applied settings, psychologists often are asked to assess the ability to sustain attention; however, several problems impede this assessment process. These problems include defining attention and component skills, selecting appropriate tests and measures, and interpreting results. Interpretation problems are compounded by the large number of factors that influence attention task performance (Corkum & Siegel, 1993). The purpose of this paper is to review the factors shown to affect vigilance task performance in diverse fields of research. Both empirical studies and prior reviews of specific factors are cited. The following sections summarize components of attention, types of vigilance tasks, factors affecting vigilance, and approaches to explaining variations in performance. Implications for the study of sustained attention are discussed.

ATTENTION

In the study of human information processing, certain cognitive processes, such as attention, are presumed to intervene between stimulus onset and behavioral response. These processes are involved in perception of the stimulus, prediction of probable outcomes of a response, selection of a response, and initiation of a motor program. Attention, like problem-solving, decision-making, motivation, and other hypothetical constructs, is an unobservable cognitive process that is inferred from observable behaviors.

Definitions and Components of Attention

A variety of processes are involved in attention. These may include basic arousal, alertness, selection, concentration, and sustaining attention

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over time (Barkley, 1988; Mirsky et al., 1991; Parasuraman & Davies, 1984). The most commonly studied components are selective and sustained attention. *Selective attention* is a process in which an organism selectively and preferentially attends to one stimulus or set of stimuli instead of others. By dividing attention, an organism allocates attentional resources to more than one task or stimulus simultaneously. By focusing attention, the organism rejects irrelevant information or stimuli while attending to relevant inputs (Davies, Jones, & Taylor, 1984; Parasuraman & Davies, 1984; Schneider, Dumais, & Shiffrin, 1984). After a focus is established, *sustained attention* involves the continuous maintenance over time of alertness and receptivity for a particular set of stimuli or stimulus changes (Davies et al., 1984; Parasuraman & Davies, 1984; Parasuraman, 1984). The term "vigilance" is used to describe the state of readiness to detect and respond to stimulus changes that are barely detectible, or which occur infrequently or at irregular intervals (Mackworth, 1957).

Methods of Assessing Sustained Attention

In both research and clinical literature, a number of measures of sustained attention have been employed. These range from paper-and-pencil cancellation tasks to subtests of intelligence tests (Lezak, 1983). However, many such measures cannot be considered "pure" tests of attention, because task requirements also include visual scanning, visual-spatial perception, mathematical ability, memory loads, or fine-motor response skills (Shum, McFarland, & Bain, 1990). The development of computerized vigilance tasks provided test formats that eliminate to some degree these requirements while engaging the subject in maintaining a vigil over time.

Early Vigilance Tasks

Early tests of sustained attention were developed to serve military needs for information regarding the limits of human performance capabilities in situations requiring the maintenance of a vigil over long periods of time (Warm, 1984). The use of the term "vigilance" to describe watchkeeping or monitoring tasks, and the development of the first vigilance task, are credited to the work of N.H. Mackworth in the 1950s (Mackworth, 1970; Warm, 1984). In Mackworth's very monotonous Clock Test, subjects monitored the jumps of the second hand of a blank-faced clock, watching for infrequent double-sized jumps (McGrath, Harabedian, & Buckner, 1968; Mackworth, 1970; Warm, 1984).

Common Features of Vigilance Tasks

Tests of the ability to sustain attention may take a variety of forms. However, all vigilance tasks require the direction of attention to one or more sources of information for relatively long, unbroken periods of time, during which subjects must detect and respond to small changes, known as "signals" or "critical stimuli" or "target stimuli," in the display being monitored (Davies et al., 1984; Mackworth, 1970; Warm, 1984). In sensory-detection vigilance tasks, the signal may be a change of color, shape, size, or position, while symbolic vigilance tasks involve discrimination of a specific symbol from other symbols. The probability that a signal will occur at any given moment is usually low, and the response typically required is to indicate when a signal has occurred (Mackworth, 1970; Warm, 1984). The signals must be discriminated either from a static, unchanging background or from a series of continuously changing nonsignal events (Davies et al., 1984; Kirchner & Knopf, 1974). Most vigilance tasks last a minimum of 30 min without interruption, and durations of 2 hr or more have been used, as in Mackworth's Clock Test (Mackworth, 1970). Performance decrements begin within the first few minutes of a vigil, and vigilance tasks as brief as 5 to 9 min discriminate groups (Kirchner & Knopf, 1974; Knopf & Mabel, 1975).

Performance Measures

A number of performance measures may be collected. The "detection rate," or "hit rate," consists of the proportion of signals to which the subject correctly responds. Conversely, "omission errors" are those signals to which the subject fails to respond. "Commission errors," also known as "false alarms," consist of responses

made when no signal has been presented. The "response latency" is the time between signal presentation and the subject's response. The "vigilance decrement" or "decrement function" is the degree to which performance declines over time, and may be plotted for detection rate or response latency. In signal detection and decision theory studies, a measure of perceptual sensitivity (*d'*) and of response criterion (*Beta*) also may be calculated (Barkley, 1988; Corkum & Siegel, 1993; Davies et al., 1984; Mackworth, 1970; McGrath et al., 1968; Parasuraman, 1984; Warm, 1984)).

Continuous Performance Tests (CPT)

The Continuous Performance Test (CPT) is a type of vigilance task originally devised by Rosvold, Mirsky, Sarason, Bransome, and Beck (1956) for use with brain-injured populations. Like any vigilance task, the CPT measures the ability to detect and respond to specified stimulus changes occurring infrequently and at random intervals over a prolonged time period, while simultaneously inhibiting responses to extraneous stimuli (Barkley, 1988; Barkley, 1990; Corkum & Siegel, 1993; Davies et al., 1984; Kirchner & Knopf, 1974; Warm, 1984). In all variations of the original task, the subject monitors a continuous presentation of letters, numerals, or other stimuli, and reports the occurrence of the critical signal, which may be a single stimulus or a series of stimuli. The test may be administered in the visual mode, often on a computer screen, or in the auditory mode. The subject's response may consist of pressing a key, raising a finger, or some other simple motor movement. In the most commonly used version of the visual CPT, the subject watches for an "X", or for an "A" followed by an "X", and presses a computer key when the signal is detected. Like other vigilance tasks, the computerized CPT yields scores of correct detections, false alarms, omissions, reaction time (response latencies), and decrements in performance over time (Barkley, 1988, 1990; Conners, 1985; Davies et al., 1984; Gordon & Mettelman, 1988; Klee & Garfinkel, 1983; Mirsky et al., 1991; Rosvold et al., 1956; Warm, 1984). Some efforts have been made to identify different types of false alarm errors, such as "A-not-X", "A-only", "X-only", and "not-A-not-X" (Halperin et al., 1988; Halperin, Matier, Bedi, Sharma, & Newcorn, 1992; Halperin, Wolf, Greenblatt, & Young, 1991; Kupietz, 1990).

Versions of the CPT are employed by clinicians in pediatric psychopharmacological research (Swanson, 1985) and in diagnostic assessments of Attention Deficit Hyperactivity Disorder (ADHD; Barkley, 1990; Bauermeister, Berrios, Jimenez, Acevedo, & Gordon, 1990; Gordon, 1986, 1987; Gordon & Mettelman, 1988; Irwin & Mettelman, 1989; Klee & Garfinkel, 1983; Post, Burko, & Gordon, 1990; Seidel & Joschko, 1991), although some have concerns regarding the sensitivity and specificity of the CPT in such assessments (DuPaul, Anastopoulos, Shelton, Guevremont, & Metevia, 1992; Halperin et al., 1992; Milich, Pelham, & Hinshaw, 1986; Trommer, Hoeppner, Lorber, & Armstrong, 1988).

The CPT involves a rapid, continuously changing background, with nonsignal event rates of approximately 60 stimulus presentations per minute, in contrast to the static background of sensory-detection vigilance tasks in which an occasional sensory change occurs (Berch & Kanter, 1984). The CPT sometimes is considered more cognitively complex than sensory signal-detection tasks because it requires a discrimination among successive symbolic stimuli, rather than simply requiring sensory detection and response to a change in stimulus conditions (Davies et al., 1984; Davies & Parasuraman, 1982; Milosevic, 1993; Parasuraman, 1984; Parasuraman & Mouloua, 1987; Warm & Jerison, 1984). Performance decrement slopes are not as steep with CPT tasks as with sensory-detection vigilance tasks, particularly when tests are briefer than 10 min. Nevertheless, significant performance decrements over time have been found in CPT as well as in sensory-detection visual vigilance tasks (Kupietz, 1976; Sykes, Douglas, & Morganstern, 1973). However, an examination of the decrement function often is not included as a dependent measure for short duration tasks. Instead, the focus with CPT

tasks more often is on overall vigilance performance, using measures of total hits and false alarms (Conners, 1985; Rosvold et al., 1956).

FACTORS AFFECTING VIGILANCE PERFORMANCE

Individual and group differences in the performance of vigilance tasks are considerable, and all measures vary across successive time periods of the same testing session, across different testing sessions, and across types of tasks (Davies et al., 1984). On the basis of a large body of empirical research, it appears that performance on CPT and other vigilance tasks is affected by three broad classes of factors: task parameters, extraneous environmental or situational variables, and individual subject characteristics.

Task Parameters

The first class of factors includes a number of task parameters that affect error rates, vigilance decrements, or both. Instructions to subjects may set up expectancies that facilitate or degrade performance (Berch & Kanter, 1984; Dember, Galinsky, & Warm, 1992; Lucaccini, Freedy, & Lyman, 1968; McGrath et al., 1968). With respect to sensory modality, visual and tactile tasks usually yield steeper decrements and lower overall accuracy than do auditory tasks (Buckner, Harabedian, & McGrath, 1968; Davies et al., 1984; Hatfield & Loeb, 1968; Warm & Jerison, 1984). Visual tasks also appear more stressful to the subject than do auditory tasks (Galinsky, Rosa, Warm, & Dember, 1993). Performance is poorer when critical signals are less "detectible," as when amplitudes or durations are just above perceptual thresholds (Chee, Logan, Schachar, Lindsay, & Wachsmuth, 1989; Warm & Jerison, 1984), when signals occur very infrequently (Baker, 1959; McGrath et al., 1968; Matthews, Davies, & Lees, 1988; Warm & Jerison, 1984), or when formats have increased processing demands or complexity (Hancock, 1984; McGrath et al., 1968; Parasuraman, 1987; Warm & Jerison, 1984). Tasks with longer durations, a high background event rate, a short interstimulus interval, or a low signal to noise ratio generally produce poorer performances, as do tasks involving symbolic rather than sensory signals (Knopf & Mabel, 1975; Parasuraman, 1985; Sykes, Douglas, Weiss, & Minde, 1971; Warm & Jerison, 1984). Reinforcement and feedback can either facilitate or degrade performance (Berch & Kanter, 1984; Mackworth, 1970; Warm & Jerison, 1984), as can different types of task-irrelevant stimulation (Gordon & Mettelman, 1988; Tarver & Hallahan, 1974). Response requirements primarily affect response latencies, with increasingly faster performance demonstrated with light-pen, full keyboard, keypad, and touch-screen media (Beaumont, 1985).

Interactions

Although many of these findings have been demonstrated repeatedly, variations in effects across studies or across different measures (e.g., omission rate or decrement function) suggest that the effects of task parameters may depend in part on other aspects of the experimental situation. For example, increasing the background event rate had a greater decremental effect on a successive discrimination vigilance task than on a simultaneous discrimination task (Lanzetta, Dember, Warm, & Berch, 1987). Deaton and Parasuraman (1993) reported the expected vigilance decrement on a sensory vigilance task, but not on a cognitive task. However, when the event rate was increased, the decrease in hit rate was more pronounced on the cognitive than on the sensory task.

Task parameters also may interact with subject characteristics to affect vigilance performance. For example, increased task demand affected younger children more than older children (Schiff & Knopf, 1985). Older adults demonstrated lower hit rates for both cognitive and sensory vigilance tasks, but a higher false alarm rate only on the sensory task (Deaton & Parasuraman, 1993). Hit rates tended to decrease and false alarms tended to increase with advancing age, particularly when stimuli were highly degraded (Parasuraman, Nestor, & Greenwood, 1989). Practice helped to reduce the decrement in hit rate seen in high-event tasks, but only for younger adults (Parasuraman & Giambra, 1991).

Gender interacted with task type in a study reported by Dittmar and colleagues (1993), in which males demonstrated greater perceptual sensitivity than females only on a spatial vigilance task. No gender differences were seen on a temporal vigilance task in which duration of stimulus presentation was the critical signal. Females also rated the spatial task as more frustrating, mentally demanding, and effortful.

Environmental "Stressors" and Situational Factors

A second class of variables that affect vigilance performance includes environmental factors that are extraneous to the task itself, but that may create some interference with performance through "stress" (Hancock, 1984; Spielberger, Vagg, Barker, Donham, & Westberry, 1980). Included among these conditions is performance of the task itself, which may act as a source of stress that affects arousal (Galinsky et al., 1993; Hancock & Warm, 1989; Munro, Dawson, Schell, & Sakai, 1987). Research efforts on the ability to sustain attention often focus on the effects of environmental factors such as noise, temperature, vibration, and situational variables.

Noise

The effects of noise on human performance have been the focus of many investigations. Noise may be categorized on several dimensions. Volume level may be high (loud) or low (quiet). Noise may be present continuously, or may be presented intermittently at fixed or irregular intervals. Noise also may vary in terms of quality from static (white noise) to varied noise, such as music or voices. Effects of noise on human performance may depend on the combination of these characteristics.

The effects of continuous noise on vigilance performance vary across studies from improvement to decrement to no change. Lysaght suggested that when results are classified on the bases of noise quality, volume, and degree of processing demand imposed by the task, a somewhat more consistent picture emerges (Hancock, 1984; Lysaght, 1982). In tasks requiring a high level of processing, high-volume continuous white noise tended to depress performance (Broadbent, 1953, 1954; Hancock, 1984; Hockey, 1973; Jerison, 1959; McGrath et al., 1968; McGrath & Hatcher, 1968). Even low-volume continuous white noise reduced performance on more cognitive vigilance tasks (Hancock, 1984; Warner & Heimstra, 1972). Neither high- nor low-volume continuous white noise appeared to affect performance on low-demand sensory tasks (Blackwell & Belt, 1971; Broadbent, 1954; Broadbent & Gregory, 1965; Davenport, 1972; Hancock, 1984; Jerison, 1957; Kirk & Hecht, 1963; McCann, 1969; McGrath et al., 1968). Effects of continuous noise on highly demanding sensory tasks have not been investigated (Hancock, 1984).

The effects of low-volume varied noise (e.g., music or voices) on performance of high-demand vigilance tasks are inconsistent, with some studies reporting improved performance (Davies, Lang, & Shackleton, 1973; McGrath, 1968), depressed performance (McGrath, 1963; McGrath & Hatcher, 1968), or no difference between low- and high-demand conditions (Thackray & Touchstone, 1979, cited in Hancock, 1984). However, low-volume varied noise may facilitate performance in low-demand tasks (Blackwell & Belt, 1971; Davenport, 1972; Hancock, 1984; Kirk & Hecht, 1963; McCann, 1969; McGrath & Hatcher, 1968). In studies of clinical populations, Brackup and Knopf (1978) demonstrated that low-volume intermittent background conversation facilitated vigilance performance of learning-disabled boys. Similarly, both background music and taped conversation improved reaction time of long-distance drivers as compared to other drivers in silent conditions (Fagerstrom & Lisper, 1977).

The effects of intermittent noise, or bursts of noise, on vigilance performance are the subject of few investigations. Sykes and colleagues (1971) found no decline in CPT performance of hyperactive subjects given intermittent blasts of white noise. Hancock (1984) suggested that, in general, when the ratio of noise-on to noise-off intervals is high, low-intensity noise bursts facilitate performance while high-intensity noise bursts degrade performance (Hancock, 1984; Warner & Heimstra, 1971). The complexity of the task also may interact with these effects, but

findings are equivocal (Hancock, 1984; Koelega & Brinkman, 1986; Poulton, 1977).

Temperature and Vibration

In general, gradual exposure to temperatures greater than 32° Celsius impairs vigilance performance, as measured both by error rates and the decrement slope, while sudden entry into the hot environment may facilitate performance (Hancock, 1984; Hancock & Warm, 1989). Both moderate and extreme cold can increase omission and commission errors on vigilance tasks, as well as interfere with manual dexterity (Enander, 1987; Hancock, 1984). Vibration effects, when found, appear attributable to physical interference with the subject's reception of visual signals (Hancock, 1984).

Situational Variables

Other factors intrinsic to the situation affect vigilance performance. For example, crowded conditions may diminish attention capability, although effects may depend on other subject variables. Time of day and related factors, such as time since the last meal (Smith & Miles, 1986), may have pronounced effects, again depending on subject and task characteristics (Davies & Davies, 1975).

Interactions

In sum, the effects on vigilance performance of environmental stressors, such as heat, vibration, and noise, may result from the interaction of a number of factors, including the intensity, quality, and duration of the stressor, other situational variables, and the level of processing demand imposed by the task. For example, interfering effects of noise may be found on cognitively demanding vigilance tasks, but not on low-demand tasks (Hancock, 1984; Hancock & Warm, 1989). In one study, the decremental effects of lowered signal frequency and stimulus degradation were more pronounced in afternoon and evening than in morning hours (Craig, Davies, & Matthews, 1987). Faster response latencies to signals were reported early in a task performed in conditions of loud noise, while decreased recall for presignal stimuli was seen in subjects working in pairs as compared to subjects working alone (Auburn, Jones, & Chapman, 1987). Finally, effects of environmental factors may depend on the subject's demographic characteristics, degree of skill or training, subjective state, personality factors, or clinical symptoms (Berch & Kanter, 1984; Davies & Hockey, 1966; Hancock, 1984).

Subject Characteristics

A third class of factors includes subject variables that affect either the vigilance decrement slope or overall error rates. These subject characteristics include demographics, clinical symptoms, personality traits, physiological state, and arousal level.

Demographics

Among demographic characteristics, gender typically has no major effects on vigilance error scores (Berch & Kanter, 1984; Breen, 1989; Davies & Parasuraman, 1982; Giambra & Quilter, 1989; Gordon & Mettelman, 1988; Horn, Wagner, & Ialongo, 1989; Kirchner & Knopf, 1974; Lam & Beale, 1991; Seidel & Joschko, 1991), although reaction time sometimes is faster for males than females (Seidel & Joschko, 1991) and males and females may respond differently to tasks with a spatial component (Dittmar, Warm, Dember, & Ricks, 1993). Early studies suggested that vigilance performance was unaffected by intelligence variations within the normal range, while poorer performance was associated with moderate to severe mental retardation (Berch & Kanter, 1984; Mackworth, 1948). More recent studies suggest a consistent relationship between better CPT performance and higher verbal IQ scores (Swanson & Cooney, 1989). Performance tends to be poorer among low socioeconomic groups (Brown et al., 1993; Knopf & Mabel, 1975; Norman & Breznitz, 1992), and CPT scores have been linked consistently with academic achievement (Campbell, D'Amato, Raggio, & Stephens, 1991; Edley & Knopf, 1987; Gordon, Thomason, & Cooper, 1990; Halperin, Sharma, Greenblatt, & Schwartz, 1991). Vigilance hit rate typically varies as an inverted U-shaped function of age across the lifespan (Berch & Kanter, 1984; Davies & Davies, 1975; Davies et al., 1984;

Halperin, Sharma, et al., 1991; Lam & Beale, 1991; Levy, 1980; Schiff & Knopf, 1985; Seidel & Joschko, 1991), although one 18-year longitudinal and cross-sectional study found curvilinear effects of age only on response latencies (Giambra & Quilter, 1988). Some evidence suggests that the capacity to sustain attention to spatial stimuli may develop during childhood and adolescence, while verbal attention skills may not develop fully until adulthood (Cornblatt, Risch, Faris, Friedman, & Erlenmeyer-Kimling, 1988).

Clinical Symptoms

Two clinical groups have been the subjects of extensive research on the capacity to sustain attention: schizophrenic adults and hyperactive children. Difficulties in sustaining attention on CPT and other vigilance tasks have been demonstrated in hospitalized and outpatient schizophrenics (Berch & Kanter, 1984; Cohen & Servan-Schreiber, 1992; Cornblatt & Keilp, 1994; Cornblatt, Lenzenweger, & Erlenmeyer-Kimling, 1989; Earle-Boyer, Serper, Davidson, & Harvey, 1991; Mirsky et al., 1991; Mirsky et al., 1992; Mussgay & Hertwig, 1990; Nestor, Faux, McCarley, Shenton, & Sands, 1990; Rund, Orbeck, & Landro, 1992; Strandburg et al., 1990), children and other first-degree relatives of schizophrenics (Mirsky et al., 1992), children at risk for schizophrenia (Rutschmann, Cornblatt, & Erlenmeyer-Kimling, 1986), and persons with schizotypal personality disorder (Condray & Steinhauer, 1992; Lenzenweger, Cornblatt, & Putnick, 1991) or schizotypal tendencies (Obiols, Garcia-Domingo, deTrincheria, & Domenech, 1993). Negative symptoms in both schizotypy (Kendler et al., 1991) and schizophrenia (Nuechterlein, Edell, Norris, & Dawson, 1986) appear to correlate most strongly with impairments in sustained attention. In contrast to normals, schizophrenics may show greater impairment on auditory than on visual CPT tasks (Mirsky et al., 1992). Of note, one group of newly-diagnosed adolescent schizophrenics did not differ in CPT performance from a comparison group of nonpsychotic adolescents with conduct disorder, Attention-Deficit Disorder, Anxiety Disorder, or eating disorders. Furthermore, neuroleptic treatment did not improve the CPT performance of these schizophrenic adolescents, while sedating side effects of medication were associated with increased reaction times and error rates (Erickson, Yellin, Hopwood, Realmuto, & Greenbery, 1984). Poor CPT performance in schizophrenic children and adults is associated with abnormalities of the P300 component of event-related potentials (ERP) (Duncan, 1988; Strandburg et al., 1990; Strandburg et al., 1994). ERP abnormalities in schizophrenics have been interpreted as evidence of thalamic dysfunction (Erwin, Mawhinney-Hee, Gur, & Gur, 1991) or of temporal lobe/hippocampal pathology (Egan et al., 1994).

Children diagnosed with hyperactivity or minimal brain dysfunction (MBD) also have been described as showing deficits in sustained attention (Aylward, Verhulst, & Bell, 1990; Barkley, DuPaul, & McMurray, 1990; Barkley, Grodzinsky, & DuPaul, 1992; Berch & Kanter, 1984; Brown & Wynne, 1982; Garfinkel et al., 1986; Grodzinsky & Diamond, 1992; Harper & Ottinger, 1992; Kirchner, 1976; Klee & Garfinkel, 1983; Levy, Horn, & Dalglish, 1987; O'Dougherty, Nuechterlein, & Drew, 1984; Sykes et al., 1973), and diagnostic nomenclature systems have recognized these findings in the name of the Attention-Deficit Disorder and the more recent Attention-Deficit Hyperactivity Disorder (ADHD) diagnostic categories (American Psychiatric Association, 1980, 1987, 1994). Diagnosed children may continue to show poor CPT performance in adulthood (Klee, Garfinkel, & Beauchesne, 1986). A variety of etiological mechanisms for ADHD have been proposed, including reduced size of the left caudate-striatal region (Hynd et al., 1993), right frontal-striatal dysfunction (Heilman, Voeller, & Nadeau, 1991), neurochemical (dopamine and norepinephrine) deficits and neurophysiological disorders (Riccio, Hynd, Cohen, & Gonzalez, 1993). In some ADHD-diagnosed samples, poor vigilance performance is correlated with low-amplitude P300 components of evoked potentials, and normalized amplitudes are sometimes seen with stimulant medication (Klorman, 1991; Michael, Klorman, & Salzman, 1981).

The results of various clinical studies of ADHD, however, are mixed, with some demonstrating no difference in vigilance performance between diagnosed and control groups (Breen, 1989; Corkum & Siegel, 1993; Schachar, Logan, Wachsmuth, & Chajczyk, 1988) or normal performance in a large proportion of diagnosed groups (Halperin et al., 1990). Other studies show little difference in CPT performance between children diagnosed with ADHD and children with other psychiatric or learning disorders (Dienske, deJonge, & Sanders-Woudstra, 1985; Robins, 1992), and still others show a high rate of poor CPT performance even among non-diagnosed normal controls (Trommer et al., 1988). Heterogeneity of ADHD-diagnosed groups is often problematic, and patterns of CPT performance may depend in part on the presence or absence of such features as hyperactivity (Barkley et al., 1992; Goodyear & Hynd, 1992), anxiety (Pliszka, 1992), learning disabilities (Tarnowski, Prinz, & Nay, 1986), conduct disorder (Halperin, 1991; Halperin et al., 1990; O'Brien et al., 1992), and other comorbid psychiatric disorders (Halperin et al., 1993). The centrality of "attention deficits" for a diagnosis of ADHD therefore may be questioned, particularly since CPT results often are not correlated with parent-teacher behavior ratings (DuPaul et al., 1992).

Poorer vigilance performance and steeper decrement functions often are associated with other clinically relevant symptoms and diagnoses, including reading and other learning disabilities (Aman, 1979; Beale, Matthew, Oliver, & Corballis, 1987; Berch & Kanter, 1984; Kirchner & Knopf, 1974; Swanson, 1981), low academic achievement (Campbell et al., 1991; Edley & Knopf, 1987), conduct disorder (Lueger & Gill, 1990), mental retardation (Berch & Kanter, 1984; Crosby, 1972; Kirby, Nettlebeck, & Bullock, 1978; Kirby, Nettlebeck, & Thomas, 1979; Semmel, 1964; Tomporowski & Allison, 1988), both heterozygous and homozygous sickle-cell syndrome (Brown et al., 1993), depression (Buchsbaum et al., 1988; Byrne, 1976; Rund et al., 1992), and anxiety (Goetsch & Adams, 1990; Kopp, 1989). Diminished performance on vigilance tasks is related to brain injury (Berch & Kanter, 1984; Chadwick, Rutter, Shaffer, & Shrout, 1981; Kaufmann, Fletcher, Levin, Miner, & Ewing-Cobbs, 1993; Parasuraman, Mutter, & Molloy, 1991; Rosvold et al., 1956; Timmermans & Christensen, 1991), as well as to risk factors for brain damage, such as chronic hypoxia in children (O'Dougherty et al., 1984) and prenatal exposure to marijuana (Fried, Watkinson, & Gray, 1992). The effect of prenatal alcohol exposure on sustained attention varies across studies (Boyd, Einhart, Greene, Sokol, & Martier, 1991; Streissguth et al., 1986). A variety of central nervous system disorders also may be associated with poor vigilance performance, including seizure disorders (Mirsky et al., 1991), Parkinson's disease with bradyphrenia (Mayeux, Stern, Sano, Cote, & Williams, 1987), Alzheimer's disease (Parasuraman & Haxby, 1993), multiple sclerosis (Filley, Heaton, Nelson, Burks, & Franklin, 1989; Rao, Leo, Bernardin, & Unverzagt, 1991), multi-infarct dementia, and other dementias (Mirsky et al., 1991).

Personality

Personality factors that may affect the ability to sustain attention are less well studied. However, there are indications of at least interaction effects of extraversion/introversion (Berch & Kanter, 1984; Fagerstrom & Lisper, 1977; Kirkcaldy, 1980; Matthews, 1989; Matthews et al., 1988; Matthews, Davies, & Lees, 1990), field dependence/independence (Berch & Kanter, 1984), and Type A personality (Perry & Laurie, 1992). Ability to cope with boredom may improve vigilance performance (Hamilton, Haier, & Buchsbaum, 1984).

Physiological State

The subject's physiological state also affects vigilance performance. Medications classified as central nervous system stimulants, such as dextroamphetamine and methylphenidate, appear to reduce error rates, decrement rates, reaction time, and susceptibility to distraction not only in hyperactive or ADHD groups (Adams, 1982; Aman, Kern, McGhee, & Arnold, 1993; Barkley, 1977; Coons, Peloquin, & Klorman, 1981; Coons, Klorman, & Borgstedt, 1987;

deSonneville, Njiokiktjien, & Hilhorst, 1991; Fitzpatrick, Klorman, Brumaghim, & Borgstedt, 1992; Garfinkel et al., 1986; Matier, Halperin, Sharma, Newcorn, & Sathaye, 1992; Michael et al., 1981; Rapport, DuPaul, Stoner, & Jones, 1986; Rapport et al., 1987), but also in normal samples (Aman, Vamos, & Werry, 1984; Rapoport et al., 1978), and in samples of mixed psychiatric inpatient children (Rapport, Carlson, Kelly, & Pataki, 1993). Similarly, a 32-mg dose of caffeine, which is equivalent to the amount of caffeine in a typical cola drink and less than that of a cup of coffee, improved auditory vigilance hit rates and visual reaction time (Lieberman, Wurtman, Emde, Roberts, & Coviella, 1987). Caffeine given in the early morning also improved overall vigilance performance during late morning (Smith, Kendrick, & Maben, 1992). Glucose improved reaction-time and frustration tolerance in normal 6- to 7-year-olds (Benton, Brett, & Brain, 1987). In contrast, central nervous system depressants tend to impair vigilance performance. For example, long-term use of benzodiazepines was associated with poor vigilance performance (Golombok, Moodley, & Lader, 1988). Alcohol intoxication lowered hit rates and increased the vigilance decrement slope (Rohrbaugh et al., 1988). Fatigue and sleep deprivation also reduce vigilance task and other sustained performance measures (Krueger, 1989; Rogers, Spencer, Stone, & Nicholson, 1989).

Arousal Level

The concept of arousal often is invoked in attempts to explain the effects of medication, fatigue, and stressful stimulation, such as noise, on human performance. According to this view, the level of performance depends on an optimum level of activation produced by sensory stimulation of the reticular activating system and its subsequent projections (Mirsky et al., 1991). Performance as a function of arousal level thus would take the classic inverted-U shape predicted by the Yerkes-Dodson law of motivation (Loeb, 1981).

Unfortunately, the relationship between physiological measures of "arousal" and vigilance performance is not consistent across studies and types of measures, which may include skin conductance, heart rate, electroencephalography (EEG), cortical evoked potentials (EP), and blood chemistry. For example, early studies showed no relationship between changes in skin conductance and response latencies (Thackray, Bailey, & Touchstone, 1977). However, studies of electrodermal and other physiological indices of the arousal levels of depressed patients indicated that individuals classified (APA, 1980) as psychotic depressives showed lower arousal levels than normals (hypoarousal) while neurotic depressives exhibited higher levels (hyperarousal). Using a hypothesized model of vigilance as a U-shaped function of arousal level, Byrne (1976) found that both groups of depressed subjects detected fewer signals than normal controls, that psychotic depressives had a lower false alarm rate than controls, and that neurotic depressives had a higher false alarm rate than either controls or psychotic depressives. Psychotic depressives also had a steeper decrement function than controls. Similarly, when anxiety patients were classified as electrodermally labile or stabile, with labile subjects showing slower habituation rates and longer electrodermal responses to verbal stimuli, the electrodermally labile subjects showed no performance decrement over time, while the stabile group had longer reaction times (Kopp, Mihaly, Linka, & Bitter, 1987). In another study, labile subjects demonstrated a rapid vigilance decrement when stimuli were degraded, suggesting decreased perceptual sensitivity, but showed better performance in short periods of high attention demand (Munro et al., 1987).

Matthews, Davies, and Lees (1988) found that higher scores on a self-report measure of arousal were associated with generally better perceptual sensitivity as compared to low-arousal subjects. These authors subsequently reported not a curvilinear but a positive linear relationship between self-reported arousal and more efficient performance on demanding attention tasks (Matthews, Davies, & Lees, 1990). They also suggested that higher arousal increases attention resource availability (Matthews, Davies, & Holley, 1990). In other studies, response latencies and omissions increased

as muscle action potential decreased, suggesting that lowered tension degraded performance (McGrath et al., 1968). On the other hand, increases in motor activity during a vigil also were associated with poorer performance (Baker, 1959). EEG records during vigilance task performance showed significant increases in alpha and theta activity, decreases in beta activity, and concurrent performance decrements across the time period of a vigil (O'Hanlon & Beatty, 1977). Some evidence suggested differential sensitivity of each waveband, as well as of amplitude and latency of evoked potentials, to performance of specific types of tasks (Gale, 1977). As noted above, abnormal amplitude of the P300 component of event-related potentials (ERPs) has been associated with poor vigilance performance in patients classified as schizophrenic (Strandburg et al., 1990; Strandburg et al., 1994) or attention-deficit disorder (Coons et al., 1987; Klorman, 1991; Michael et al., 1981). Alcoholic men and their sons also demonstrated abnormal electrophysiological responses to performance of CPT tasks (Whipple, Berman, & Noble, 1991). In studies of blood chemistry changes, mean adrenaline levels dropped across a vigil, in concert with performance decrements, while noradrenaline levels did not change significantly (O'Hanlon, 1965). Taken together, these results suggest that measures thought to reflect lower autonomic or electrocortical arousal are associated with performance decrements and/or decreased response speed, but it may be that unusually high levels of arousal impair performance as well.

Interactions

Vigilance performance appears to depend on a variety of interaction effects. In addition to the effects noted above, demographic factors may interact with other subject or situational variables to influence vigilance. For example, performance of older adults improved in the afternoon, while performance of younger adults did not (Davies & Davies, 1975). Older and younger children with diagnoses of ADHD, Reading Disability (RD), or both, demonstrated different patterns of errors on vigilance tasks, and improved CPT performance with age was found for children with RD but not ADHD (Kupietz, 1990). Closed-head injury was related to poorer CPT performance for children than for adolescents as compared to age-mates, and additional interactive effects of age and severity of injury were found (Kaufmann et al., 1993). In persons with schizotypal personality disorder, only negative symptom schizotypy was significantly correlated with attention dysfunction (Kendler et al., 1991). Benzodiazepines impaired vigilance performance in normal controls, but not in anxiety patients (Koelega, 1989). Subject variables also affect vigilance through interactions with task parameters. For example, Tomporowski and Allison (1988) found that mildly mentally retarded adults performed poorly relative to normals only on a vigilance task requiring detection of a sequence of stimuli, and not on a task involving response to a single stimulus. Schizophrenics performed more poorly than alcoholics and normal controls on a variety of CPT formats, but particularly on auditory and combined auditory/visual tasks (Mussgay & Hertwig, 1990). Interactive effects of subjects' test anxiety and their beliefs about the nature of the task were demonstrated by Geen (1985). Vigilance decrements in this study were greatest for highly test-anxious subjects who believed the task was a test of their own ability. In contrast, persons low in test anxiety showed greater decrements if they believed that the task was designed to evaluate the usefulness of the vigilance test. Interactions of environmental and subject variables also have been reported. For example, noise effects in reducing vigilance performance may be attenuated by a moderate dose of alcohol (Patel, 1988). Alcohol effects were more pronounced for a prolonged spatial discrimination vigilance task than for a brief verbal information-processing CPT (Linnoila, Erwin, Cleveland, Logue, & Gentry, 1978).

EXPLAINING VARIATIONS IN VIGILANCE PERFORMANCE

Results of prior studies support the view of "attention" as a multifaceted construct, with numerous underlying substrates and with equally

numerous possibilities for measurement. Group and individual variations in well-described vigilance phenomena, such as the decrement slope, the "hit" rate, and the "false alarm" rate, are not explained fully by any of the existing theories of attention (Loeb & Alluisi, 1977; Parasuraman, 1985; Warm, 1977). Cognitive models of attention have provided interesting metaphors for attentional processes, but none are adequate for explaining the multi-faceted nature of attention. In addition, most are limited by efforts to explain the hypothetical construct of attention in terms of other hypothetical constructs, leading to substantial circular reasoning. Although neurological arousal-state models have been quite useful in describing between-subjects variations in overall error rates and within-subject variations over time and associated arousal changes, results are equivocal regarding whether a monotonic or an inverted-U relationship exists between arousal level and vigilance performance (Deese, 1955; Hebb, 1955; Hockey, 1984; Matthews et al., 1988; Matthews, Davies, & Lees, 1990; Parasuraman, 1984; Welford, 1962). In addition, as Hockey (1984) noted, it often is possible to fit performance data to the U-shaped function by assuming effects on arousal. Hockey emphasized the importance of conducting independent evaluation of arousal changes, rather than inferring arousal changes from performance data. Furthermore, arousal changes appear more likely to affect overall error rates than the decrement function (Parasuraman, 1984), and arousal theories often do not address the consistent findings of environmental and task effects on vigilance performance, as well as the typically low intercorrelations between different measures of arousal (Loeb & Alluisi, 1977).

The failure of any one theory of attention to account for well-described vigilance phenomena, coupled with the diversity of factors shown to affect vigilance performance, has led many researchers to an elemental, or interactive approach to explaining variations in vigilance performance (Hancock, 1984). Such an approach involves consideration of the specific effects and interactive effects of individual factors. Several investigators (Hancock, 1984; Hockey, 1984; Loeb & Alluisi, 1977; Loeb, 1981; Lysaght, 1982; Parasuraman, 1985; Parasuraman & Davies, 1977; Warm, 1977) suggest that task parameters, environmental stressors, and subject variables may yield complex interaction effects on overall vigilance performance and on performance decrements over time. Variations in the effects of specific variables, such as noise, therefore may depend on levels of other variables, such as task difficulty and/or the subject's physiological state. Some evidence for complex interactive effects of task, environmental, and subject factors has been demonstrated. For example, Smith and Miles (1986) demonstrated several interesting interactions, including post-meal impairments in signal detection that were improved by the presence of noise during the task, although noise also increased the false alarm rate. In the same study, low-anxious subjects showed the greatest post-lunch impairments in performance, although no differences across anxiety groups was seen after a night meal. As noted in many of the studies described in the preceding sections, task parameters may interact with other task characteristics or environmental variables to affect vigilance performance. Similarly, the effects of environmental factors may depend on subject characteristics or task demand, while the effects of subject variables may differ depending on characteristics of the task or the situation.

Effects of task parameters and other manipulations also may be seen for one CPT measure, but not another. For example, Matier et al. (1992) reported improved CPT performance with stimulant medication for both aggressive and nonaggressive children with ADHD, but only on omission and "X-only" commission errors, not on "A-not-X" and "A-only" commission errors. Other researchers suggested that the overall vigilance level (hit rate and false alarms) may be related to "effort demand" of the task, while the vigilance decrement over time may be related to the use of sensory or cognitive stimuli (Koelega, Brinkman, Hendricks, & Verbaten, 1989). Each of these studies illustrates interactive effects of some factors, and suggests the possibility of additional interactions across all three classes of factors. However, al-

though interactive effects of task demands, environmental factors, and subject characteristics often are assumed or inferred, no studies have adequately examined examples of all such effects simultaneously.

DISCUSSION

Review of empirical studies of vigilance task performance revealed that tests of sustained attention are affected by a large number of factors. Such factors include a variety of task, environmental, and subject characteristics. In addition to main effects of these variables, interaction effects appear to contribute further to variation in vigilance task performance. Unfortunately, relatively few studies have been designed to evaluate such interactions.

Furthermore, the existing literature lacks systematic attempts at describing patterns of effects within the context of a developmental neurofunctional theory of attention (Cooley & Morris, 1990). A few such efforts are noteworthy (e.g., Mirsky et al., 1991), but additional empirical study is needed to support these theories. Without corroboration of "arousal level" by independent physiological measures, even a neurologically based arousal theory cannot account for all observed effects on vigilance performance (Hockey, 1984). The use of taxonomic, or elemental approaches, such as those suggested by Lysaght (1982), Hockey (1984), Hancock (1984), and Parasuraman (1985), appear more useful in clarifying the nature of the variables that affect vigilance performance, and in elucidating the common and/or disparate systems involved in these effects.

Additional research, using such an elemental framework, is needed to clarify the nature of attention and the implications of vigilance task performance measures. Of particular importance will be studies that demonstrate patterns of interactive effects of task, environmental, and subject factors. Also needed is further elucidation of possible differential effects on the different measures derived from vigilance tasks (e.g., omissions and false alarms). Additional analysis of omission and false alarm error patterns is needed. The work of Halperin (1991) and associates (Halperin et al., 1988; Halperin, Sharma, et al., 1991; Halperin, Wolf, et al., 1991, Halperin et al., 1992) and Kupietz (1990) provides some indication that false alarm error analysis should include consideration of the type of commission errors observed.

For researchers using the vigilance task, the combination of omissions and commissions into a single "error rate" is unwarranted, and may cloud or obscure effects (Halperin, Wolf, et al., 1991). Instead, exploration of the differences and changes in omission and false alarm error rates may help to elucidate the relationship of these performance measures to factors known to affect overall vigilance performance. If reliable dissociable effects on the two measures can be shown for manipulations of different factors, it may be that categorical descriptions of effects can provide support for theoretical and/or neuroanatomical models of the multi-faceted construct of attention. Similarly, it may prove useful to classify subjects on the basis of multivariate response characteristics, such as tendencies to demonstrate high or low hit rates, high or low false alarm rates, slow or fast response latencies, and steep or gradual performance decrements. Such classification may help to clarify the nature and basis for performance differences between previously studied groups classified on such dimensions as extraversion/introversion, field dependence/independence, electrodermal lability/stability, ERP amplitude and latency, or clinical diagnostic categories. Support for the utility of this approach is found in the work of Mirsky and his associates (Mirsky et al., 1991), who demonstrated different patterns of errors on CPT tasks by patients with different seizure types. Similarly, Barkley et al. (1990) found comparable omission rates for groups diagnosed with Attention-Deficit Disorder with Hyperactivity (ADD+H) and without Hyperactivity (ADD-H), but more commission errors for the ADD+H group.

The variety of factors affecting vigilance task performance suggests that the use of such tasks in clinical or other applied settings may be problematic. Specifically, poor task performance may reflect individual subject differences other

than global "attention deficits." Further evaluation of individual patients may be needed to rule out these possibilities. In addition, clinical settings may not allow adequate control of task parameters and environmental factors that can affect performance. Without such control, comparisons across subjects, or even within subjects across time, are not appropriate. Efforts at collecting normative data will be problematic for similar reasons, with resulting problems in generalizing to uncontrolled situations.

On the other hand, computerized vigilance tasks may continue to be quite useful in research settings where the goal is the study of attentional processes, rather than identification or diagnosis of individuals with specific deficits. On the basis of review of empirical findings regarding vigilance tasks, the following guidelines are suggested for researchers using computerized CPT and other vigilance tests:

1. Task parameters should be described carefully and comprehensively to allow both for replication and for comparison across studies. At a minimum, reports should include descriptions of signal type, background stimuli, event rate, signal duration, interstimulus interval, signal-to-noise ratio, task duration, and response requirements.

2. When task parameters are the focus of study, experimental designs should avoid confounding different, but related, parameters. For example, effects of interstimulus interval often are confounded either with task duration or background event rate.

3. Careful description of environmental and situational variables should be included to allow replication and comparison. When study designs do not allow control of such variables as time of day, the possible effects of such factors should be considered.

4. Comparison of groups defined on the basis of subject characteristics must use reliable measures of the subject variable of interest, and must equate groups in terms of other characteristics. Results of such studies must be considered correlational, and cause-effect statements should be avoided.

5. Whenever feasible, the interactive effects of manipulated variables and subject factors should be evaluated to add to understanding of the complex relationship between the ability to sustain attention and the variety of factors affecting this ability.

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