# Research Article

# SEARCHING NIGHT AND DAY:
## A Dissociation of Effects of Circadian Phase and Time Awake on Visual Selective Attention and Vigilance

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**Abstract**—*How does sleepiness affect selective attention? We studied the effect of circadian phase and time awake on visual search. The generalized-cognitive-slowing hypothesis predicts that search rate will be slower, feature guidance less effective, and response time (RT) lengthened when observers are sleepy. Observers performed spatial-configuration (finding a 5 among 2s) and conjunction (finding red vertical among red horizontal and green vertical) search tasks during 38 hr of wakefulness under constant conditions. Adverse circadian phases and elapsed time awake did lead to increased RT (corrected for errors). However, contrary to the hypothesis, search rates (indexed by RT × Set Size slopes) were constant across the protocol. This was true for conjunction as well as for spatial-configuration search, indicating that feature guidance was also insensitive to sleepiness. The locus of sleepiness effects on search is probably downstream from the bottleneck of attentional selection. Observers did trade accuracy for speed when sleepy. This implicates decision-stage impairments.*

How does sleepiness affect attention? The question is complex because both sleepiness and attention have multiple components. Sleepiness is governed by the joint influence of two processes: the circadian pacemaker and the sleep homeostat (Åkerstedt & Folkard, 1995). The pacemaker generates a near-24-hr rhythm that has been shown to control or influence a wide variety of physiological and psychological functions. The homeostat reflects the current drive for sleep, which increases with time awake and decreases in a nonlinear fashion during sleep (Dijk & Czeisler, 1995).

Attention is an umbrella term for a diverse set of psychological phenomena. Here we discuss two aspects of attention: (a) vigilant attention, the ability to sustain concentration on a task, and (b) selective attention, the ability to single out desired stimuli for processing at the expense of undesired stimuli. Selection and vigilance are known to be separable, and states of heightened vigilance can result in reduced selection (Parasuraman, Warm, & See, 1998).

Many aspects of cognition are modulated by time of day (decision making—Bodenhausen, 1990; memory—May, 1999; processing speed—Monk & Carrier, 1997). However, because circadian phase and homeostatic sleep drive change together throughout the day, time of day confounds these variables. Long-term sleep-deprivation protocols, in which subjects are kept awake for more than 24 hr, typically reveal an overall decline in alertness and performance as time awake increases, with a circadian effect superimposed (De Gennaro, Ferrara, Curcio, & Bertini, 2001). To properly decouple these factors, the phase angle between the circadian pacemaker and the sleep/wake cycle must be varied, either within subjects, as in forced desynchrony studies (Carskadon, Labyak, Acebo, & Seifer, 1999), or between subjects, as in the protocol we introduce here.

In general, decreased alertness is associated with decreased accuracy and slowed processing (Dinges & Kribbs, 1991). Studies of attention have focused primarily on vigilance, which is quite sensitive to circadian phase and sleep deprivation (Dinges et al., 1997). Little is known about circadian or homeostatic control of selective attention. There are promising studies indicating time-of-day effects on selection (Broadbent, Broadbent, & Jones, 1989; Morton & Diubaldo, 1993), but no experiments that allow effects of the pacemaker and the homeostat to be disentangled.

Sleepy subjects' performance decrements on a broad range of tasks, from choice reaction time (RT) to cognitive throughput to short-term memory tasks (Babkoff, Caspy, & Mikulincer, 1991; Babkoff, Mikulincer, Caspy, Kempinski, & Sing, 1988; Dijk, Duffy, & Czeisler, 1992), have been explained by two factors: lapsing and cognitive slowing. Lapsing refers to the tendency of sleepy subjects to fall into brief microsleeps, leading to missed stimuli or dramatically slowed responses (Williams, Lubin, & Goodnow, 1959). Cognitive slowing refers to an overall increase in response latency; even the fastest responses tend to be slower when subjects are sleepy (Dinges, 1992).

Lapses represent a global state lability in the brain: a heightened tendency to drop into sleep. Cognitive slowing is also held to be a global phenomenon because it affects a wide range of tasks. However, the tasks employed in sleep-deprivation studies typically do not allow effects of different processing stages to be separated. Cognitive theorists distinguish between three processing stages: perceptual, decision, and response (Pashler, 1998). Visual selective attention is held to mediate between perception and decision. Selection proceeds in two stages, according to an influential class of models (feature integration theory—Treisman & Sato, 1990; guided search theory—Wolfe, 1994). A parallel, preattentive front end coarsely codes information about basic features like color, size, and motion. This information generates a salience map (Li, 2002) that guides selective attention to likely target stimuli. Items are made salient by differing from neighboring items (Nothdurft, 1991) or resembling desired targets (Duncan & Humphreys, 1989). Selective attention, in this view, binds object features into holistic representations ("object files"—Kahneman, Treisman, & Gibbs, 1992), which are passed on to the decision stage. Data from visual search experiments suggest that focal attention can be deployed at 20 to 30 Hz.

Our question in this study was whether performance deficits associated with reduced alertness can be attributed to either a slowing of preattentive guidance processes or the rate of selective attention itself. We employed two well-understood visual search tasks, spatial-configuration search and conjunction search. In a spatial-configuration task, stimuli are designed to be roughly identical from the point of view of preattentive salience mechanisms, differing only in relative spatial ar-

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rangement of line segments; we used a block *5* among block *2*s. Because no guidance is available, spatial-configuration search rate (measured by the RT × Set Size slope) is held to represent the rate at which attention is shifted from item to item. In the conjunction task, subjects are asked to search for a target composed of two preattentively discriminable features that are present separately in the distractors: in this case, a red vertical bar among red horizontal and green vertical bars. Items that are red or vertical will generate more activity on the salience map than green or horizontal items. Even with some noise, the red vertical item will be among the most salient items. Attention is directed to the most salient objects, and they will usually include the target. Because the number of items that must be examined is a fraction of the total number, search slopes are substantially shallower in this task, typically one half to one third those observed in spatial-configuration tasks.

Given this theoretical framework, we reasoned that we might see the impact of reduced alertness on visual search performance in three ways. First, cognitive slowing and reduced attentional capacity might be expressed in a reduction of search rate, the speed at which attention moves. In this case, sleepiness would be associated with increased search slopes for both tasks. Second, conjunction slopes might increase relative to spatial-configuration slopes, which would indicate that reduced alertness affects processes that guide attention to salient targets. Third, effects outside the selection bottleneck might show up in the intercepts of the RT × Set Size slopes for the two tasks. We would interpret this as a "nonsearch" effect on perceptual, decision, or response stages; further experiments would be required to precisely determine the contribution of each stage to the effect. These three data patterns are not mutually exclusive, and we reasoned that we might see all three effects in the data.

In addition, remember that alertness is no more a unified phenomenon than is attention; the effects of the circadian pacemaker and the sleep homeostat are separable. In this study, we analyzed the results as a function of both time awake and circadian phase in order to determine whether these two components of alertness affected selection in the same way.

For comparison, we also included a standard vigilance assay, the psychomotor vigilance task (PVT; Kribbs & Dinges, 1994), known to be sensitive to circadian phase and time awake. The PVT requires subjects to respond to a series of infrequent, unpredictable events during a 10-min episode. RT and missed events (lapses) are the primary dependent variables. Subjective alertness was also recorded via a visual analog scale (VAS).

## METHOD

### Subjects

There were 54 participants (27 females and 27 males) ages 20 to 40 (*M* = 26.99 years, *SD* = 6.22 years).

### Design

As discussed, circadian phase and the sleep homeostat covary during sleep-deprivation protocols. However, prior to the protocol described next, our subjects underwent a 7-day rotating-shift work simulation (see Horowitz, Cade, Wolfe, & Czeisler, 2001). This procedure resulted in a wide range of clock times, from 9:01 p.m. to 11:02 a.m. (*M* = 4:31 a.m., *SD* = 3:44), at which the midpoint of the melatonin secretion episode occurred during *constant routines* (CRs; see the next paragraph)

that began at approximately the same clock hour. This ensured that circadian phase and the sleep homeostat were decoupled across subjects.

### CR

The purpose of the well-established CR method (Minors & Waterhouse, 1983) is to minimize effects of any external stimuli on physiology, either by keeping those stimuli constant or by distributing them across the CR (Duffy & Dijk, 2002). Subjects arrived at the laboratory at 5:00 p.m. and were placed in individual suites, each equipped with a bed and a computer. Subjects were asked to remain in bed in a semirecumbent posture. Beds were adjusted so that subjects' heads were approximately at a 45° angle. Subjects were restricted to bed rest while on this protocol; bedpans or urinals were provided when necessary. Saliva samples, later assayed for melatonin, were collected hourly. Light levels were maintained at less than 8 lux in the angle of gaze to minimize melatonin suppression. Meals were provided in hourly snacks. Subjects were required to remain awake throughout the protocol, and a technician was always present with each subject to monitor and help maintain wakefulness. Wakefulness was also monitored via electroencephalogram. A computer monitor and keyboard were placed on a table over each bed once per hour for the 30-min battery of performance tests, which included the search, vigilance, and subjective-alertness tests reported here. The CR lasted for 38 hr. Eight hours of recovery sleep followed the CR. For more experimental details, see Horowitz et al. (2001).

### Search tasks

For the spatial-configuration search task, the target was a white block numeral *5* measuring 0.8° × 1.2° of visual angle, and the distractors were white block numeral *2*s on a black background. For the conjunction search task, the target was a red vertical bar (0.4° × 2.1°), and distractors were divided equally between green vertical bars and red horizontal bars (2.1° × 0.4°) on a black background.

Set sizes of 10, 20, 30, and 40 items were used. A target was present on 50% of trials. Each trial was preceded by a white fixation cross for 500 ms. Subjects were instructed to press the "/" key for "yes" and the "z" key for "no." There were 100 trials per session. Subjects were asked to respond as quickly and accurately as possible. The two search tasks alternated so that each search task was given once every 2 hr. Subjects practiced both search tasks for at least 2,000 trials during the simulated work shifts that preceded the CR.

We used median RTs of correct trials, rather than means, to minimize the effect of lapses or microsleeps without explicitly deciding which long RTs reflected genuinely long searches and which represented lapses. Median RTs were regressed on set size to compute the RT × Set Size slopes. Because interpreting RT data when error rates are inconstant (and low) across conditions can be difficult, we also computed a unified measure of capacity (Townsend & Ashby, 1983) by dividing median RT by proportion correct to yield a *corrected RT*. Corrected RT is identical to uncorrected RT if accuracy is perfect and increases with the error rate. RT × Set Size functions were also computed from corrected RTs.

### PVT

The PVT is a sustained-attention test in which subjects are asked to make a speeded response to visual stimuli appearing at random inter-

vals of 1,000 to 9,000 ms. Subjects monitor a central rectangle for the appearance of digits, which count up from 0 every 20 ms until the response. A number of dependent variables can be derived from this task. We focus on median RT and lapses. In this task, lapses are defined as RTs greater than 500 ms (Kribbs & Dinges, 1994). The PVT was administered every 2 hr.

### Subjective sleepiness rating

Every hour, subjects were given a brief VAS mood questionnaire. For each item, a 100-mm line was presented on the computer monitor. Each end of the line was labeled with the endpoints of a subjective dimension ("alert"-"sleepy," "sad"-"happy," etc. ). Subjects moved the cursor with a mouse to indicate the point on the line that represented their current state along that dimension. Here we report data from the "alert"-"sleepy" dimension measured in millimeters toward "sleepy" and away from "alert."

### Data Analysis

#### Circadian phase

Circadian phase was estimated as the midpoint between onset and offset of the melatonin secretion episode. Onset was defined as the time that melatonin concentration reached 25% of the maximum value for the first 24 hr of the CR, and offset was defined as the time that melatonin concentration dropped below this value. Linear interpolation between samples was used to estimate melatonin onset and offset times. Two subjects (both male) were eliminated because of insuffi-
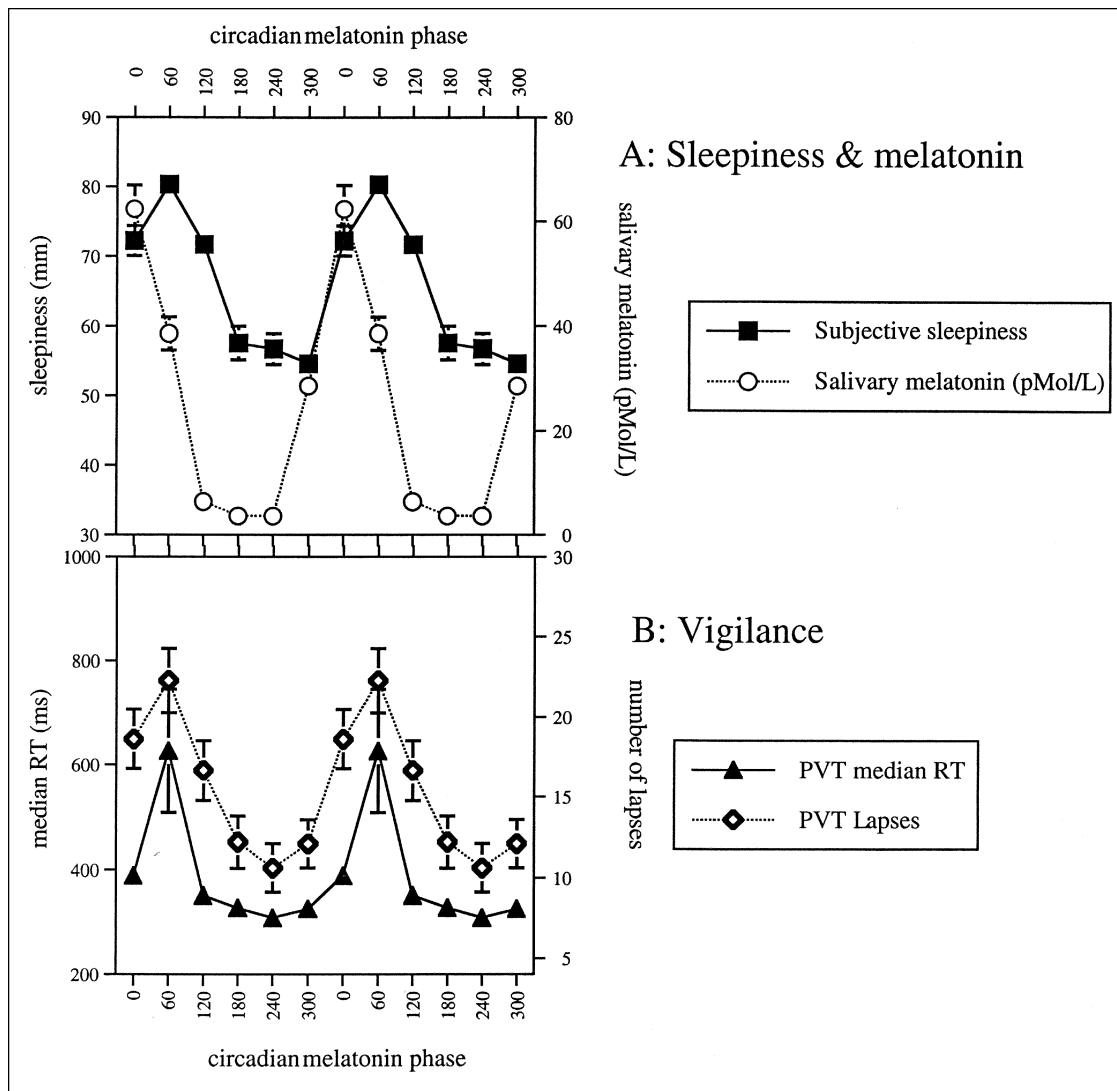


**Fig. 1.** Subjective sleepiness ratings (a), salivary melatonin concentration (a), and vigilance (b) as a function of circadian phase. Data are double-plotted against the phase of the melatonin rhythm (see Method). Two measures of vigilance from the Psychomotor Vigilance Task (PVT) are reported: median reaction time (RT) and the number of lapses (RTs longer than 500 ms). Error bars indicate the standard error of the mean.

cient melatonin data. Each test session was assigned a phase relative to the midpoint (defined as phase 0°). Circadian phase is conventionally notated in degrees, with 15° representing 1 hr. The data were grouped in 60° bins. Because each search task was given every 2 hr (30°), a bin included at least 200 trials. Our 38-hr CR covered 1.58 cycles of 24 hr, so 58% of bins (different bins from subject to subject) included data from two cycles, comprising 400 trials.

To examine the effect of time awake, we also assigned each session to a 4-hr bin based on time elapsed from the start of the CR. Each bin comprised 200 trials for each search task, except for the initial and final bins, which contained only one session (100 trials) of each task. Three subjects were missing data in either the first or last bin; for each of these subjects, the subject's mean score was used in the bin with missing data for all analyses.

### Statistical tests

Repeated measures analyses of variance were used to assess statistical significance. The standard significance criterion ($\alpha = .05$) was used. However, all effects were significant at $p < .0001$ unless indicated otherwise. Effects described as nonsignificant had a $p$ value greater than .10. We also report as marginal effects with a $p$ value between .05 and .10 (Keppel, 1991).
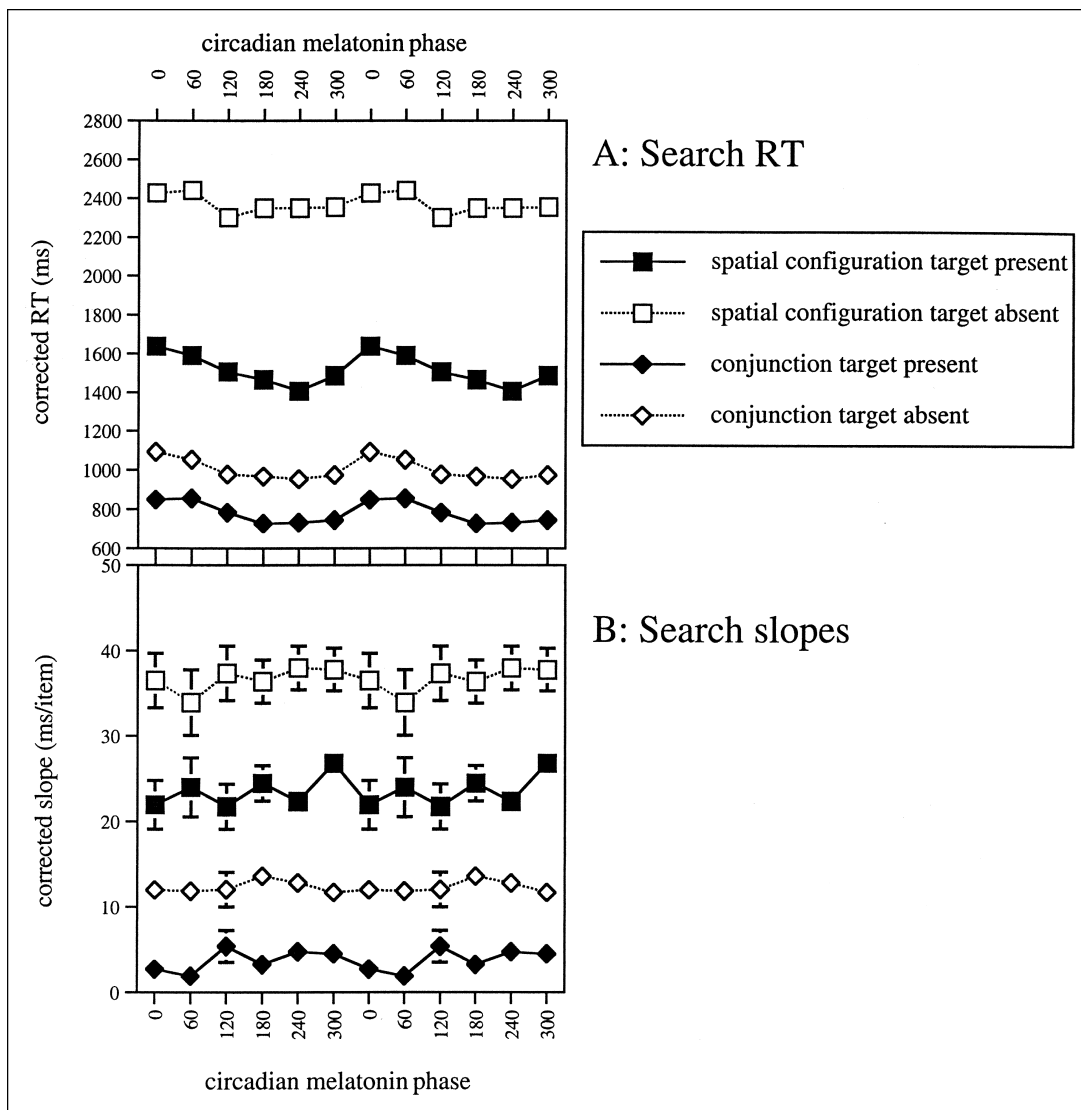


**Fig. 2.** Visual search as a function of circadian phase: overall median corrected reaction time (RT), collapsed across set size (a), and slope of the Median Corrected RT × Set Size function (b). Data are double-plotted against the phase of the melatonin rhythm. Data for the spatial-configuration task (squares) and conjunction task (diamonds) are shown separately for target-absent (open symbols) and target-present (filled symbols) trials. Error bars indicate the standard error of the mean.

## RESULTS

### Circadian Phase

We discuss the results for the circadian-phase analyses first. In all figures, good performance is indicated by lower values. The reference circadian rhythm in salivary melatonin is plotted in Figure 1a (open circles), peaking by definition at 0°. Subjective sleepiness (VAS score; solid squares) showed maximal sleepiness near 60° and maximal alertness near 240°.

Vigilance exhibited the same pattern as subjective sleepiness. Figure 1b plots two components of the PVT: median RT and number of lapses. The PVT showed the typical strong effect of circadian phase: Vigilance was most impaired around 60° (concurrent with habitual wake time for humans on a regular schedule) and peaked 180° later, at 240°.

Search performance is depicted in Figure 2. We observed expected effects of task, target presence/absence, and set size on search RT (Fig.

2a). Spatial-configuration search RTs were markedly slower than conjunction search RTs, target-absent RTs were slower than target-present RTs, and RT increased linearly with set size. All of these factors interacted, but the two-way interactions were subsumed into a three-way interaction: Target-absent RTs increased more steeply with set size than target-present RTs, and this effect was more pronounced for spatial-configuration search than for conjunction search.

The effect of circadian phase was also significant. RT was slowest at the peak of the melatonin curve and fastest at 240°. Phase did not interact reliably with any other factor, though there were two marginal interactions: a two-way interaction with target presence/absence, $F(5, 250) = 2.19$, $p = .056$, and a three-way Phase × Target Presence/Absence × Task interaction, $F(5, 20) = 2.13$, $p = .062$. Analyzing corrected RTs separately by task, we observed a greater circadian amplitude for target-present trials than for target-absent trials for spatial-
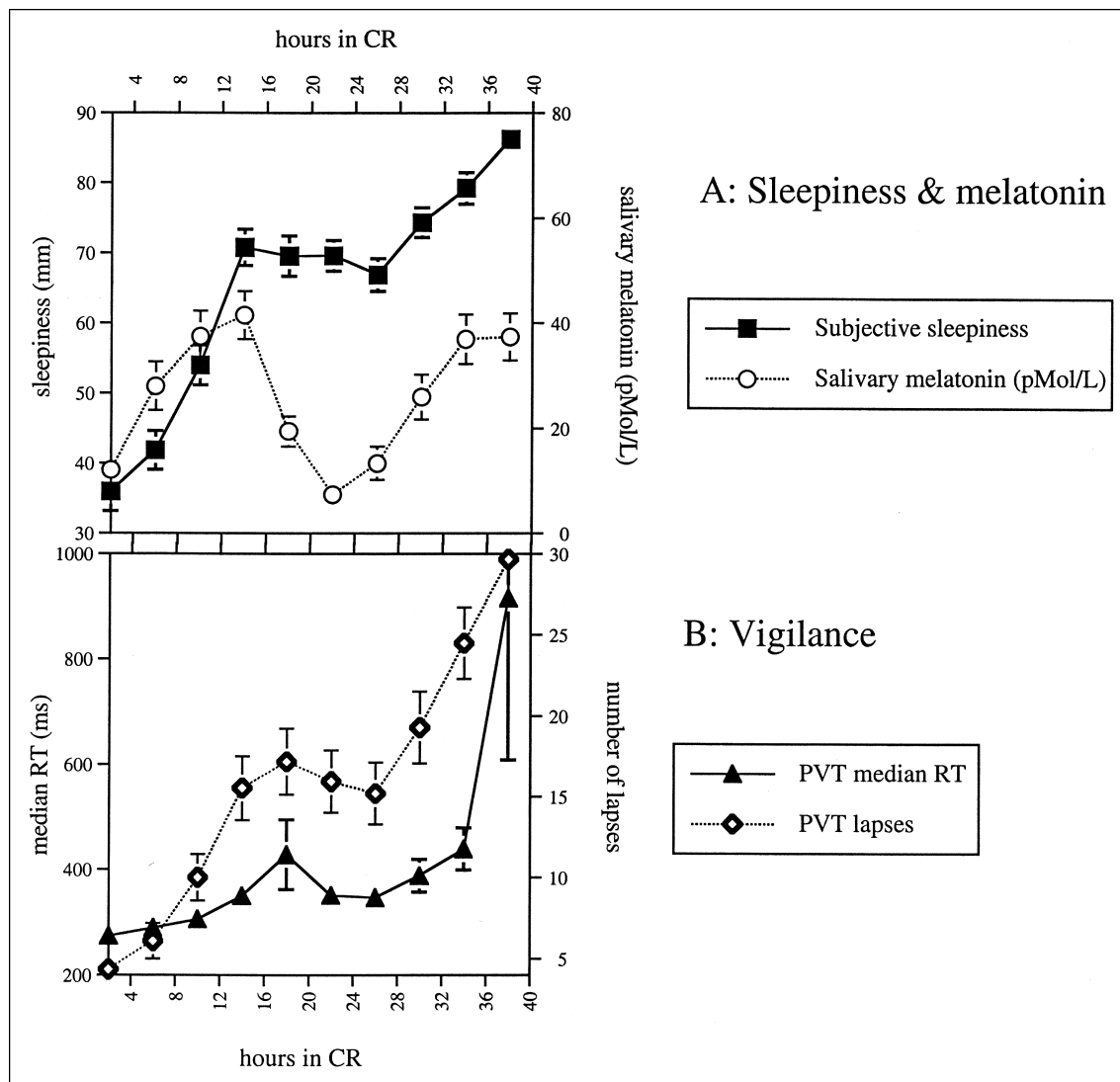


**Fig. 3.** Subjective sleepiness ratings (a), salivary melatonin concentration (a), and vigilance (b) as a function of time elapsed in the constant routine (CR). Two measures of vigilance from the Psychomotor Vigilance Task (PVT) are reported: median reaction time (RT) and the number of lapses (RTs longer than 500 ms). Error bars indicate the standard error of the mean.

configuration search, $F(5, 250) = 2.35$, $p < .05$, but not for conjunction search, $F(5, 250) = 1.37$, $p > .10$.

We also observed expected RT × Set Size slopes (Fig. 2b). Spatial-configuration search slopes were markedly steeper than conjunction search slopes, and target-absent slopes were steeper than target-present slopes. Task interacted with target presence/absence, $F(1, 50) = 5.34$, $p < .05$, because the differences between target-absent and target-present slopes were greater for spatial-configuration search than for conjunction search. We compared the mean slopes we observed here with a large, published data set (Wolfe, 1998). The target-present slope for spatial-configuration search (23.6 ms/item) was near average for such tasks, whereas the target-present conjunction slope (3.7 ms/item) was somewhat shallow. Target-absent slopes for spatial-configuration search (36.6 ms/item) were shallower than we would have predicted, but conjunction search target-absent slopes (12.3 ms/item) were in the expected range.

The results we have summarized so far were as expected. But what was the effect of circadian phase on search slope? Interestingly, circadian phase had no significant effect on search slope, $F(5, 520) = 1.09$, $p > .10$. Phase did not interact with task ($F < 1$) or with target presence/absence ($F < 1$), nor was there a three-way interaction, $F(5, 250) = 1.12$, $p > .10$.

**Time Awake**

Now we turn to the effects of time in the CR. Because our subjects did not display the full range of phase angles, circadian phase and time awake covary in these data. This is clear in the top panel of Figure 3, in which the average concentration of salivary melatonin is plotted against elapsed time. The average melatonin peak was around 14 hr, and again 24 hr later, at the end of the protocol. The residual circadian effect propagated to subjective sleepiness, which illustrates how the effects of the pacemaker and
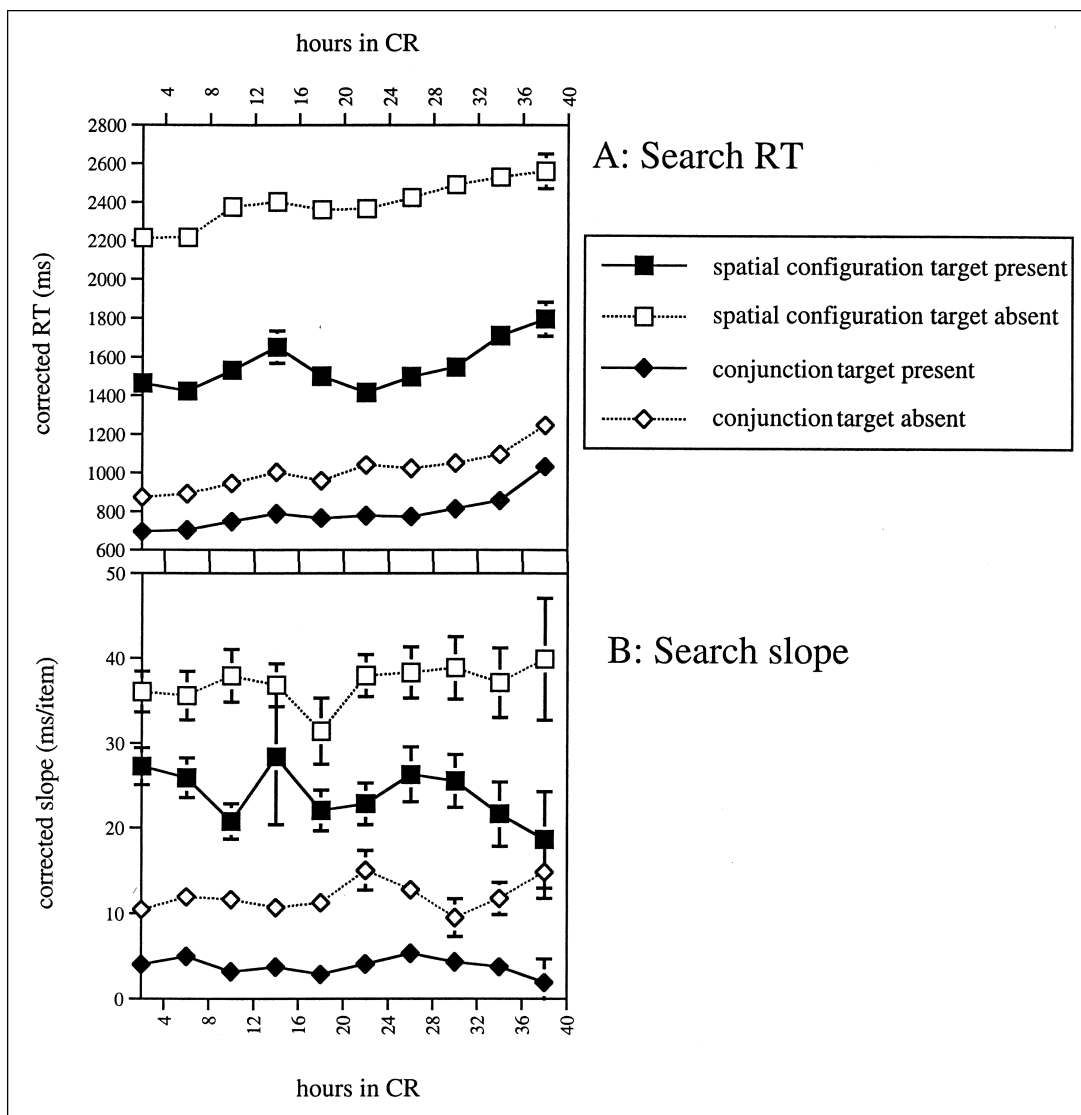


**Fig. 4.** Visual search as a function of time elapsed in the constant routine (CR): overall median corrected reaction time (RT), collapsed across set size (a), and slope of the Median Corrected RT × Set Size function (b). Data for the spatial-configuration task (squares) and conjunction task (diamonds) are shown separately for target-absent (open symbols) and target-present (filled symbols) trials. Error bars indicate the standard error of the mean.
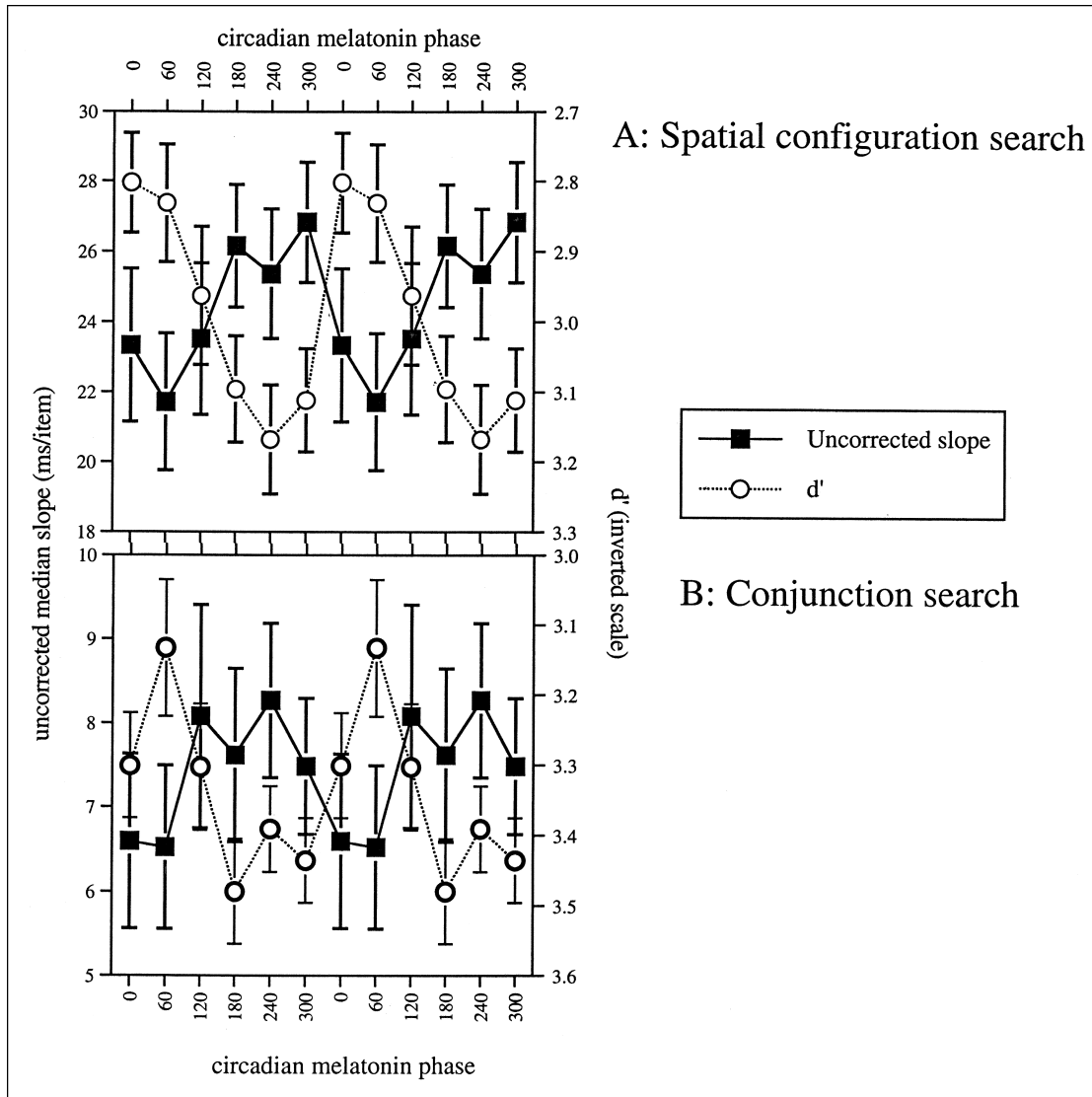
**Fig. 5.** Visual search $d'$ and slope of the Median Uncorrected Reaction Time × Set Size function as a function of circadian phase in the spatial-configuration task (a) and conjunction task (b). Data are double-plotted against the phase of the melatonin rhythm. Slope results are collapsed across target presence/absence. Note that the $d'$ scale is inverted, so that good performance is consistently plotted downward. Error bars indicate the standard error of the mean.

the sleep homeostat combine. The rising leg of the curve from 2 to 14 hr reflects the increase in both circadian-dependent and time-awake-dependent sleepiness. After the average melatonin peak, sleepiness plateaued, because the circadian component (tracked by the melatonin curve) was decreasing, counteracting the continually increasing time awake. Once the average melatonin curve began to rise again, after 26 hr, sleepiness climbed again. Similar patterns can be seen in vigilance (Fig. 2b). Both lapses and median RT climbed steadily throughout the protocol, except for a brief respite from 18 to 26 hr in.

Figure 4 shows search data as a function of time in the CR. The standard search effects (task, set size, etc.) were again replicated. However, because these are the same data we have already discussed for the phase analysis, we discuss here only the effect of hours in the protocol and any interactions with that factor. Time awake had a significant effect on me-

dian corrected RT (Fig. 4a), and it interacted with target presence/absence, $F(9, 441) = 1.95$, $p < .05$, such that target-absent RTs appeared to increase more steeply with elapsed time than did target-present RTs, the opposite of the pattern observed with phase. There was also a trend toward a three-way Hours in CR × Target Presence/Absence × Set Size interaction, $F(27, 1323) = 1.39$, $p = .09$, which was not supported by analysis of slope data. Unlike phase, time elapsed in the protocol did not affect overall RT differently in the two tasks (all $ps > .10$). Time elapsed in the protocol did not affect slope (Fig. 4b; all $ps > .10$)

### DISCUSSION

We found that the RT × Set Size slope was constant across all circadian phases and 38 hr of wakefulness. This was true for both spatial-

configuration and conjunction search tasks. Simultaneously, we observed large increases in overall RT at adverse circadian phases and extended time awake. What do these results indicate about how sleepiness affects selection?

We proposed three possible ways in which generalized cognitive slowing might affect selection. First, one obvious prediction was that sleepiness would be accompanied by slowed shifts of attention, which would have been reflected in increased RT × Set Size slopes for both search tasks. Second, sleepiness might be accompanied by reduced efficiency of guidance, leading to an increase in conjunction slopes relative to spatial-configuration slopes. Neither of these effects was observed. Search slope was remarkably unaffected by sleepiness, whether analyzed in terms of circadian phase or in terms of time elapsed in the protocol. We conclude, in terms of the two-stage theory of selection, that neither the parallel front end nor the deployment of focal attention is affected by cognitive slowing associated with sleepiness.

However, the third prediction, an increase in the RT × Set Size intercept for both search tasks, was borne out. This effect may involve perceptual, decision-stage, or response-stage effects of sleepiness. Humphrey, Kramer, and Stanny (1994) have provided convincing physiological evidence that the response stage is unaffected by sleepiness. We cannot rule out effects of sleepiness on early perceptual processes. However, we can infer impaired decision processes. Figure 5 plots speed and accuracy separately. Specifically, the graph shows slope computed on *uncorrected* median RTs and $d'$[1] as a function of phase (similar effects were observed in the time-elapsed data). Accuracy was, of course, significantly better for the conjunction task than for the spatial-configuration task. There was also a strong circadian variation, with $d'$ lowest near the melatonin peak and greatest 180° later. The uncorrected slopes show the opposite pattern, paradoxically shallowest at the circadian nadir, when subjects were sleepiest, and steeper when subjects were more alert. This is a form of speed-error trade-off.[2] We suggest that the shallower slopes result either from subjects spending less time on each item, leading to a degraded representation of the stimuli, or from subjects examining a smaller proportion of the items before generating a response. In other contexts, sleepy subjects have been shown to be aware that their performance is impaired (Dorrian, Lamond, & Dawson, 2000). If our subjects had wished to avoid an increased error rate as their alertness declined, they should have searched more slowly, leading to steeper slopes. Instead, they searched more recklessly when sleepy, accepting an increased error rate in order to reduce total search time.

These results have significant practical implications. Subjects behaved recklessly when their alertness decreased, responding on the basis of insufficient information. Furthermore, overall RT (corrected or not) increased dramatically at adverse circadian phases and with increasing time awake. The combination of slowed RT and increased error rates could be quite dangerous in people entrusted with critical visual search tasks, such as screening airport baggage, piloting vehicles (e.g., Fairclough & Maternaghan, 1993), performing surgical procedures (e.g., Grantcharov, Bardram, Funch-Jensen, & Rosenberg, 2001), or interpreting radiological images (e.g., Gale & Walker, 1993).

The term attention refers to a variety of processes served by different networks of brain areas (Leonards, Sunaert, Van Hecke, & Orban, 2000; Posner & Petersen, 1990; Webster & Ungerleider, 1998). In this study, we found that the effects of the circadian pacemaker and homeostatic sleep drive on global vigilance and alertness are strikingly different from the effects on selective attention. Cognitive slowing does not imply a reduction in the speed with which observers can shift attention during search, or a change in the efficiency of search guidance. Sleepiness does impair overall search performance, increasing overall RTs and error rates. However, our data suggest that homeostatic and circadian factors probably modulate performance downstream from the locus of selective attention, impairing decision making. These results also suggest that the profound effects of circadian phase and sleep deprivation on RT are not due to impaired ability to select relevant stimuli.

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1. $d'$ is a detectability measure derived from signal detection theory (cf. Macmillan & Creelman, 1991). Because all other dependent measures are plotted so that good performance is downward on the figure, we have inverted the $d'$ axis. Slopes have been collapsed across target presence/absence, both for concision and because $d'$ combines information about errors on both types of trials.

2. Criterion ($c$) was more conservative for the conjunction task, but did not vary with circadian phase.

## REFERENCES

Åkerstedt, T., & Folkard, S. (1995). Validation of the S and C components of the three-process model of alertness regulation. *Sleep*, *18*, 1–6.

Babkoff, H., Caspy, T., & Mikulincer, M. (1991). Subjective sleepiness ratings: The effects of sleep deprivation, circadian rhythmicity and cognitive performance. *Sleep*, *14*, 534–539.

Babkoff, H., Mikulincer, M., Caspy, T., Kempinski, D., & Sing, H. (1988). The topology of performance curves during 72 hours of sleep loss: A memory and search task. *Quarterly Journal of Experimental Psychology: Human Experimental Psychology*, *40A*, 737–756.

Bodenhausen, G.V. (1990). Stereotypes as judgmental heuristics: Evidence of circadian variations in discrimination. *Psychological Science*, *1*, 319–322.

Broadbent, D.E., Broadbent, M.H.P., & Jones, J.L. (1989). Time of day as an instrument for the analysis of attention. *European Journal of Cognitive Psychology*, *1*, 69–94.

Carskadon, M.A., Labyak, S.E., Acebo, C., & Seifer, R. (1999). Intrinsic circadian period of adolescent humans measured in conditions of forced desynchrony. *Neuroscience Letters*, *260*, 129–132. Retrieved from http://www.sro.org

De Gennaro, L., Ferrara, M., Curcio, G., & Bertini, M. (2001). Visual search performance across 40 h of continuous wakefulness: Measures of speed and accuracy and relation with oculomotor performance. *Physiology and Behavior*, *74*, 197–204.

Dijk, D.-J., & Czeisler, C.A. (1995). Contribution of the circadian pacemaker and the sleep homeostat to sleep propensity, sleep structure, electroencephalographic slow waves and sleep spindle activity in humans. *Journal of Neuroscience*, *15*, 3526–3538.

Dijk, D.-J., Duffy, J.F., & Czeisler, C.A. (1992). Circadian and sleep/wake dependent aspects of subjective alertness and cognitive performance. *Journal of Sleep Research*, *1*, 112–117.

Dinges, D.F. (1992). Probing the limits of functional capability: The effects of sleep loss on short-duration tasks. In R.J. Broughton & R. Ogilvie (Eds.), *Sleep, arousal and performance: Problems and promises* (pp. 176–188). Boston: Birkhauser.

Dinges, D.F., & Kribbs, N.B. (1991). Performing while sleepy: Effects of experimentally-induced sleepiness. In T.H. Monk (Ed.), *Sleep, sleepiness and performance* (pp. 97–128). Chichester, England: John Wiley and Sons.

Dinges, D.F., Pack, F., Williams, K., Gillen, K.A., Powell, J.W., Ott, G.E., Aptowicz, C., & Pack, A.I. (1997). Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 hours per night. *Sleep*, *20*, 267–277.

Dorrian, J., Lamond, N., & Dawson, D. (2000). The ability to self-monitor performance when fatigued. *Journal of Sleep Research*, *9*, 137–144.

Duffy, J.F., & Dijk, D.-J. (2002). Getting though to circadian oscillators: Why use constant routines? *Journal of Biological Rhythms*, *17*, 4–13.

Duncan, J., & Humphreys, G. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*, 433–458.

Fairclough, S., & Maternaghan, M. (1993). Changes in drivers' visual behaviour due to the introduction of complex versus simple route navigation information. In D. Brogan, A. Gale, & K. Carr (Eds.), *Visual search 2* (pp. 419–432). London: Taylor & Francis.

Gale, A.G., & Walker, G.E. (1993). Visual search in breast cancer screening. In D. Brogan, A. Gale, & K. Carr (Eds.), *Visual search 2* (pp. 231–238). London: Taylor & Francis.

Grantcharov, T.P., Bardram, L., Funch-Jensen, P., & Rosenberg, J. (2001). Laparoscopic performance after one night on call in a surgical department: Prospective study. *British Medical Journal*, *323*, 1222–1223.

Horowitz, T.S., Cade, B.E., Wolfe, J.M., & Czeisler, C.A. (2001). Efficacy of bright light and sleep/darkness scheduling in alleviating circadian maladaptation to night work. *American Journal of Physiology: Endocrinology & Metabolism*, *281*, E384–391.

Humphrey, D.G., Kramer, A.F., & Stanny, R.R. (1994). Influence of extended wakefulness on automatic and nonautomatic processing. *Human Factors, 36*, 652–669.

Kahneman, D., Treisman, A., & Gibbs, B.J. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, *24*, 175–219.

Keppel, G. (1991). *Design and analysis: A researcher's handbook* (3rd ed.). Englewood Cliffs, NJ: Prentice Hall.

Kribbs, N.B., & Dinges, D.F. (1994). Vigilance decrement and sleepiness. In J.R. Harsh & R.D. Ogilvie (Eds.), *Sleep onset mechanisms* (pp. 113–125). Washington, DC: American Psychological Association.

Leonards, U., Sunaert, S., Van Hecke, P., & Orban, G.A. (2000). Attention mechanisms in visual search—an fMRI study. *Journal of Cognitive Neuroscience*, *12*(Suppl. 2), 61–75.

Li, Z. (2002). A saliency map in primary visual cortex. *Trends in Cognitive Sciences*, *6*, 9–16.

Macmillan, N.A., & Creelman, C.D. (1991). *Detection theory: A user's guide*. Cambridge, England: Cambridge University Press.

May, C.P. (1999). Synchrony effects in cognition: The costs and a benefit. *Psychonomic Bulletin & Review*, *6*, 142–147.

Minors, D.S., & Waterhouse, J.M. (1983). Does 'anchor sleep' entrain circadian rhythms? Evidence from constant routine studies. *Journal of Physiology*, *345*, 451–467.

Monk, T.H., & Carrier, J. (1997). Speed of mental processing in the middle of the night. *Sleep*, *20*, 399–401.

Morton, L.L., & Diubaldo, D. (1993). Circadian differences in the dichotic processing of voicing. *International Journal of Neuroscience*, *68*, 43–52.

Nothdurft, H.C. (1991). Texture segmentation and pop-out from orientation contrast. *Vision Research*, *31*, 1073–1078.

Parasuraman, R., Warm, J.S., & See, J.E. (1998). Brain systems of vigilance. In R. Parasuraman (Ed.), *The attentive brain* (pp. 221–256). Cambridge, MA: MIT Press.

Pashler, H.E. (1998). *The psychology of attention*. Cambridge, MA: MIT Press.

Posner, M.I., & Petersen, S.E. (1990). The attention system of the human brain. *Annual Review of Neuroscience*, *13*, 25–42.

Townsend, J.T., & Ashby, F.G. (1983). *The stochastic modeling of elementary psychological processes*. Cambridge, England: Cambridge University Press.

Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 459–478.

Webster, M.J., & Ungerleider, L.G. (1998). Neuroanatomy of visual attention. In R. Parasuraman (Ed.), *The attentive brain* (pp. 19–34). Cambridge, MA: MIT Press.

Williams, H.L., Lubin, A., & Goodnow, J.J. (1959). Impaired performance with acute sleep loss. *Psychological Monographs*, *73*, 1–26.

Wolfe, J.M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, *1*, 202–238.

Wolfe, J.M. (1998). What can 1 million trials tell us about visual search? *Psychological Science*, *9*, 33–39.