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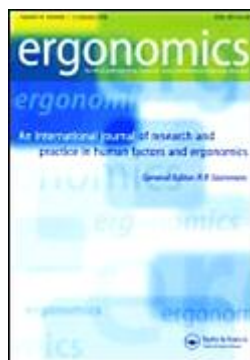
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Investigation of task performance variations according to task requirements and alertness across the 24-h day in shift-workers

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3 **Running head: Task performance in shift-workers**
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8 **Investigation of task performance variations according to task requirements**
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10 **and alertness across the 24-h day in shift-workers**
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6 The study investigated time-of-day effects on task performance in shift-workers in
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8 different tasks (reaction-time, discrimination, probe recognition, free recall), by
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10 varying task-specific features. On each of six recordings, each programmed on a
11
12 different day and in a randomized order, operators rated alertness and performed
13
14 different tasks. Self-rated alertness varied according to a typical diurnal trend.
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16 Time of day also affected reaction time (slower responses at 03:00),
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18 discrimination performance (lower accuracy at 03:00 in the most difficult
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20 condition), and recall (superior recall at 07:00 and 11:00 following deeper
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22 processing at encoding). The data demonstrated time-of-day effects on cognitive
23
24 processes also involved in many real-job activities, despite the lack of control for
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26 a number of exogenous factors known to interfere with performance in work
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28 settings. Since in the cognitively more loaded tasks, time-of-day effects depended
29
30 on task conditions, the findings are of operational concern in shift-work situations
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32 involving differential task requirements.
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41 *Keywords:* Shift-workers, Alertness, Reaction time, Non-verbal Discrimination,
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43 Memory Tasks
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Statement of relevance

In a real-job setting, performance variations were observed according to time-of-day and task-requirements in a set of cognitively more or less demanding tasks. Task-specific research across the 24-h day enables a better understanding of operators' tasks and the development of supporting technology.

1. Introduction

Over the last few decades, a number of studies showed how performance measures are affected by sleep drive (homeostatic influence) and circadian phase. The demonstration of an interaction of circadian phase and time awake in the regulation of performance came from laboratory studies under controlled conditions and/or manipulation of the sleep/wake cycle (for a review, Akerstedt, 2007). Several theoretical models conceptualized this interaction by proposing an optimal position and duration for sleep, with any deviation impairing performance and alertness (Folkard & Akerstedt, 1992; Achermann & Borbély, 1994; Van Dongen, Maislin, Mullington, & Dinges, 2003). Systematic performance measures in relation to different simulated shift systems further confirmed a sharp performance drop in the early morning hours (Colquhoun, 1969). This was observed in most tasks that require sustained attention, such as reaction time performance or throughput in cognitive tasks (Fröberg, 1975; Colquhoun, 1968; Johnson, 1992). At the same time, physiological, and subjective arousal were reported to strongly decrease (Akerstedt & Gillberg, 1990). A simulation study revealed that at high fatigue levels errors involving a failure to act (errors of omission) were increased, whereas incorrect responses (errors of commission) were decreased in a simulated train driving task (Dorrian, Roach, Fletcher, & Dawson, 2007). The differential effect of fatigue on error type was explained by a cognitive disengagement with the virtual train, which increased accident risk. In real shift-work settings, the findings of higher occurrences of risk and accidents on night- compared to day-duty, further stressed the potential consequences of

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2
3 reduced arousal on safety and security (Folkard & Tucker, 2003). Shift-work
4 would further aggravate the nocturnal decline in cognitive abilities observed under
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6 controlled conditions due to a chronic sleep debt that shift-workers carry over to
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8 the night-shift and also to day-shifts following early morning-shift start
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10 (Akerstedt, 1991; Dinges, Pack, Williams, Gillen, Powell, et al., 1997; Fletcher &
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12 Dawson, 2001; Pilcher, Lambert, & Huffcutt, 2000). Though a nocturnal work
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14 performance drop has been reported in several studies (for a review: Folkard &
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16 Tucker, 2003), reliable performance measures may not be available in all
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18 occupational settings. In addition, masking effects of work performance changes
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20 across the 24-h day have been suggested for work activity itself (Andorre &
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22 Queinnec, 1998) and for incentives (Blake, 1971).

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29 Several field studies collected, instead, interpolated performance measures by
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31 using simple and short neuropsychological tests. They reported reduced
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33 performance on the night-shift for reaction time, mental arithmetic, and search
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35 performance (Tilley, Wilkinson, Warren, Watson, & Drud, 1982; Hossain,
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37 Reinish, Heslegrave, Hall, Kayumov, et al., 2004; Wojtczak-Jaroszova,
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39 Makowska, Rzepecki, Banaszkiwicz, and Romejko, 1978). However,
40
41 performance changes have not systematically been reported in field studies, for
42
43 instance for serial reaction time, digit symbol substitution, and manual tracking
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45 (Costa, Gaffuri, Perfranceschi, Tansella, 1979; Lowden, Kecklund, Axelsson, &
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47 Akerstedt, 1998). Further, in memory tasks, 24-h performance variations have
48
49 been shown to depend on task requirements. Thus, process controllers' recall
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51 performance was higher at 18:00 compared to 02:00 for words associated with
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53 semantic encoding, while the contrary was observed for words processed
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55 according to physical attributes (Maury & Queinnec, 1992). Another study
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3 revealed that air traffic controllers' recall performance depended on the modality
4 of presentation and the recall procedure used (Mélan, Galy, & Cariou, 2007). In a
5 free recall task they remembered systematically fewer words during the night and
6 early morning hours. In a probe recognition task this effect was only observed
7 when they had to recall visual items but not auditory items.
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10 Taken together, these findings indicate that performance trends depend both on
11 the task used, and on the task components under investigation. This interpretation
12 is in agreement with the results obtained by more systematic investigations of
13 performance variations in controlled laboratory studies. In perceptual-motor tasks,
14 such as simple reaction time tasks restricted to immediate throughput of
15 information, performance was usually shown to peak in the evening (Monk,
16 Fookson, Moline, & Pollak, 1985; Monk & Carrier, 1997; Casagrande, Violani,
17 Curcio, & Bertini, 1997; Heuer, Spijkers, Kiesswetter, & Schmidtke, 1998;
18 Owens, Macdonald, Tucker, Sytnik, Totterdell, & et al., 2000; Gennaro, Ferrara,
19 Curcio, & Bertini, 2001; Wright, Hull, & Czeisler, 2002). A reduction in response
20 speed during the night coincident with an increase in response accuracy,
21 suggested a strategy change rather than a global nocturnal performance drop
22 (Monk & Carrier, 1997). When the emphasis was on short-term memory
23 processing, superior performance was reported in the morning, while for long-
24 term memory tasks performance peaks were observed on the late afternoon
25 (Baddeley, Hatter, Scott & Snashall, 1970; Folkard, Knauth, Monk, & Rutenfranz,
26 1976; Folkard & Monk, 1980; Oakhill & Davies, 1989).
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54 These findings have been interpreted as indicating that low arousal in the morning
55 would favour more automatic processes, such as maintenance rehearsal in short-
56 term memory. Progressive increment of arousal as the day progresses would tend
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3 to favour more demanding processing, involving, in particular, semantic attributes
4 from long term memory sources (Folkard, 1979; Folkard & Monk, 1981). This
5 interpretation may also account for the differences of recall performance across
6 the 24-h day according to the recall procedure, as reported by a previously-
7 mentioned field study (Mélan et al., 2007), but also in a controlled laboratory
8 study (Lorenzetti & Natale, 1996). The latter study indeed revealed superior recall
9 in the afternoon when subjects had been instructed to use a free recall procedure,
10 and in the morning when they had been informed to use a recognition procedure.
11 Greater degrees of elaboration would be necessary for free recall (relying on
12 subjects' ability to actively retrieve memory traces) compared to recognition
13 (requiring subjects to simply discriminate memory traces; Brébion, David,
14 Bressan, & Pilowski, 2005; Prince, Daselaar, & Cabeza, 2005). A similar
15 hypothesis has been proposed to account for recall performance differences over
16 the 24-h day according to item modality. Auditory presented items would benefit
17 from a longer-lasting sensory trace, and/or automatic phonological encoding
18 compared to visually presented items (Baddeley, 1986; Penney, 1989; Cowan,
19 Saults, Elliott, & Moreno, 2002). This would explain that only recall for visually
20 presented items was reduced when alertness was low (Mélan et al., 2007).

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The present study tested these hypotheses in a real shift-work setting by
investigating operators' task performance across the 24-h day in a set of
experimental tasks. In a repeated measures design operators (in charge of in-door
security of a nuclear power plant) provided alertness self-ratings every four hours
and performed tasks involving cognitive functions ranging from psychomotor
reaction time to elaborate processing of meaningful words. While a nocturnal
performance decrement was expected for all tasks, diurnal performance peaks

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3 were expected to vary between tasks. Performance would peak in the morning for
4 visual discrimination and probe recognition, involving more automatic processing,
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6 and later during the day for free recall, requiring more elaborate processing. In
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8 each task, the overall trend should be modulated by an interaction with the task
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10 component that was manipulated, i.e. difficulty in the discrimination task (parallel
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12 bars shifted by 0, 1, 2, or 3 pixels), item modality in the probe recognition task
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14 (visual and auditory list and probe presentation), and item attributes in the free
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16 recall task (typographic, structural and semantic encoding conditions). In
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18 agreement with the variations observed in laboratory studies, we expected to find
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20 later performance peaks or larger performance variations in the more demanding
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22 task conditions.
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33 **2. Method**

34 **2.1. Subjects**

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36 The study was carried out with 23 volunteer shift-workers supervising, on various
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38 control monitors, the in-door security of a nuclear plant in the south-west of
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40 France. They were issued from six teams of operators (total of 36), and were all
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42 men, aged 41.5 years (range 35 to 53 years), working in shift-work systems for
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44 11.8 years (range 4 to 20 years). They worked a continuous rapidly forward
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46 rotating shift-system, with 3 mornings, 2 afternoons, 2 nights followed by 5 days
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48 off. The 8-h shifts started at 06:00, 14:00, and 22:00 respectively.
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58 **2.2. Material and procedure**

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Satellite controllers completed Thayer's check-list and performed four different neuropsychological tasks on each of six testing times that were distributed over the 24-h day. Testing took place in a quiet room, during duty-pauses introduced for the sake of the study, by avoiding meal-times and shift-changeover times, i.e. at 03:00, 07:00, 11:00, 15:00, 19:00 and 23:00. The subject first completed the check-list, then performed a discrimination task, followed by two memory tasks (starting randomly with either) and a reaction-time task. To ensure no confounding effects of time of day and practice, testing times were randomized across participants, with a single testing time per day for a given subject. Prior to the beginning of the study, operators completed Horne and Östberg's (1977) questionnaire. The results indicated that no participant displayed extreme morningness or eveningness.

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2.2.1. Alertness: Participants completed a French paper-and-pencil version of Thayer's activation-deactivation adjective checklist (Thayer, 1978). They quoted, for each of 20 adjectives, one of the following responses "not at all", "don't know", "little", "much", having an assigned weight respectively of 1, 2, 3 and 4. Two adjectives, however, have a negative weight assigned to them. The scores were grouped into four factors, general activation (GA), deactivation sleep (DS), high activation (HA), and general deactivation (GD). The ratio GA/DS provided an index of subjects' alertness.

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2.2.2. Visual discrimination: Each of 24 trials started with the display of two horizontal parallel bars, 3-cm long and 0.5 cm apart. Depending on the trial, the bars were either shifted horizontally to each other by 1, 2 or 3 pixels (in each case,

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3 1/4 of trials), or they were not shifted (1/4 of the trial). Items were displayed in the
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5 centre of a computer screen while the following instruction occurred on the
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7 bottom of the screen “The lines are shifted (press the key M) / The lines are not
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9 shifted (press key Q)”. The participant’s response initiated a 2-sec inter-trial-
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11 interval, before the next trial started. Software, specifically designed for this
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13 study, presented the four discrimination conditions randomly, and recorded the
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15 subject’s response accuracy and latency.
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22 **2.2.3. Probe recognition:** On each of 32 trials, six common French nouns were
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24 presented, one by one (750 ms), at a rate of one word per second. Four seconds
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26 after presentation of the last list-item, a probe item was presented together with
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28 the following response instruction “The word figured in the list (press M-button) /
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30 The word did not figure in the list (press Q-button)”. The subject’s response
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32 initiated a 5-sec ITT, followed by a brief sound signalling the start of the next
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34 trial. The list-items were randomly selected from a 24-item set and on half the
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36 trials the probe had occurred in the list. Item-lists and probes could be presented
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38 either in the visual modality (centre of a computer screen), or in the auditory
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40 modality (loud-speakers). The four trial types resulting from presentation
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42 modality of lists and probes (auditory-visual, auditory-auditory, visual-visual,
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44 visual-auditory) were randomized across trials by the aforementioned tailor-made
45
46 software. To rule out practice effects across the six testing times, six different
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48 item-sets were used. All items of a set belonged to the same word category (fruit,
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50 vegetables, music instruments, furniture, and animals).
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2.2.4. Free recall: This protocol was previously described by Maury and Queinnec (1992). Briefly, on each of 18 trials, a common French noun was presented in the middle of a computer screen (300 ms), immediately preceded by a question that induced processing of the word's typographical attributes ("Is the word written in capitals", 1/3 trials), structural attributes ("Do the vowels of the word occur in an alphabetical order", 1/3 trials), or semantic aspects (1/3 trials). In the latter case, the question varied according to the item presented, like "Is it used to open a door", followed by the item "handle". Simultaneously with each word, the following instruction occurred on the bottom of the screen: "Response 'Yes', press key M; Response 'No', press key Q". The response initiated an interpolated reaction-time task (see below) before the next trial started. Following the last trial, subjects were asked to write on a white sheet all the words they could remember from the 18-item list.

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2.2.5. Reaction-time: This task was interpolated after each trial in the free recall task, in order to prevent maintenance rehearsal. The response after each question/word sequence in the free recall task automatically generated a 1-px spot that moved randomly on the screen during several seconds and finally 'exploded'. Following this event, the subject had to press the 'space' bar as rapidly as possible, which initiated a second, and then a third trial. Thereafter, the program shifted back to the recall task, with the presentation of a question starting the second trial, and so on.

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2.3. Statistics

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All measures recorded were analysed by parametric tests. ANOVAs with repeated measures across time of day (TOD) were used to analyse subjects' self-reported

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3 alertness (1-way ANOVA), and factorial ANOVAs investigated time-of-day
4 effects together with task-specific components in the cognitive tasks. Tukey's test
5 was used for post hoc analyses. We further explored whether task performance
6 variations observed across time of day were associated with variations in subjects'
7 alertness. This hypothesis was tested by using Pearson's correlation test as
8 follows. Correlations were computed within participants (n=6 for each person
9 separately), by using alertness/test scores at the 6 time-of-day values. Then, the 23
10 r values were tested against the null hypothesis by using a 1-sample t test. Though
11 this procedure violates the assumption of independence of scores, it provides an
12 indication whether, in general, alertness was correlated with test performance.
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30 **3. Results**

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34 Operators' alertness curve obtained by concurrent ratings on six recordings across
35 the 24-h day is represented by Figure 1. A one-way ANOVA with repeated
36 measures revealed a significant time-of-day effect ($F(5,5) = 3.73, p < .01$), with
37 significant lower alertness at 03:00 than at 15:00 and 19:00.
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43 The effects of time of day (TOD) on operators' performance in the cognitive tasks
44 were explored together with task-specific factors by using factorial ANOVAs. In
45 the visual discrimination task, a 2-way ANOVA of TOD (repeated measures) and
46 discrimination condition revealed a significant effect of discrimination condition
47 on response accuracy ($F(3,23) = 199.13, p < .001$; Figure 2), and an interaction
48 between response accuracy and TOD ($F(5,23) = 1,5639, p < .05$). Post-hoc
49 analyses indicated that the latter effect resulted from less accurate responding at
50 03:00 compared to 11:00 in the 1 pixel shift condition ($p < .01$). Furthermore,
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3 subjects responded overall more accurately in the most obvious discrimination
4 conditions (3-px shift, no-shift) compared to the 1- and 2-pixel shift conditions (in
5 each case, $p < .01$), and in the 2-pixel compared to the 1-pixel discrimination
6 condition ($p < .001$). Discrimination condition also affected subjects' response
7 latency ($F(3,23) = 4.783$, $p < .01$), with more rapid responding in the 3-px shift
8 condition compared to the remaining conditions (in each case, $p < .01$).
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11 Figure 3 illustrates the mean number of correct responses in a verbal probe
12 recognition task according to TOD, and presentation modality of the verbal items.
13
14 A 2-way ANOVA with repeated measures revealed that task performance was
15 affected by presentation modality of the item lists ($F(1,23) = 22.11$, $p < .001$), and
16 of the probes ($F(1,23) = 9.66$, $p < .01$), indicating better performance following
17 auditory rather than visual item presentation, both at encoding and recall. Further,
18 TOD interacted with presentation modality ($F(5,23) = 2.166$, $p < .05$), due to
19 significant higher recall at 03:00 following auditory compared to visually encoded
20 words ($p < .001$).
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24 In a free recall task, the mean number of words recalled according to TOD was
25 analysed together with the type of question that was presented prior to each word
26 at encoding (Figure 4), and the position in the list (Table 1). The figure indicates
27 more marked TOD effects following questions inducing processing of semantic or
28 typographic aspects rather than of structural aspects. Furthermore, whether items
29 were issued from the initial (positions 1 to 6), intermediary (positions 7-12), or
30 end (positions 13-18) portion of the list, recall performance was overall higher on
31 day-time compared to night-time recordings. A 3-way ANOVA of these factors
32 revealed significant effects for encoding question type ($F(2,23) = 22.30$, $p < .001$),
33 and list-portion ($F(2,23) = 3.9$, $p < .05$), and an interaction between each of these
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3 factors and time of day (TOD x question type $F(10,23) = 1.99, p < .05$; TOD x
4 list portion $F(10,23) = 2.01, p < .05$); ($F(4,23) = 5.97, p < .001$). Post-hoc analyses
5
6 revealed superior recall for words preceded by a semantic question rather than by
7
8 a structural question at 07:00 and 11:00 (respectively, $p < .05$, and $p < .01$), or by
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10 a typographic question at 11:00. ($p < .01$). In addition, items issued from the
11
12 initial list-portion were better recalled at 07:00 than at 19:00 ($p < .05$). Moreover,
13
14 a significant interaction between question type and list-portion indicated
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16 significant higher recall performance when words issued from the initial list-
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18 portion were preceded by a semantic question rather than by a structural or
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20 typographical question ($p < .001$ in each case). A similar effect was observed
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22 when items issued from the end-portion of the list were preceded by a semantic
23
24 rather than by a typographical question ($p < .01$).

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27 A similar analysis was performed for operators' performance in a detection task
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29 that was interpolated following each question/word presentation in the free recall
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31 task. Time-of-day effects on subjects' mean response latencies on each of three
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33 successive trials (Table 2) were investigated by including two additional factors
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35 (Table 3), i.e. the question type preceding the detection task (structural,
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37 typographic, and semantic), and the list portion (initial, intermediary, and end-
38
39 portions). A four-way ANOVA of these factors revealed a significant effect of
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41 time of recording ($F(5,161) = 2.94, p < .05$), indicating slower responses at 03:00
42
43 compared to 07:00 ($p < .05$), and 19:00 ($p < .01$). Furthermore, highly significant
44
45 differences between trials ($F(2,161) = 40.86, p < .001$), and list-portions ($F(2,161)$
46
47 = 10.24, $p < .001$), resulted from slower responses on the first compared to the
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49 second and third trials ($p < .001$, in each case), and on trials inserted in the
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3 intermediary ($p < .001$) and end portions ($p < .001$) of the list compared to the
4 initial list-portion. No interaction was found between task factors and TOD.
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8 To investigate whether trends of task performance and self-reported alertness
9 trends were associated, correlations across time of day were calculated between
10 alertness scores and either performance measure for each participant. Table 4
11 summarizes ranges of individual correlation values for each performance measure
12 and the corresponding mean correlation. Testing the 23 r values against the null
13 hypothesis revealed overall significant correlations across time of day between
14 alertness on one hand, and discrimination latency, visual recognition performance
15 and free recall performance on the other hand (Table 4).
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32 **4. Discussion**

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36 In real-job conditions, operators displayed reliable alertness variations and task
37 performance variations across the 24-h day. A nocturnal drop was found for task
38 performance and self-reported alertness, despite a lack of control for a number of
39 factors that have been shown to affect psychological measures in controlled
40 laboratory conditions, including light exposure, noise and motivation (Smith,
41 McEvoy, & Gevins, 2002; Wright et al., 2002). In shift-workers, the nocturnal
42 decline of psychological measures is generally aggravated by chronic sleep
43 deprivation (Akerstedt, 1991; Dinges et al., 1996; Fletcher & Dawson, 2001;
44 Pilcher et al., 2000). The disruptive effects of shift-work have been shown to
45 depend on various shift-scheduling features. Somewhat smaller effects have been
46 shown for rapid compared to slow rotations, for systems including a limited
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3 number of successive night-shifts, and for late versus early morning-shift start
4 (Della Rocco & Nesthus, 2005; Knauth, 1996; Tucker et al., 1998). As in the
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6 present job-situation operators worked according to a rapid forward rotating shift-
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8 scheduling system that included a maximum of two or three successive night-
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10 shifts, and late night-to-morning shift changeover, the disruptive effects on the
11
12 nocturnal decline of operators' psychological measures may have been less
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14 pronounced than may have been expected in other shift-scheduling systems.
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19 Operators' self-rated alertness displayed a typical day-oriented trend that peaked
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21 at 19:00 and reached its minimum at 03:00. The finding of a trend similar to those
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23 reported in other real work settings (Akerstedt, 1991; Dinges et al., 1997; Tucker
24
25 et al., 1998), supports the hypothesis of a strong dependency of alertness on the
26
27 endogenous systems underlying circadian rhythms (Achermann & Borbély, 1994;
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29 Folkard & Akerstedt, 1992). The marked differences between day- and night-
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31 time reported in the present study contrasted, however, with the restricted range of
32
33 alertness ratings reported in another shift-work study (Tucker et al., 1998). This
34
35 difference may be related to methodological differences, given that in the present
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37 study operators rated alertness concurrently on four hourly intervals, rather than
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39 retrospectively on a single session. In addition, the alertness score was computed
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41 from responses to a list of adjectives rather than by quoting a single-item scale,
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43 and could thus provide a more precise description of operators' functional state.
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Though other factors may explain the finding of more or less shaded alertness
curves in shift-work studies, the idea that the rating method used contributes to
this difference may deserve further investigation. On the other hand, the
possibility cannot be excluded that in real-job conditions operators rate alertness

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3 simply according to what they should feel like while being at work or what they
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5 expect to feel like given the time of day.
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8 This latter interpretation may, however, not account for the task performance
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10 variations observed over the 24-hr day in the present study. The role of practice
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12 effects may also be excluded, given that performance trends were obtained by
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14 randomizing the order of the six recording sessions across participants, and by
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16 performing a single session on a given day. Similarly, in the memory tasks
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18 learning effects were, in principle, ruled out by randomizing different task
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20 versions across participants and recordings. In light of these considerations, task
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22 performance variations according to time of day most probably resulted from
23
24 operators' functional state at the time of testing. Thus, with increasing alertness
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26 during day-time, operators' displayed significant superior performance in several
27
28 cognitively more or less demanding tasks. More specifically, they responded more
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30 rapidly in a reaction time task, performed more accurate responses in a non-verbal
31
32 visual discrimination task, and recalled more verbal items in the memory tasks.
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34 The finding that time of day affected different performance measures may indicate
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36 that operators' nocturnal performance drop resulted from the impairment of some
37
38 general non specific capacity involved during information processing. This is in
39
40 agreement with the hypothesis that sleep deprivation reduces the non-specific
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42 arousal level of the body, but has no specific effects (see for instance Wilkinson,
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44 1992). According to this point of view, sleep deprivation effects on reaction time
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46 and trough-put in cognitively more loaded tasks would result from the monotony
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48 and lack of novelty that characterize these tasks. In contrast, tasks that are "too
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50 complex, too interesting, too variable and, above all, too short" would intrinsically
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52 encourage sleep-deprived people to apply compensatory efforts and to perform
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3 normally (pp. 254-256). Likewise, Balkin et al. (2004) found that monotonous
4 tests that demanded constant attention, like psychomotor vigilance tests, were
5 most sensitive to partial sleep deprivation compared to tests involving higher
6 cognitive load, like logical reasoning, problem-solving and decision-making,
7 which were least sensitive (Balkin, Bliese, Belenky, Sing, Thorne, Thomas, et al.,
8 2004).
9

10 Accordingly, the present results may reflect a differential sensitivity of the tasks to
11 sleep deprivation as shift-work is associated with systematic partial sleep loss
12 (Pilcher et al., 2000). Our results only partly support this assumption. On the one
13 hand, task performance decrements in early morning hours have been observed
14 for reaction time. This finding is also in agreement with a number of studies
15 performed under controlled conditions in the laboratory (Monk et al., 1985; Monk
16 & Carrier, 1997; Casagrande et al., 1997; Heuer et al., 1998; Owens et al., 2000;
17 Gennaro et al., 2001; Wright et al., 2002), in simulated shift-work conditions
18 (Fröberg et al., 1975; Colquhoun et al., 1968; Johnson et al., 1992), and in real
19 shift-work settings (Tilley et al., 1982; Hossain et al., 2004). On the other hand, in
20 the more demanding cognitive tasks, time-of-day effects interacted with the task
21 components that were manipulated. Thus, time of day impaired response accuracy
22 in the discrimination task only in two out of four task conditions, i.e. when the
23 difference between items to be discriminated was least obvious, while no such
24 effect was found in those conditions involving a more marked to-be-discriminated
25 difference. Likewise, recognition performance was superior on early morning
26 hours for auditory compared to visually encoded words. In a free recall task,
27 operators displayed superior recall during day-time, but only when elaborate
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3 processing was favoured during encoding, rather than processing of structural or
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5 physical word attributes.
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8 Harrison and Horne (2000) proposed to differentiate those cognitive demanding
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10 tasks involving divergent skills, such as innovating and updating strategies, from
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12 those based on convergent rule-based skills. The authors reported a number of
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14 studies demonstrating sleep deprivation effects in the former but not in the latter
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16 tasks. Though the tasks used in the present study were rule-based, it may be that
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18 the changing task conditions involved strategy changes that may have increased
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20 the task-sensitivity to time-of-day effects. Strategy changes in relation to arousal
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22 changes have also been proposed to account for performance variations observed
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24 in laboratory studies. In the morning, when arousal was low, performance was
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26 shown to peak in those tasks involving more automatic processing, while
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28 increasing arousal across the day would favour more elaborate processing, like
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30 processing of semantic aspects from long-term memory (Baddeley et al., 1970;
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32 Folkard, 1979; Folkard et al., 1976; Folkard & Monk, 1980; Lorenzetti & Natale,
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34 1996; Oakhill & Davies, 1989). This hypothesis was favoured by the finding of
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36 significant correlations between operators' self-rated alertness and their task
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38 performance. More especially, when they rated alertness at a low level, their
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40 response speed in the discrimination task and their recall and recognition
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42 performance were also reduced, and vice versa. In addition, as reported above,
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44 significant time-of-day effects were observed in all the neuropsychological tests
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46 used, with overall higher performance during the day. However, no clear
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48 performance peak was observed in either task in the present study. This may be
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50 related to the marked inter-individual task performance differences, evidenced by
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52 large standard errors, in particular in the cognitively more loaded tasks. Inter-
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3 individual task performance differences may be related to differences in
4 operators' sleepiness, workload, adjustment to shift-work, and work conditions
5 (Akerstedt, 2007; Bustamante, Bliss, & Anderson, 2007 ; Costa & Sartori, 2007),
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10 in addition to the afore-mentioned lack of control for external factors.

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12 Accordingly, future field studies of the present kind should include objective
13 sleep measures, in addition to subjective alertness or sleepiness ratings in order to
14 explore the effects of sleepiness and adjustment to shift-work on operators' task
15 performance (Tucker et al., 1998). The tests used in the present study may be of
16 limited ecological value as far as job-task complexity, real-job performance, and
17 consequences of performance impairments on safety and security are concerned.
18
19 In this respect it may be useful to include in future studies a workload index, as
20 discussed in several recent studies (Pretorius & Cilliers, 2007; Noyes & Bruneau,
21 2007 ; Roth, Scott, Deutsch, Kuper, Schmidt, et al ., 2006). Thus, though no direct
22 relation may exist between the present results and real-job performance, the
23 neuropsychological tests enabled suitable outcome measures reflecting cognitive
24 processes also involved in real-job operations. Furthermore, data provided
25 evidence of subtle changes in operators' information processing strategies in
26 relation to time of day. This further confirmed that time-of-day effects on memory
27 depend on specific task-related factors (Mélan et al., 2007). Moreover, the data
28 emphasize that organizing shift-work and work-break systems to maintain
29 adequate concentration and avoid fatigue and boredom is still a major concern, in
30 particular for safety-related occupations. Practical implications also include often-
31 overlooked recommendations based on laboratory studies, and in particular on the
32 findings of systematic performance variations according to presentation modality
33 and depth of processing of verbal material (see INTRODUCTION). The
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3 demonstration of superior recall for auditory compared to visual material is of
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5 particular relevance given the rather limited use of auditory compared to visual
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8 interfaces in many job-situations, even for signalling emergency conditions.
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Table captions

Table 1. Mean number of words recalled (\pm -S.E.) according to their position in the list (initial list-portion: positions 1 to 6, intermediary list-portion: positions 7 to 12, terminal list-portion: positions 13 to 18).

Table 2. Mean response latencies (\pm -S.E.) in a visual detection task according to time of day and trial.

Table 3. Mean response latencies (\pm -S.E.) across trials in the detection task according to time of day, type of inducing question (upper panel), and list-portion (lower panel).

Table 4. Ranges and mean (\pm -SD) values for Perason's correlation test computed across time of day between alertness scores and each performance measure in the different tasks. The asterisk in the last column indicates that mean r values differed from the null hypothesis, with $p < .05$.

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Tables

Table 1.

	Time of day					
List-portion	3:00	7:00	11:00	15:00	19:00	23:00
initial	1.83 (.30)	2.57 (.27)	2.45 (.26)	2.00 (.27)	1.75 (.29)	2.14 (.27)
intermediary	1.91 (.31)	1.39 (.26)	1.77 (.27)	1.77 (.27)	1.95 (.27)	1.33 (.24)
terminal	1.87 (.33)	1.61 (.23)	1.91 (.35)	1.95 (.26)	2.20 (.32)	1.62 (.28)

Table 2.

	Time of day					
	3:00	7:00	11:00	15:00	19:00	23:00
Trial 1	0.28 (.03)	0.29 (.03)	0.42 (.07)	0.35 (.06)	0.29 (.03)	0.30 (.04)
Trial 2	0.28 (.04)	0.31 (.05)	0.46 (.09)	0.47 (.14)	0.41 (.08)	0.23 (.07)
Trial 3	0.53 (.17)	0.40 (.08)	0.31 (.06)	0.35 (.08)	0.46 (.08)	0.40 (.09)

Table 3.

		Time of day					
		03:00	07:00	11:00	15:00	19:00	23:00
Type of inducing question	Structural	0.41 (.14)	0.34 (.10)	0.41 (.10)	0.37 (.04)	0.35 (.05)	0.36 (.03)
	Typographic	0.37 (.09)	0.36 (.08)	0.36 (.06)	0.45 (.10)	0.36 (.04)	0.38 (.05)
	Semantic	0.40 (.12)	0.36 (.05)	0.40 (.08)	0.39 (.05)	0.37 (.06)	0.36 (.04)
List portion	Beginning	0.24 (.02)	0.35 (.06)	0.38 (.07)	0.43 (.09)	0.42 (.07)	0.36 (.07)
	Intermediary	0.55 (.22)	0.39 (.09)	0.40 (.06)	0.47 (.13)	0.37 (.06)	0.32 (.06)
	End	0.38 (.07)	0.35 (.05)	0.40 (.09)	0.33 (.06)	0.41 (.08)	0.41 (.07)

Table 4.

	Performance measure	Range of r values	Mean r values	t(22)
Discrimination	Latency	-0.91 - 0.75	-.24 (.11)	-2.21*
	Errors	-0.68 to 0.44	-.11 (0.09)	-1.18
Probe	Auditory	-0.77 to 0.72	0.13 (0.11)	1.25
Recognition	Visual	-0.58 to 0.86	.25 (.09)	2.68*
Free Recall	Physical	-0.64 to 0.83	.22 (.10)	2.23*
	Structural	-0.72 to 0.96	.21 (.09)	2.38*
	Semantic	-0.42 to 0.86	.19 (.08)	2.36*

Figure captions

Figure 1. Mean (\pm S.E.) self-ratings of alertness on a check-list provided every 4 hours across the 24-h day.

Figure 2. a) Mean (\pm S.E.) number of errors and b) mean (\pm S.E.) response latency in four visual discrimination conditions, at six times across the 24-h day.

Figure 3. Mean (\pm S.E.) number of correct responses in a probe recognition task according to presentation modality of item-lists, at six times across the 24-h day.

Figure 4. Mean (\pm S.E.) number of words recalled according to the type of inducing question preceding each word, at each of six times across the 24-h day.

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3 **Running head: Task performance in shift-workers**
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8 **Investigation of task performance variations according to task requirements**
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10 **and alertness across the 24-h day in shift-workers**
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15 **E. GALY, C. MÉLAN* and M. CARIOU**
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6 The study investigated time-of-day effects on task performance in shift-workers in
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8 different tasks (reaction-time, discrimination, probe recognition, free recall), by
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10 varying task-specific features. On each of six recordings, each programmed on a
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12 different day and in a randomized order, operators rated alertness and performed
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14 different tasks. Self-rated alertness varied according to a typical diurnal trend.
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16 Time of day also affected reaction time (slower responses at 03:00),
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18 discrimination performance (lower accuracy at 03:00 in the most difficult
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20 condition), and recall (superior recall at 07:00 and 11:00 following deeper
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22 processing at encoding). The data demonstrated time-of-day effects on cognitive
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24 processes also involved in many real-job activities, despite the lack of control for
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26 a number of exogenous factors known to interfere with performance in work
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28 settings. Since in the cognitively more loaded tasks, time-of-day effects depended
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30 on task conditions, the findings are of operational concern in shift-work situations
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32 involving differential task requirements.
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41 *Keywords:* Shift-workers, Alertness, Reaction time, Non-verbal Discrimination,
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Statement of relevance

In a real-job setting, performance variations were observed according to time-of-day and task-requirements in a set of cognitively more or less demanding tasks. Task-specific research across the 24-h day enables a better understanding of operators' tasks and the development of supporting technology.

1. Introduction

Over the last few decades, a number of studies showed how performance measures are affected by sleep drive (homeostatic influence) and circadian phase. The demonstration of an interaction of circadian phase and time awake in the regulation of performance came from laboratory studies under controlled conditions and/or manipulation of the sleep/wake cycle (for a review, Akerstedt, 2007). Several theoretical models conceptualized this interaction by proposing an optimal position and duration for sleep, with any deviation impairing performance and alertness (Folkard & Akerstedt, 1992; Achermann & Borbély, 1994; Van Dongen, Maislin, Mullington, & Dinges, 2003). Systematic performance measures in relation to different simulated shift systems further confirmed a sharp performance drop in the early morning hours (Colquhoun, 1969). This was observed in most tasks that require sustained attention, such as reaction time performance or throughput in cognitive tasks (Fröberg, 1975; Colquhoun, 1968; Johnson, 1992). At the same time, physiological, and subjective arousal were reported to strongly decrease (Akerstedt & Gillberg, 1990). A simulation study revealed that at high fatigue levels errors involving a failure to act (errors of omission) were increased, whereas incorrect responses (errors of commission) were decreased in a simulated train driving task (Dorrian, Roach, Fletcher, & Dawson, 2007). The differential effect of fatigue on error type was explained by a cognitive disengagement with the virtual train, which increased accident risk. In real shift-work settings, the findings of higher occurrences of risk and accidents on night- compared to day-duty, further stressed the potential consequences of

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3 reduced arousal on safety and security (Folkard & Tucker, 2003). Shift-work
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5 would further aggravate the nocturnal decline in cognitive abilities observed under
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7 controlled conditions due to a chronic sleep debt that shift-workers carry over to
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9 the night-shift and also to day-shifts following early morning-shift start
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11 (Akerstedt, 1991; Dinges, Pack, Williams, Gillen, Powell, et al., 1997; Fletcher &
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13 Dawson, 2001; Pilcher, Lambert, & Huffcutt, 2000). Though a nocturnal work
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15 performance drop has been reported in several studies (for a review: Folkard &
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17 Tucker, 2003), reliable performance measures may not be available in all
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19 occupational settings. In addition, masking effects of work performance changes
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21 across the 24-h day have been suggested for work activity itself (Andorre &
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23 Queinnec, 1998) and for incentives (Blake, 1971).

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29 Several field studies collected, instead, interpolated performance measures by
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31 using simple and short neuropsychological tests. They reported reduced
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33 performance on the night-shift for reaction time, mental arithmetic, and search
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35 performance (Tilley, Wilkinson, Warren, Watson, & Drud, 1982; Hossain,
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37 Reinish, Heslegrave, Hall, Kayumov, et al., 2004; Wojtczak-Jaroszova,
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39 Makowska, Rzepecki, Banaszkiwicz, and Romejko, 1978). However,
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41 performance changes have not systematically been reported in field studies, for
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43 instance for serial reaction time, digit symbol substitution, and manual tracking
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45 (Costa, Gaffuri, Perfranceschi, Tansella, 1979; Lowden, Kecklund, Axelsson, &
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47 Akerstedt, 1998). Further, in memory tasks, 24-h performance variations have
48
49 been shown to depend on task requirements. Thus, process controllers' recall
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51 performance was higher at 18:00 compared to 02:00 for words associated with
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53 semantic encoding, while the contrary was observed for words processed
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55 according to physical attributes (Maury & Queinnec, 1992). Another study
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3 revealed that air traffic controllers' recall performance depended on the modality
4 of presentation and the recall procedure used (Mélan, Galy, & Cariou, 2007). In a
5 free recall task they remembered systematically fewer words during the night and
6 early morning hours. In a probe recognition task this effect was only observed
7 when they had to recall visual items but not auditory items.
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10 Taken together, these findings indicate that performance trends depend both on
11 the task used, and on the task components under investigation. This interpretation
12 is in agreement with the results obtained by more systematic investigations of
13 performance variations in controlled laboratory studies. In perceptual-motor tasks,
14 such as simple reaction time tasks restricted to immediate throughput of
15 information, performance was usually shown to peak in the evening (Monk,
16 Fookson, Moline, & Pollak, 1985; Monk & Carrier, 1997; Casagrande, Violani,
17 Curcio, & Bertini, 1997; Heuer, Spijkers, Kiesswetter, & Schmidtke, 1998;
18 Owens, Macdonald, Tucker, Sytnik, Totterdell, & et al., 2000; Gennaro, Ferrara,
19 Curcio, & Bertini, 2001; Wright, Hull, & Czeisler, 2002). A reduction in response
20 speed during the night coincident with an increase in response accuracy,
21 suggested a strategy change rather than a global nocturnal performance drop
22 (Monk & Carrier, 1997). When the emphasis was on short-term memory
23 processing, superior performance was reported in the morning, while for long-
24 term memory tasks performance peaks were observed on the late afternoon
25 (Baddeley, Hatter, Scott & Snashall, 1970; Folkard, Knauth, Monk, & Rutenfranz,
26 1976; Folkard & Monk, 1980; Oakhill & Davies, 1989).
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54 These findings have been interpreted as indicating that low arousal in the morning
55 would favour more automatic processes, such as maintenance rehearsal in short-
56 term memory. Progressive increment of arousal as the day progresses would tend
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3 to favour more demanding processing, involving, in particular, semantic attributes
4 from long term memory sources (Folkard, 1979; Folkard & Monk, 1981). This
5 interpretation may also account for the differences of recall performance across
6 the 24-h day according to the recall procedure, as reported by a previously-
7 mentioned field study (Mélan et al., 2007), but also in a controlled laboratory
8 study (Lorenzetti & Natale, 1996). The latter study indeed revealed superior recall
9 in the afternoon when subjects had been instructed to use a free recall procedure,
10 and in the morning when they had been informed to use a recognition procedure.
11 Greater degrees of elaboration would be necessary for free recall (relying on
12 subjects' ability to actively retrieve memory traces) compared to recognition
13 (requiring subjects to simply discriminate memory traces; Brébion, David,
14 Bressan, & Pilowski, 2005; Prince, Daselaar, & Cabeza, 2005). A similar
15 hypothesis has been proposed to account for recall performance differences over
16 the 24-h day according to item modality. Auditory presented items would benefit
17 from a longer-lasting sensory trace, and/or automatic phonological encoding
18 compared to visually presented items (Baddeley, 1986; Penney, 1989; Cowan,
19 Saults, Elliott, & Moreno, 2002). This would explain that only recall for visually
20 presented items was reduced when alertness was low (Mélan et al., 2007).

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The present study tested these hypotheses in a real shift-work setting by
investigating operators' task performance across the 24-h day in a set of
experimental tasks. In a repeated measures design operators (in charge of in-door
security of a nuclear power plant) provided alertness self-ratings every four hours
and performed tasks involving cognitive functions ranging from psychomotor
reaction time to elaborate processing of meaningful words. While a nocturnal
performance decrement was expected for all tasks, diurnal performance peaks

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3 were expected to vary between tasks. Performance would peak in the morning for
4 visual discrimination and probe recognition, involving more automatic processing,
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6 and later during the day for free recall, requiring more elaborate processing. In
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8 each task, the overall trend should be modulated by an interaction with the task
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10 component that was manipulated, i.e. difficulty in the discrimination task (parallel
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12 bars shifted by 0, 1, 2, or 3 pixels), item modality in the probe recognition task
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14 (visual and auditory list and probe presentation), and item attributes in the free
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16 recall task (typographic, structural and semantic encoding conditions). In
17
18 agreement with the variations observed in laboratory studies, we expected to find
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20 later performance peaks or larger performance variations in the more demanding
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22 task conditions.
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33 **2. Method**

34 **2.1. Subjects**

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36 The study was carried out with 23 volunteer shift-workers supervising, on various
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38 control monitors, the in-door security of a nuclear plant in the south-west of
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40 France. They were issued from six teams of operators (total of 36), and were all
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42 men, aged 41.5 years (range 35 to 53 years), working in shift-work systems for
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44 11.8 years (range 4 to 20 years). They worked a continuous rapidly forward
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46 rotating shift-system, with 3 mornings, 2 afternoons, 2 nights followed by 5 days
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48 off. The 8-h shifts started at 06:00, 14:00, and 22:00 respectively.
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58 **2.2. Material and procedure**

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Satellite controllers completed Thayer's check-list and performed four different neuropsychological tasks on each of six testing times that were distributed over the 24-h day. Testing took place in a quiet room, during duty-pauses introduced for the sake of the study, by avoiding meal-times and shift-changeover times, i.e. at 03:00, 07:00, 11:00, 15:00, 19:00 and 23:00. The subject first completed the check-list, then performed a discrimination task, followed by two memory tasks (starting randomly with either) and a reaction-time task. To ensure no confounding effects of time of day and practice, testing times were randomized across participants, with a single testing time per day for a given subject. Prior to the beginning of the study, operators completed Horne and Östberg's (1977) questionnaire. The results indicated that no participant displayed extreme morningness or eveningness.

2.2.1. Alertness: Participants completed a French paper-and-pencil version of Thayer's activation-deactivation adjective checklist (Thayer, 1978). They quoted, for each of 20 adjectives, one of the following responses "not at all", "don't know", "little", "much", having an assigned weight respectively of 1, 2, 3 and 4. Two adjectives, however, have a negative weight assigned to them. The scores were grouped into four factors, general activation (GA), deactivation sleep (DS), high activation (HA), and general deactivation (GD). The ratio GA/DS provided an index of subjects' alertness.

2.2.2. Visual discrimination: Each of 24 trials started with the display of two horizontal parallel bars, 3-cm long and 0.5 cm apart. Depending on the trial, the bars were either shifted horizontally to each other by 1, 2 or 3 pixels (in each case,

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1/4 of trials), or they were not shifted (1/4 of the trial). Items were displayed in the centre of a computer screen while the following instruction occurred on the bottom of the screen “The lines are shifted (press the key M) / The lines are not shifted (press key Q)”. The participant’s response initiated a 2-sec inter-trial-interval, before the next trial started. Software, specifically designed for this study, presented the four discrimination conditions randomly, and recorded the subject’s response accuracy and latency.

2.2.3. Probe recognition: On each of 32 trials, six common French nouns were presented, one by one (750 ms), at a rate of one word per second. Four seconds after presentation of the last list-item, a probe item was presented together with the following response instruction “The word figured in the list (press M-button) / The word did not figure in the list (press Q-button)”. The subject’s response initiated a 5-sec ITT, followed by a brief sound signalling the start of the next trial. The list-items were randomly selected from a 24-item set and on half the trials the probe had occurred in the list. Item-lists and probes could be presented either in the visual modality (centre of a computer screen), or in the auditory modality (loud-speakers). The four trial types resulting from presentation modality of lists and probes (auditory-visual, auditory-auditory, visual-visual, visual-auditory) were randomized across trials by the aforementioned tailor-made software. To rule out practice effects across the six testing times, six different item-sets were used. All items of a set belonged to the same word category (fruit, vegetables, music instruments, furniture, and animals).

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2.2.4. Free recall: This protocol was previously described by Maury and Queinnec (1992). Briefly, on each of 18 trials, a common French noun was presented in the middle of a computer screen (300 ms), immediately preceded by a question that induced processing of the word's typographical attributes ("Is the word written in capitals", 1/3 trials), structural attributes ("Do the vowels of the word occur in an alphabetical order", 1/3 trials), or semantic aspects (1/3 trials). In the latter case, the question varied according to the item presented, like "Is it used to open a door", followed by the item "handle". Simultaneously with each word, the following instruction occurred on the bottom of the screen: "Response 'Yes', press key M; Response 'No', press key Q". The response initiated an interpolated reaction-time task (see below) before the next trial started. Following the last trial, subjects were asked to write on a white sheet all the words they could remember from the 18-item list.

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2.2.5. Reaction-time: This task was interpolated after each trial in the free recall task, in order to prevent maintenance rehearsal. The response after each question/word sequence in the free recall task automatically generated a 1-px spot that moved randomly on the screen during several seconds and finally 'exploded'. Following this event, the subject had to press the 'space' bar as rapidly as possible, which initiated a second, and then a third trial. Thereafter, the program shifted back to the recall task, with the presentation of a question starting the second trial, and so on.

2.3. Statistics

All measures recorded were analysed by parametric tests. ANOVAs with repeated measures across time of day (TOD) were used to analyse subjects' self-reported

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3 alertness (1-way ANOVA), and factorial ANOVAs investigated time-of-day
4 effects together with task-specific components in the cognitive tasks. Tukey's test
5 was used for post hoc analyses. We further explored whether task performance
6 variations observed across time of day were associated with variations in subjects'
7 alertness. This hypothesis was tested by using Pearson's correlation test as
8 follows. Correlations were computed within participants (n=6 for each person
9 separately), by using alertness/test scores at the 6 time-of-day values. Then, the
10 r values were tested against the null hypothesis by using a 1-sample t test. Though
11 this procedure violates the assumption of independence of scores, it provides an
12 indication whether, in general, alertness was correlated with test performance.
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30 3. Results

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34 Operators' alertness curve obtained by concurrent ratings on six recordings across
35 the 24-h day is represented by Figure 1. A one-way ANOVA with repeated
36 measures revealed a significant time-of-day effect ($F(5,5) = 3.73, p < .01$), with
37 significant lower alertness at 03:00 than at 15:00 and 19:00.
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43 The effects of time of day (TOD) on operators' performance in the cognitive tasks
44 were explored together with task-specific factors by using factorial ANOVAs. In
45 the visual discrimination task, a 2-way ANOVA of TOD (repeated measures) and
46 discrimination condition revealed a significant effect of discrimination condition
47 on response accuracy ($F(3,23) = 199.13, p < .001$; Figure 2), and an interaction
48 between response accuracy and TOD ($F(5,23) = 1,5639, p < .05$). Post-hoc
49 analyses indicated that the latter effect resulted from less accurate responding at
50 03:00 compared to 11:00 in the 1 pixel shift condition ($p < .01$). Furthermore,
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3 subjects responded overall more accurately in the most obvious discrimination
4 conditions (3-px shift, no-shift) compared to the 1- and 2-pixel shift conditions (in
5 each case, $p < .01$), and in the 2-pixel compared to the 1-pixel discrimination
6 condition ($p < .001$). Discrimination condition also affected subjects' response
7 latency ($F(3,23) = 4.783$, $p < .01$), with more rapid responding in the 3-px shift
8 condition compared to the remaining conditions (in each case, $p < .01$).
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11 Figure 3 illustrates the mean number of correct responses in a verbal probe
12 recognition task according to TOD, and presentation modality of the verbal items.
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14 A 2-way ANOVA with repeated measures revealed that task performance was
15 affected by presentation modality of the item lists ($F(1,23) = 22.11$, $p < .001$), and
16 of the probes ($F(1,23) = 9.66$, $p < .01$), indicating better performance following
17 auditory rather than visual item presentation, both at encoding and recall. Further,
18 TOD interacted with presentation modality ($F(5,23) = 2.166$, $p < .05$), due to
19 significant higher recall at 03:00 following auditory compared to visually encoded
20 words ($p < .001$).
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24 In a free recall task, the mean number of words recalled according to TOD was
25 analysed together with the type of question that was presented prior to each word
26 at encoding (Figure 4), and the position in the list (Table 1). The figure indicates
27 more marked TOD effects following questions inducing processing of semantic or
28 typographic aspects rather than of structural aspects. Furthermore, whether items
29 were issued from the initial (positions 1 to 6), intermediary (positions 7-12), or
30 end (positions 13-18) portion of the list, recall performance was overall higher on
31 day-time compared to night-time recordings. A 3-way ANOVA of these factors
32 revealed significant effects for encoding question type ($F(2,23) = 22.30$, $p < .001$),
33 and list-portion ($F(2,23) = 3.9$, $p < .05$), and an interaction between each of these
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3 factors and time of day (TOD x question type $F(10,23) = 1.99$, $p < .05$; TOD x
4 list portion $F(10,23) = 2.01$, $p < .05$); ($F(4,23) = 5.97$, $p < .001$). Post-hoc analyses
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6 revealed superior recall for words preceded by a semantic question rather than by
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8 a structural question at 07:00 and 11:00 (respectively, $p < .05$, and $p < .01$), or by
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10 a typographic question at 11:00. ($p < .01$). In addition, items issued from the
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12 initial list-portion were better recalled at 07:00 than at 19:00 ($p < .05$). Moreover,
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14 a significant interaction between question type and list-portion indicated
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16 significant higher recall performance when words issued from the initial list-
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18 portion were preceded by a semantic question rather than by a structural or
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20 typographical question ($p < .001$ in each case). A similar effect was observed
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22 when items issued from the end-portion of the list were preceded by a semantic
23
24 rather than by a typographical question ($p < .01$).

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27 A similar analysis was performed for operators' performance in a detection task
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29 that was interpolated following each question/word presentation in the free recall
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31 task. Time-of-day effects on subjects' mean response latencies on each of three
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33 successive trials (Table 2) were investigated by including two additional factors
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35 (Table 3), i.e. the question type preceding the detection task (structural,
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37 typographic, and semantic), and the list portion (initial, intermediary, and end-
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39 portions). A four-way ANOVA of these factors revealed a significant effect of
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41 time of recording ($F(5,161) = 2.94$, $p < .05$), indicating slower responses at 03:00
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43 compared to 07:00 ($p < .05$), and 19:00 ($p < .01$). Furthermore, highly significant
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45 differences between trials ($F(2,161) = 40.86$, $p < .001$), and list-portions ($F(2,161)$
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47 $= 10.24$, $p < .001$), resulted from slower responses on the first compared to the
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49 second and third trials ($p < .001$, in each case), and on trials inserted in the
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3 intermediary ($p < .001$) and end portions ($p < .001$) of the list compared to the
4
5 initial list-portion. No interaction was found between task factors and TOD.
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8 To investigate whether trends of task performance and self-reported alertness
9
10 trends were associated, correlations across time of day were calculated between
11
12 alertness scores and either performance measure for each participant. Table 4
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14 summarizes ranges of individual correlation values for each performance measure
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16 and the corresponding mean correlation. Testing the 23 r values against the null
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18 hypothesis revealed overall significant correlations across time of day between
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20 alertness on one hand, and discrimination latency, visual recognition performance
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22 and free recall performance on the other hand (Table 4).
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32 **4. Discussion**

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36 In real-job conditions, operators displayed reliable alertness variations and task
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38 performance variations across the 24-h day. A nocturnal drop was found for task
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40 performance and self-reported alertness, despite a lack of control for a number of
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42 factors that have been shown to affect psychological measures in controlled
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44 laboratory conditions, including light exposure, noise and motivation (Smith,
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46 McEvoy, & Gevins, 2002; Wright et al., 2002). In shift-workers, the nocturnal
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48 decline of psychological measures is generally aggravated by chronic sleep
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50 deprivation (Akerstedt, 1991; Dinges et al., 1996; Fletcher & Dawson, 2001;
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52 Pilcher et al., 2000). The disruptive effects of shift-work have been shown to
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54 depend on various shift-scheduling features. Somewhat smaller effects have been
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56 shown for rapid compared to slow rotations, for systems including a limited
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3 number of successive night-shifts, and for late versus early morning-shift start
4 (Della Rocco & Nesthus, 2005; Knauth, 1996; Tucker et al., 1998). As in the
5
6 present job-situation operators worked according to a rapid forward rotating shift-
7
8 scheduling system that included a maximum of two or three successive night-
9
10 shifts, and late night-to-morning shift changeover, the disruptive effects on the
11
12 nocturnal decline of operators' psychological measures may have been less
13
14 pronounced than may have been expected in other shift-scheduling systems.
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19 Operators' self-rated alertness displayed a typical day-oriented trend that peaked
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21 at 19:00 and reached its minimum at 03:00. The finding of a trend similar to those
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23 reported in other real work settings (Akerstedt, 1991; Dinges et al., 1997; Tucker
24
25 et al., 1998), supports the hypothesis of a strong dependency of alertness on the
26
27 endogenous systems underlying circadian rhythms (Achermann & Borbély, 1994;
28
29 Folkard & Akerstedt, 1992). The marked differences between day- and night-
30
31 time reported in the present study contrasted, however, with the restricted range of
32
33 alertness ratings reported in another shift-work study (Tucker et al., 1998). This
34
35 difference may be related to methodological differences, given that in the present
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37 study operators rated alertness concurrently on four hourly intervals, rather than
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39 retrospectively on a single session. In addition, the alertness score was computed
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41 from responses to a list of adjectives rather than by quoting a single-item scale,
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43 and could thus provide a more precise description of operators' functional state.
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Though other factors may explain the finding of more or less shaded alertness
curves in shift-work studies, the idea that the rating method used contributes to
this difference may deserve further investigation. On the other hand, the
possibility cannot be excluded that in real-job conditions operators rate alertness

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3 simply according to what they should feel like while being at work or what they
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5 expect to feel like given the time of day.
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8 This latter interpretation may, however, not account for the task performance
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10 variations observed over the 24-hr day in the present study. The role of practice
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12 effects may also be excluded, given that performance trends were obtained by
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14 randomizing the order of the six recording sessions across participants, and by
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16 performing a single session on a given day. Similarly, in the memory tasks
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18 learning effects were, in principle, ruled out by randomizing different task
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20 versions across participants and recordings. In light of these considerations, task
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22 performance variations according to time of day most probably resulted from
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24 operators' functional state at the time of testing. Thus, with increasing alertness
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26 during day-time, operators' displayed significant superior performance in several
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28 cognitively more or less demanding tasks. More specifically, they responded more
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30 rapidly in a reaction time task, performed more accurate responses in a non-verbal
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32 visual discrimination task, and recalled more verbal items in the memory tasks.
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34 The finding that time of day affected different performance measures may indicate
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36 that operators' nocturnal performance drop resulted from the impairment of some
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38 general non specific capacity involved during information processing. This is in
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40 agreement with the hypothesis that sleep deprivation reduces the non-specific
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42 arousal level of the body, but has no specific effects (see for instance Wilkinson,
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44 1992). According to this point of view, sleep deprivation effects on reaction time
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46 and trough-put in cognitively more loaded tasks would result from the monotony
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48 and lack of novelty that characterize these tasks. In contrast, tasks that are "too
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50 complex, too interesting, too variable and, above all, too short" would intrinsically
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52 encourage sleep-deprived people to apply compensatory efforts and to perform
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3 normally (pp. 254-256). Likewise, Balkin et al. (2004) found that monotonous
4 tests that demanded constant attention, like psychomotor vigilance tests, were
5 most sensitive to partial sleep deprivation compared to tests involving higher
6 cognitive load, like logical reasoning, problem-solving and decision-making,
7 which were least sensitive (Balkin, Bliese, Belenky, Sing, Thorne, Thomas, et al.,
8 2004).
9

10 Accordingly, the present results may reflect a differential sensitivity of the tasks to
11 sleep deprivation as shift-work is associated with systematic partial sleep loss
12 (Pilcher et al., 2000). Our results only partly support this assumption. On the one
13 hand, task performance decrements in early morning hours have been observed
14 for reaction time. This finding is also in agreement with a number of studies
15 performed under controlled conditions in the laboratory (Monk et al., 1985; Monk
16 & Carrier, 1997; Casagrande et al., 1997; Heuer et al., 1998; Owens et al., 2000;
17 Gennaro et al., 2001; Wright et al., 2002), in simulated shift-work conditions
18 (Fröberg et al., 1975; Colquhoun et al., 1968; Johnson et al., 1992), and in real
19 shift-work settings (Tilley et al., 1982; Hossain et al., 2004). On the other hand, in
20 the more demanding cognitive tasks, time-of-day effects interacted with the task
21 components that were manipulated. Thus, time of day impaired response accuracy
22 in the discrimination task only in two out of four task conditions, i.e. when the
23 difference between items to be discriminated was least obvious, while no such
24 effect was found in those conditions involving a more marked to-be-discriminated
25 difference. Likewise, recognition performance was superior on early morning
26 hours for auditory compared to visually encoded words. In a free recall task,
27 operators displayed superior recall during day-time, but only when elaborate
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3 processing was favoured during encoding, rather than processing of structural or
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5 physical word attributes.
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8 Harrison and Horne (2000) proposed to differentiate those cognitive demanding
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10 tasks involving divergent skills, such as innovating and updating strategies, from
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12 those based on convergent rule-based skills. The authors reported a number of
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14 studies demonstrating sleep deprivation effects in the former but not in the latter
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16 tasks. Though the tasks used in the present study were rule-based, it may be that
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18 the changing task conditions involved strategy changes that may have increased
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20 the task-sensitivity to time-of-day effects. Strategy changes in relation to arousal
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22 changes have also been proposed to account for performance variations observed
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24 in laboratory studies. In the morning, when arousal was low, performance was
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26 shown to peak in those tasks involving more automatic processing, while
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28 increasing arousal across the day would favour more elaborate processing, like
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30 processing of semantic aspects from long-term memory (Baddeley et al., 1970;
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32 Folkard, 1979; Folkard et al., 1976; Folkard & Monk, 1980; Lorenzetti & Natale,
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34 1996; Oakhill & Davies, 1989). This hypothesis was favoured by the finding of
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36 significant correlations between operators' self-rated alertness and their task
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38 performance. More especially, when they rated alertness at a low level, their
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40 response speed in the discrimination task and their recall and recognition
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42 performance were also reduced, and vice versa. In addition, as reported above,
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44 significant time-of-day effects were observed in all the neuropsychological tests
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46 used, with overall higher performance during the day. However, no clear
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48 performance peak was observed in either task in the present study. This may be
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50 related to the marked inter-individual task performance differences, evidenced by
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52 large standard errors, in particular in the cognitively more loaded tasks. Inter-
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3 individual task performance differences may be related to differences in
4 operators' sleepiness, workload, adjustment to shift-work, and work conditions
5 (Akerstedt, 2007; Bustamante, Bliss, & Anderson, 2007 ; Costa & Sartori, 2007),
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10 in addition to the afore-mentioned lack of control for external factors.

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12 Accordingly, future field studies of the present kind should include objective
13 sleep measures, in addition to subjective alertness or sleepiness ratings in order to
14 explore the effects of sleepiness and adjustment to shift-work on operators' task
15 performance (Tucker et al., 1998). The tests used in the present study may be of
16 limited ecological value as far as job-task complexity, real-job performance, and
17 consequences of performance impairments on safety and security are concerned.
18
19 In this respect it may be useful to include in future studies a workload index, as
20 discussed in several recent studies (Pretorius & Cilliers, 2007; Noyes & Bruneau,
21 2007 ; Roth, Scott, Deutsch, Kuper, Schmidt, et al ., 2006). Thus, though no direct
22 relation may exist between the present results and real-job performance, the
23 neuropsychological tests enabled suitable outcome measures reflecting cognitive
24 processes also involved in real-job operations. Furthermore, data provided
25 evidence of subtle changes in operators' information processing strategies in
26 relation to time of day. This further confirmed that time-of-day effects on memory
27 depend on specific task-related factors (Mélan et al., 2007). Moreover, the data
28 emphasize that organizing shift-work and work-break systems to maintain
29 adequate concentration and avoid fatigue and boredom is still a major concern, in
30 particular for safety-related occupations. Practical implications also include often-
31 overlooked recommendations based on laboratory studies, and in particular on the
32 findings of systematic performance variations according to presentation modality
33 and depth of processing of verbal material (see INTRODUCTION). The
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3 demonstration of superior recall for auditory compared to visual material is of
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5 particular relevance given the rather limited use of auditory compared to visual
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8 interfaces in many job-situations, even for signalling emergency conditions.
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Table captions

Table 1. Mean number of words recalled (\pm -S.E.) according to their position in the list (initial list-portion: positions 1 to 6, intermediary list-portion: positions 7 to 12, terminal list-portion: positions 13 to 18).

Table 2. Mean response latencies (\pm -S.E.) in a visual detection task according to time of day and trial.

Table 3. Mean response latencies (\pm -S.E.) across trials in the detection task according to time of day, type of inducing question (upper panel), and list-portion (lower panel).

Table 4. Ranges and mean (\pm -SD) values for Perason's correlation test computed across time of day between alertness scores and each performance measure in the different tasks. The asterisk in the last column indicates that mean r values differed from the null hypothesis, with $p < .05$.

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Tables

Table 1.

	Time of day					
List-portion	3:00	7:00	11:00	15:00	19:00	23:00
initial	1.83 (.30)	2.57 (.27)	2.45 (.26)	2.00 (.27)	1.75 (.29)	2.14 (.27)
intermediary	1.91 (.31)	1.39 (.26)	1.77 (.27)	1.77 (.27)	1.95 (.27)	1.33 (.24)
terminal	1.87 (.33)	1.61 (.23)	1.91 (.35)	1.95 (.26)	2.20 (.32)	1.62 (.28)

Table 2.

	Time of day					
	3:00	7:00	11:00	15:00	19:00	23:00
Trial 1	0.28 (.03)	0.29 (.03)	0.42 (.07)	0.35 (.06)	0.29 (.03)	0.30 (.04)
Trial 2	0.28 (.04)	0.31 (.05)	0.46 (.09)	0.47 (.14)	0.41 (.08)	0.23 (.07)
Trial 3	0.53 (.17)	0.40 (.08)	0.31 (.06)	0.35 (.08)	0.46 (.08)	0.40 (.09)

Table 3.

		Time of day					
		03:00	07:00	11:00	15:00	19:00	23:00
Type of inducing question	Structural	0.41 (.14)	0.34 (.10)	0.41 (.10)	0.37 (.04)	0.35 (.05)	0.36 (.03)
	Typographic	0.37 (.09)	0.36 (.08)	0.36 (.06)	0.45 (.10)	0.36 (.04)	0.38 (.05)
	Semantic	0.40 (.12)	0.36 (.05)	0.40 (.08)	0.39 (.05)	0.37 (.06)	0.36 (.04)
List portion	Beginning	0.24 (.02)	0.35 (.06)	0.38 (.07)	0.43 (.09)	0.42 (.07)	0.36 (.07)
	Intermediary	0.55 (.22)	0.39 (.09)	0.40 (.06)	0.47 (.13)	0.37 (.06)	0.32 (.06)
	End	0.38 (.07)	0.35 (.05)	0.40 (.09)	0.33 (.06)	0.41 (.08)	0.41 (.07)

Table 4.

	Performance measure	Range of r values	Mean r values	t(22)
Discrimination	Latency	-0.91 - 0.75	-.24 (.11)	-2.21*
	Errors	-0.68 to 0.44	-.11 (0.09)	-1.18
Probe	Auditory	-0.77 to 0.72	0.13 (0.11)	1.25
Recognition	Visual	-0.58 to 0.86	.25 (.09)	2.68*
Free Recall	Physical	-0.64 to 0.83	.22 (.10)	2.23*
	Structural	-0.72 to 0.96	.21 (.09)	2.38*
	Semantic	-0.42 to 0.86	.19 (.08)	2.36*

Figure captions

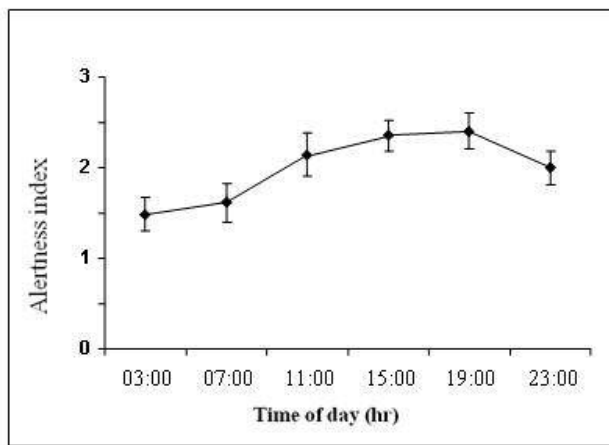
Figure 1. Mean (\pm S.E.) self-ratings of alertness on a check-list provided every 4 hours across the 24-h day.

Figure 2. a) Mean (\pm S.E.) number of errors and b) mean (\pm S.E.) response latency in four visual discrimination conditions, **at six times** across the 24-h day.

Figure 3. Mean (\pm S.E.) number of correct responses in a probe recognition task according to presentation modality of item-lists, **at six times** across the 24-h day.

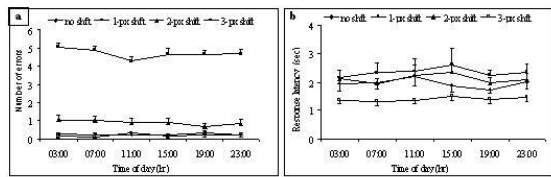
Figure 4. Mean (\pm S.E.) number of words recalled according to the type of inducing question preceding each word, **at each of six times** across the 24-h day.

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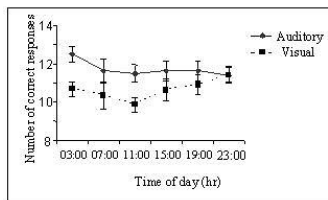
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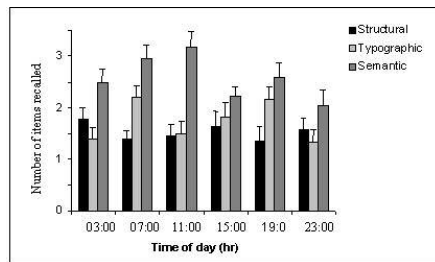
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