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Research report

Gender and age differences in psychomotor vigilance performance under differential sleep pressure conditions

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Abstract

The effects of sleep pressure and circadian phase on neurobehavioral function can be sensitively measured with the psychomotor vigilance task (PVT). We compared PVT performance in 16 young (8 men and 8 women, 20–31 years) and 16 elderly healthy subjects (8 men and 8 women, 57–74 years) during a 40-h sleep deprivation (SD, high sleep pressure) and a 40-h multiple nap protocol (NAP, low sleep pressure) under dim light and constant posture conditions in a balanced crossover design. Independent of age and sleep pressure conditions, women exhibited significantly slower reaction times (RTs) than men. This effect became more apparent with increasing time elapsed into both the 40-h NAP and SD protocol. However, women tended to have fewer premature key presses than men. Independent of gender, the elderly showed slower RTs than the young in the NAP protocol during the biological day (8–24 h) but not during the biological night (24–8 h). In the SD protocol, they had also significantly slower RTs but only during the first 16 h under low to moderate levels of sleep pressure conditions. The relative PVT performance decline after SD was significantly less pronounced in the elderly than in the young, so that both age groups exhibited similar performance decrements after 16 h into the SD protocol. Thus, nighttime- and sleep pressure-related RT slowing in the young "makes them old", or the elderly are less susceptible to circadian and wake-dependent PVT performance decrements. We interpret the gender effect as a different strategy in women when performing the PVT, although the instructions to be 'as fast as possible' were identical. Not only sleepiness and circadian phase, but also age and gender are major factors that may contribute to attentional failures in extended work shifts and during nighttime work shifts.

Keywords: Sleep pressure; Circadian phase; PVT; Reaction time; Gender; Aging

1. Introduction

Sustained attention as a global function is fundamental for optimal cognitive functioning. Neurobehavioral and cognitive functioning have been shown to be strongly influenced by two interlinked systems: the circadian timing system and the homeostatic sleep regulatory system (for a review see Cajochen et al. [8]). This interplay of processes leads to a characteristic circadian performance pattern most clearly reflected in vigilance tasks like the Mackworth clock procedure [15] and the psychomotor vigilance task (PVT) [11], both using reaction time (RT) paradigms [16,12].

Besides its sensitivity to circadian and homeostatic modulation, RT is highly susceptible to the effects of age [20] with a performance decline already starting in the third decade of life [26]. Astonishingly, several authors have reported that age-related performance differences were attenuated when subjects were sleep deprived [4,5]. Philip et al. [21,22] showed that the different lengths of wake duration differentially impacted vigilance performance in different age groups, such that RTs of older subjects remained almost unaffected while young subjects' RTs increased with time awake. Similarly, Smulders et al. [24] used three choice-RT tasks to demonstrate that sleep loss effects are smaller in the elderly compared to young study participants. The same result was presented initially by Brendel et al. [7], who used the Mackworth clock procedure in a protocol with one night of total sleep deprivation (SD). The attenuated impact of prior wakefulness in elderly participants may be due to a relatively flattened circadian amplitude of the vigilance performance

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curve as suggested by Monk and Kupfer [16], who employed the Mackworth clock procedure in a constant routine (CR) protocol. Another possibility is that the reduced effect of sleep loss in the elderly is due to a less profound build-up of homeostatic sleep pressure as indexed by a reduced relative increase of frontal EEG delta activity in the elderly during recovery sleep [17].

Taken together, the above mentioned data suggest that age-related performance decrements in vigilance tasks depend on the level of the sleep–wake homeostat. Our aim was to further elucidate the impact of not only the sleep–wake homeostat but also the circadian system on age-related decrements in the PVT under constant conditions during 40-h of sleep deprivation and 40-h of sleep satiation (multiple nap protocol, NAP). We hypothesised as follows:

1. PVT performance in the two age groups is not the same in the NAP protocol under low sleep pressure conditions: the young participants show better performance.
2. Under high sleep pressure conditions in the SD protocol, the age-related decline in PVT performance disappears.
3. There are no gender differences in the age-related decline in PVT performance.

2. Methods

2.1. Study participants

Sixteen healthy young (8 women and 8 men, mean age 25 ± 3.5 years, range 20–31) and 16 healthy older volunteers (8 women and 8 men, mean age 65 ± 5.5 years, range 57–74) completed the study. All were non-smokers, free from medical, psychiatric, neurologic and sleep disorders (Pittsburgh Sleep Quality Index score ≤ 5) and average chronotypes (score between 12 and 23) as assessed by screening questionnaires, a physical examination and a polysomnographically recorded screening night. An additional neuropsychological assessment ensured that none of the volunteers suffered motor, attentional or memory impairments [23]. Other exclusion criteria were: shift work within 3 months and transmeridian flights within 1 month prior to the study, excessive caffeine and alcohol consumption, drug consumption and excessive physical activity. Female participants of the young group started the study on days 1–5 after menses onset in order to complete the entire study block within the follicular phase. All the study participants gave signed informed consent. The local Ethical Committee approved the study protocol, screening questionnaires and consent form. All procedures conformed to the Declaration of Helsinki.

2.2. Protocol

The entire study consisted of two study legs of 5 days each with 2 weeks in between. During the week prior to each study leg (baseline week) participants were instructed to maintain a regular sleep–wake-cycle (bed- and wake-times within ±30 min of self-selected target time), which was verified by wrist activity monitors (Cambridge Neurotechnologies®, UK) and sleep logs.

The two study legs comprised two conditions: high sleep pressure (SD protocol) and low sleep pressure (NAP protocol), which were conducted in a balanced crossover design. Each study leg consisted of one adaptation night and one baseline night, followed by 40-h of either sleep deprivation or sleep satiation, as well as one recovery night (Fig. 1). The sleep–wake schedules were calculated by centering the 8-h sleep episodes at the midpoint of each individual's habitual sleep episode as assessed by actigraphy and sleep logs during the baseline week.

Low sleep pressure was realised by 10 alternating cycles of 75 min of scheduled sleep (naps) and 150 min of scheduled wakefulness (Fig. 1). In both the SD and NAP protocols, the wake episodes were spent under constant routine conditions (constant dim light levels < 8 lux, semi-recumbent posture in bed, food and liquid intake at regular intervals, no time cues; for details of the CR method, see Cajochen et al. [9]). During scheduled sleep episodes a minor shift to supine posture was allowed and lights were turned off (0 lux).

2.3. Psychomotor vigilance task

The PVT is a sustained attention performance task [11] known to be sensitive to sleep loss and circadian rhythmicity [10,27]. The study participants are required to quickly press a button as soon as red digits appear on a millisecond counter. The digits are presented in intervals randomly varying from 3 to 7 s. During both protocols, 11 test bouts of 5 min duration were performed every 225 min starting 75 min after lights on in the morning. In the NAP condition the PVT was scheduled 75 min before and after each nap (see Fig. 1). The day before the protocols started, two PVT bouts had been administered to familiarise the subjects with the task. All participants were instructed to press the response button as fast as possible as soon as the red digits appeared.

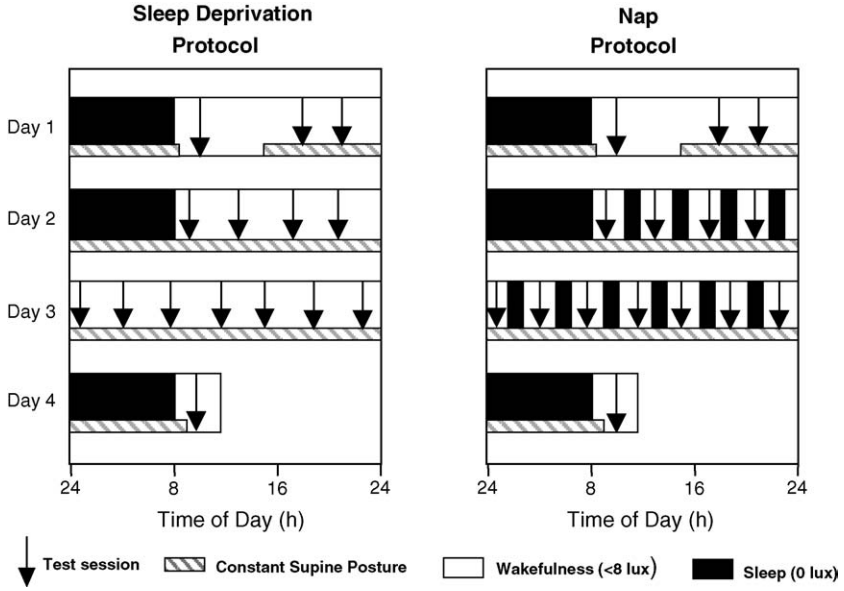

Fig. 1. Overview of the protocol design. After 2 nights and 1 day in the laboratory, a 40-h sleep deprivation (left panel) or a short sleep–wake cycle paradigm (75 min/150 min) (right panel) under constant routine conditions was carried out, followed by an 8-h recovery night.

2.4. Data analyses

The default performance metrics (median RT, response errors, lapses, etc.) were computed by the standard software REACT® Version 1.1.03 data analyses for the PVT 192. We have analysed median RT, mean of the 10% fastest, and of the 10% slowest RTs, all converted to reciprocal RTs. In addition, we have calculated the interpercentile range between the 10th and 90th percentile according to [13]. In a first step, an analysis of variance for repeated measures (rANOVA) with the repeated factors 'condition' (NAP, SD) and 'time' (sessions 1–11) and the between subject-factors 'age group' (young, old) and 'gender' (male, female) was performed. In a next step, a two-way rANOVA with the repeated factor 'time' and the within factor 'age group' was carried out for each sleep pressure condition separately. All derived *P*-values were based on the Huynh–Feldt's corrected degrees of freedom, but the original degrees of freedom are reported. For post hoc comparisons Curran Everett's alpha-corrected *t*-test was employed. Alpha criterion was set at $P = 0.05$. SPSS® (SPSS Inc., SPSS for Windows, Chicago, IL, USA, Version 11.0) and Statistica® (StatSoft Inc. 1999, Statistica for Windows, Tulsa, OK, USA, Version 6.0) were used.

3. Results

The main factor 'gender' yielded significance for the three dependent variables (i.e. medium, 10% fastest and 10% slowest RT; *P* at least 0.003) with significantly slower reaction times in women than in men (median RT for women: 250.6 ms versus 210.2 ms for men). The interpercentile range tended to be wider in women than in men ($F_{1,28} = 3.1$, $P = 0.09$). Fig. 2 depicts the distribution of all measured RTs in men and women pooled for both age groups. The factor 'gender' did not significantly interact with the factors 'age group' and 'condition', but with the factor 'time', with gender differences becoming more pronounced with increasing time elapsed into the SD and NAP protocols (median RT: $F_{1,10} = 3.5$, $P < 0.02$; 10% fastest RT: $F_{1,10} = 2.4$, $P < 0.03$; 10% slowest RT: $F_{1,10} = 2.3$, $P < 0.03$). Other combinations of interactions between gender and the above mentioned factors did not yield any significance. Therefore, for further analyses the factor gender was not included in the ANOVAs. However, to test whether the gender-related slower RTs were related to more accurate response button presses, premature key presses (false starts, error of commission) were defined as reaction times < 100 ms and analysed with a rANOVA with the above mentioned factors. The factor gender tended to be significant ($P = 0.07$) and the average level of false starts was lower in women than in men (0.18 ± 0.05 SE in women versus 0.08 ± 0.05 SE in men).

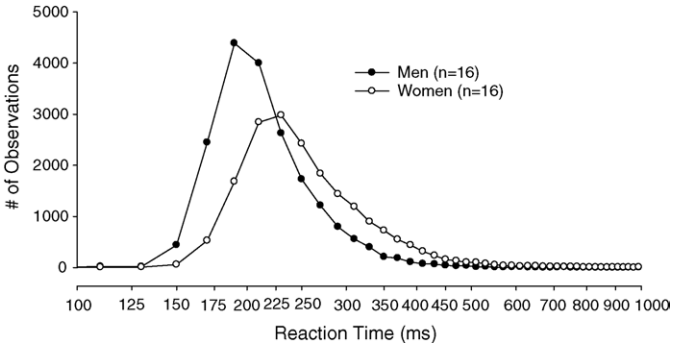

Fig. 2. Frequency curve of the distribution of RTs (ms, log scale) in male and female study participants.

In a second step, age group specific responses were compared in a rANOVA with the three factors 'age group', 'condition' and 'time' (see Table 1). For all four above mentioned variables, the main factors 'condition' and 'time' and their interaction were significant ($P < 0.01$, except for 10% fastest RTs a tendency $P < 0.1$), whereas 'age group' was not, nor was its three-way interaction with 'time' and 'condition'. However, for the 10% slowest RTs the interaction between 'age group' and 'time' yielded significance ($F_{10,300} = 2.6$, $P = 0.014$). In addition, there was a significant interaction of 'age group' and 'condition' for median RT, which revealed group differences depending on the sleep pressure condition ($F_{1,30} = 4.3$, $P = 0.047$) (Fig. 3). Under low sleep pressure in the NAP protocol the elderly had slower reaction times than the young subjects.

Table 1
Results of the rANOVAs of the measures 'median RT', '10% slowest RTs', '10% fastest RTs', and the interpercentile range (10th–90th percentile)

	d.f.	Median RT		10% slowest RTs		10% fastest RTs		Interpercentile range (10th–90th)	
		F-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value	*F*-value	*P*-value
Effect									
Age group	1, 30	1.28	0.266	2.70	0.111	2.09	0.159	0.54	0.470
Condition	1, 30	16.79	**0.000**	23.67	**0.000**	5.23	**0.029**	19.1	**0.000**
Time	10, 30	18.39	**0.000**	15.10	**0.000**	7.94	**0.000**	6.7	**0.000**
Age group × condition	1, 30	4.29	**0.047**	3.13	0.087	2.44	0.129	4.0	0.054
Age group × time	10, 300	2.09	0.060	2.58	**0.014**	1.59	0.125	1.0	0.451
Condition × time	10, 30	6.27	**0.000**	10.04	**0.000**	1.82	0.080	4.8	**0.000**
Age group × condition × time	10, 300	0.8	0.594	0.94	0.480	1.40	0.205	0.77	0.657
SD									
Age group	1, 30	0.33	0.569	0.78	0.383	1.02	0.321	0.03	0.867
Time	10, 300	16.62	**0.000**	18.14	**0.000**	5.59	0.000	12.6	**0.000**
Age group × time	10, 300	1.73	0.101	2.13	**0.039**	1.20	0.293		
NAP									
Age group	1, 30	2.89	0.100	5.38	**0.027**	3.47	0.072	3.72	0.062
Time	10, 300	5.95	**0.000**	4.18	**0.000**	3.78	**0.000**	2.10	**0.023**
Age group × time	10, 300	1.06	0.388	1.51	0.168	2.00	**0.046**	0.456	0.917

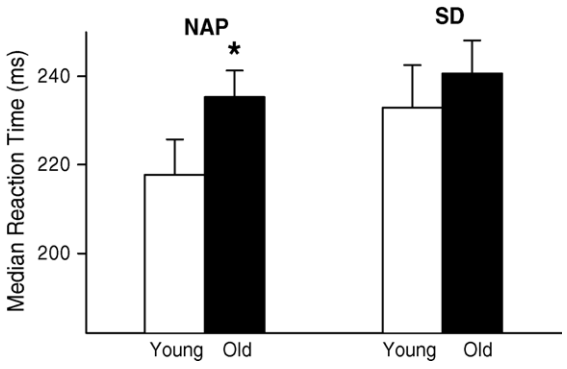

Fig. 3. Median RT (ms) of the young and the older group under low (NAP) and high (SD) sleep pressure conditions. Asterisk indicates a significant group difference on 1/RT transformed values.

To further investigate the differential effect of sleep pressure in the two age groups, a two-way rANOVA with 'time' and 'age group' was performed for each sleep condition separately (see Table 1). Significant interactions between 'age group' and 'time' were found for the 10% slowest RTs during SD (Fig. 4, lower panel). Post hoc comparisons between the two groups yielded significant results for the first, and a tendency ($P < 0.1$) for the second, third and fourth test sessions.

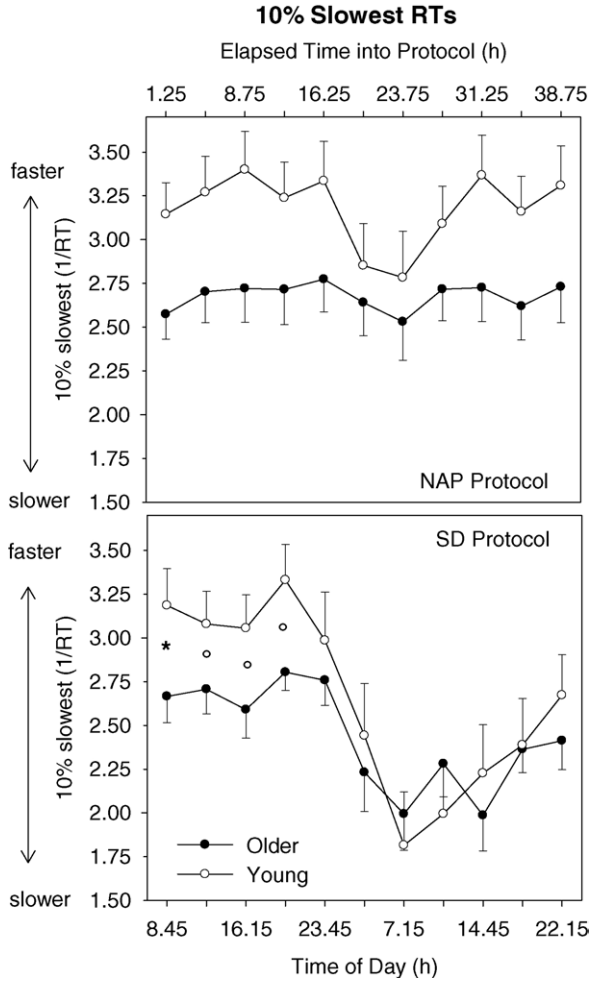

Fig. 4. Vigilance performance exemplified by the *slow* reaction time domain (10% slowest RTs) of the young and the older group under low (NAP) and high (SD) sleep pressure conditions. Asterisk indicates a significant difference and circles indicate a tendency in post hoc comparisons (Curran Everett's alpha-corrected *t*-test).

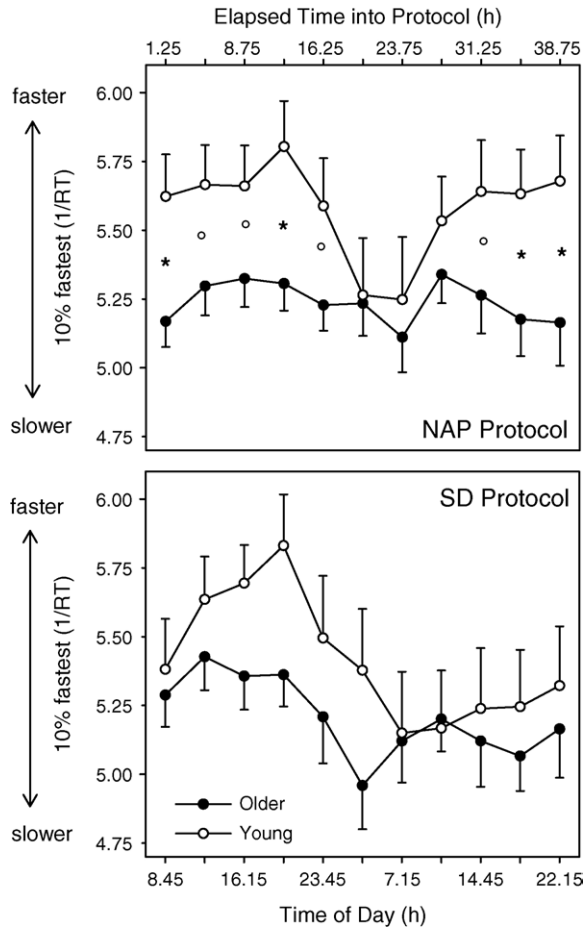

Fig. 5. Vigilance performance exemplified by the *fast* reaction time domain (10% fastest RTs) of the young and the older group under low (NAP) and high (SD) sleep pressure conditions. Asterisks indicate significant differences and circles indicate a tendency in post hoc comparisons (Curran Everett's alpha-corrected *t*-test).

In the NAP protocol, it was the 10% fastest RTs, that yielded a significant interaction between 'age group' and 'time' ($F_{10,300} = 2.00$, $P = 0.046$) (Fig. 5, upper panel). As post hoc analyses revealed, the significant group differences occurred in the first, fourth and the last two sessions, and a tendency ($P < 0.1$) in the second, third and ninth test sessions. Under the low sleep pressure condition the difference between the two age groups appears more clearly; even the main effect 'age group' for the 10% fastest RTs tended to be significant (Fig. 5, upper panel), while it yielded significance for the 10% slowest RTs (Fig. 4, upper panel).

Visual inspection of the two groups' performance curves in the NAP protocol leads to the assumption that the circadian modulation of the elderly subjects' performance was attenuated compared to the young group. Therefore, in a further analysis the amplitudes of the fitted group's mean performance curves were compared by calculating upper and lower limits of a 95% confidence interval of each group (young group: 0.20 ± 0.09;

older group: 0.07 ± 0.05). Even though the amplitude values are clearly distinct from each other, the upper limit of the older group and the lower limit of the younger group did slightly overlap.

4. Discussion

Based on earlier observations that sleep pressure has a differential effect on age-related reaction time decrements in vigilance tasks [7,21,24], we investigated performance differences between young and elderly volunteers in the PVT under different levels of sleep pressure. We hypothesised that under sleep satiation young participants show better performance than the elderly, whereas under sleep deprivation this performance difference disappears. The unmasking temperature-, posture- and light-controlled conditions of the constant routine protocol allowed us to further elucidate possibly different circadian amplitudes of the two age groups' performance curves as suggested by Monk and Kupfer [16]. Moreover, we hypothesised that there is no gender difference in the age-related decline of PVT performance.

This study shows that PVT performance does depend on gender independent of age, with overall slower RTs in women than in men. Age-related slowing in RT is particularly pronounced during low sleep pressure conditions (<16 h of prior wakefulness) and is the same in men and women. These results were obtained for median RT, thus independent of any RT distribution domain, which points to a general validity of the differential age and gender group differences.

4.1. Gender effect

We did detect an overall clear gender difference with slower reaction times in women than in men independent of age. Furthermore, our study is in agreement with Jevas and Yan [14] who reported in their meta-analysis that men and women showed the same age-related deterioration in RT. This confirms other results pointing out faster reaction times in males than in females in almost every age group both in choice as well as simple reaction time paradigms [1,19,25]. Additionally, more practice did not reduce the female disadvantage. Bellis [3] reported that the mean time to press a key in response to a light was 220 ms for males and 260 ms for females, a gender-related difference very similar to the one we observed (∼40 ms). Botwinick and Thompson [6] found that almost all of the male–female difference was accounted for by the lag between the presentation of the stimulus and the beginning of muscle contraction. Muscle contraction times were the same for males and females. In our protocol the task instructions, to press as fast as possible, were identical for everyone. However, women had the tendency to inhibit their PVT response to maintain accuracy (i.e. avoid false starts) more so than men, particularly the young men, as shown in the lesser error rate. In both genders the behavioral responses most probably reflect a high level of motivation but different strategies to achieve optimal results: in women by avoiding errors and in men by being as fast as possible.

4.2. Age effect

When subjects were sleep satiated in the NAP condition, the expected age difference was present (10% fastest RTs), with the older group showing slower RTs than the young one (Fig. 5, upper panel). Also during the first 16 h into the SD protocol, the two subject groups showed performance differences, as evidenced by the significant single comparison in the first and the tendencies in the second to fourth test bouts (10% slowest RTs) (Fig. 4, lower panel). However, when wake duration exceeded habitual time awake, as was the case in the SD condition from the fifth test session on, the group differences disappeared and the performance of older and young participants was equally slow (10% slowest RTs). The age difference under low sleep pressure is no longer apparent under high sleep pressure, so that there is less of a relative performance decrement during SD in the elderly. Whether this is related to a reduced susceptibility to wake-dependent performance decrements and the reduction in the relative increase in SWA found in frontal brain areas as reported for the elderly in the same experiment [17], remains to be elucidated. Our results are in accordance with recent data [2] showing less of a decline in PVT performance across a 40-h sleep deprivation protocol in older men. However, in contrast to those data, our older subjects never attained better performance than the young, even after more than 16 h of prior wakefulness.

Remarkably, also under low sleep pressure in the NAP condition, the performance difference between the two age groups disappeared at the circadian trough (10% fastest RTs) as the insignificant post hoc tests of the sixth, seventh and eighth test bouts indicated (Fig. 5, upper panel). The fact that the elderly subjects' performance curve follows a flattened time course, especially around the circadian temperature minimum (see Fig. 5), suggests an attenuated circadian amplitude. This is in accordance with an age-related reduction in the circadian output as indexed by a reduced circadian modulation of the salivary melatonin rhythm and the circadian arousal signal in the evening as reported in the same experiment by Münch et al. [18]. Furthermore, this observation is consistent with Monk and Kupfer [16], who reported a flattening of the vigilance performance curve for the elderly. They concluded that this attenuation is reflected by a weaker relationship between the circadian pacemaker (as measured by the core body temperature rhythm) and the "[circadian performance] rhythm(s) downstream from the pacemaker".

In summary, women react slower but are more accurate than men, and sleep deprivation makes the young "old" since the elderly do not manifest greater decrements under high sleep pressure.

Acknowledgements

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