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Differential interactions of age and sleep deprivation in driving and spatial perception by male drivers in a virtual reality environment

FARAMOSH RASHID IZULLAH[1] ANNA AF SCHULTEN,[1] MIKA KOIVISTO,[1] VALTTERI NIEMINEN,[1] MIKA LUIMULA[2] and HEIKKI HÄMÄLÄINEN[1]

[1]*Department of Psychology, and Turku Brain and Mind Center, University of Turku, Turku, Finland*
[2]*Turku Game Lab, Turku University of Applied Sciences, Turku, Finland*

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We determined the effects of age and sleep deprivation on driving and spatial perception in a virtual reality environment. Twenty-two young (mean age: 22 years, range: 18–35) and 23 old (mean age: 71 years, range: 65–79) participants were tested after a normal night of sleep and a night of sleep deprivation. The participants drove a virtual car while responding to uni- and bilateral visual and auditory stimuli. Driving errors (crossing the lane borders), reaction times and accuracy to visual and auditory stimuli, performance in psychological tests, and subjective driving ability and tiredness were measured. Age had no effect on the number of driving errors, whereas sleep deprivation increased significantly especially the number of left lane border crossings. Age increased the number of stimulus detection errors, while sleep deprivation increased the number of errors particularly in the young and in the auditory modality as response omissions. Age and sleep deprivation together increased the number of response omissions in both modalities. Left side stimulus omissions suggest a bias to the right hemispace. The subjective evaluations were consistent with the objective measures. The psychological tests were more sensitive to the effects of age than to those of sleep deprivation. Driving simulation in a virtual reality setting is sensitive in detecting the effects of deteriorating factors on both driving and simultaneous spatial perception.

Key words: Aging, driving, sleep deprivation, spatial perception, virtual reality.

Faramosh Rashid Izullah, Department of Psychology, 20014 University of Turku, Finland. E-mail: farash@utu.fi

INTRODUCTION

Aging impairs the perception of visual and auditory stimuli (for reviews, see Klencklen, Després & Dufour, 2012; Pichora-Fuller & Singh, 2006; see also Passow, Westerhausen, Wartenburger *et al*., 2012), and attention and working memory (for review, see Drag & Bieliauskas, 2010). Aging, for example, impairs the perception of stimuli in the peripheral visual field by reducing the useful field of view (Ball, Beard, Roenker, Miller & Griggs, 1988; Edwards, Ross, Wadley *et al*., 2006). The useful field of view capacity correlates negatively with the number of actual road accidents (Clay, Wadley, Edwards, Roth, Roenker & Ball, 2005; Edwards *et al*., 2006). The difference between the young and the old is particularly notable in complex and dynamic environments, such as those in driving among heavy traffic (Conlon, Brown, Power & Bradbury, 2015).

Sleep deprivation, like aging, affects alertness, speed of psychomotor, and cognitive functioning of both the young and the old, though significantly more in the young (for review, see Alhola & Polo-Kantola, 2007). Divided and selective attention, speeded decision making, and the accuracy of speeded responses to stimuli are all affected by sleep deprivation (for reviews, see Alhola & Polo-Kantola, 2007; Durmer & Dinges, 2005; Goel, Rao, Durmer & Dinges, 2009; Harrison & Horne, 2000; Lim & Dinges, 2008; see also Tomasi, Rao, Durmer & Dinges, 2009). Sleep deprivation impairs visuospatial and auditory temporal perception across age groups (for review, see Killgore & Weber, 2013). Cognitive control including attention and working memory are also affected (for reviews, see Durmer & Dinges, 2005; Goel *et al*., 2009; Killgore & Weber, 2013). The useful field of view is reduced by sleep deprivation in younger (18–30 years) and older (40–51 years) participants with consequences for driving (Rogé, Pébayle, El Hannachi & Muzet, 2003). The adverse effects of sleep deprivation are more distinct on those of the young than old adults (Adam, Retey, Khatami & Landolt, 2006; Blatter, Graw, Munch, Knoblauch, Wirz-Justice & Cajochen, 2006; Bonnet, 1989; Brendel, Reynolds, Jennings *et al*., 1990; Duffy, Willson, Wang & Czeisler, 2009; Kong, Soon & Chee, 2012; Philip, Taillard, Sagaspe *et al*., 2004). Adam *et al*. (2006), for example, found that sleep deprivation affected vigilance more in the young than in the old when measured as more lapses, higher performance instability, and higher feeling of sleepiness after the sleep deprivation night.

In healthy individuals, aging induces asymmetricity in the visual and auditory spatial perception (Takio, Koivisto, Laukka & Hämäläinen, 2011, 2013; for a review, see also, Takio, Koivisto & Hämäläinen, 2014). Perception in older adults seems to favor the right hemispace (Benwell, Thut, Grant & Harvey, 2014; Fujii, Fukatsu, Yamadori & Kimura, 1995). Indeed, Takio *et al*. (2011, 2013) found a right side auditory and visual-spatial bias for both children (age: 5–11) and older (age: 59–79) right-handed individuals. Further, Takio *et al*., (2014) suggested that this age-dependent rightward perceptual bias results from early development and late decline of executive functions, that is, changes in the interaction between perceptual and executive functions (Hugdahl, Westerhause, Alho, Medvedev, Laine & Hämäläinen, 2009; Takio *et al*., 2014). Hämäläinen, Rashid Izullah, Koivisto, Takio and Luimula (2018) further demonstrated similar right-side bias in the old group by utilizing an ecologically more valid (virtual reality (VR) headset based) driving simulator task.

Research on the effect of sleep deprivation on visual and auditory spatial perceptual bias is scarce. Some studies suggest that sleep deprivation causes visual perceptual bias and also affects auditory temporal perception (for review, see Killgore & Weber, 2013). For example, Manly, Dobler, Dodds and George (2005) showed that sleep deprivation causes a significant rightward bias in attention in adults.

To date, to our knowledge, there is no data in the literature on simultaneous measurements of driving behavior and driving-related perceptual (auditory and visual) performance while concurrently being sensitive to factors such as age and driver sleep deprivation. With the current VR-system, simultaneous measurements of these different variables and factors are possible.

In the present study, we determined the effects of aging and sleep deprivation on spatial perception and driving ability in a virtual driving environment. Based on previous findings (Hämäläinen *et al.*, 2018), we expected poorer driving performance and detection of spatial stimuli in the old than in the young group. On the other hand, we hypothesized on the basis of previous studies (Adam *et al.*, 2006; Blatter *et al.*, 2006; Bonnet, 1989; Brendel *et al.*, 1990; Duffy *et al.*, 2009; Kong *et al.*, 2012; Philip *et al.*, 2004), that the effects of sleep deprivation are more pronounced in the performance of the young than the old participants. In addition, we studied whether aging and sleep deprivation induce spatial perceptual bias, possibly accentuating the bias toward the right hemispace. Finally, because the drivers' subjective estimations of their own driving ability are linked to driving safety (Horswill, Anstey, Hatherly, Wood & Pachana, 2011; Ross, Dodson, Edwards, Ackerman & Ball, 2012), we compared the subjective tiredness and driving ability and actual performance in young and old age groups.

METHODS

Participants

The total initial number of participants who volunteered for the study was 53. Four of the old participants experienced nausea or dizziness due to the virtual reality setting and were excluded from the study. Data of these and of four others whose tests were interrupted due to technical problems or who withdrew from the study were not included in the analyses. The remaining number of participants was 45, except for the driving test the number was 44, as one old participant could not complete the driving test. The results of the participant's other tests were applicable and were used. The participants consisted of two groups, the young ($N = 22$, mean age: 22 years, range: 18–35) and the old ($N = 22$ or 23 depending on the test, mean age: 71 years, range: 65–79). The young group covered those from young novices (fresh driver's license) to young adults, and the old group those from retirement age onwards. Participants were recruited through advertisements in university media, and personal contacts. All participants were male and right-handed. Because previous research (e.g., Al-Balbissi, 2003; Aldred, Johnson, Jackson & Woodcock, 2021; Rhodes & Pivik, 2011) has shown that male and female differ in their driving performance, we included only male participants to reduce the variability caused by gender in the data. The inclusion criteria were a valid driving license and good overall health (based on self-reports by the participants) relative to the participants' age. Exclusion criteria were neurological or psychiatric disorders, diabetes, sight or hearing problems that had not been corrected with eyeglasses or hearing aids, hand-related motor disorders, or any kind of clinically diagnosed sleep disorders or other self-reported regular sleep difficulties. All participants signed a form, which explained the content of the study, and the participant's right to withdraw from the study at any point. This study was approved by the Ethics Committee of the University of Turku. As an incentive, they were given 120 euro fee for participating in the study.

Procedure

Before arriving to the laboratory, the participants filled forms on their education, medications, alcohol use, neurological and psychiatric disorders, depression, handedness, video game habits, sleep quality and the number of hours slept the night before the daytime tests. The measurements (psychological tests, subjective evaluations, driving tests) were conducted twice for each participant: in the sleep deprivation condition and in the non-sleep deprivation condition. Psychological tests were administered and subjective evaluations were collected before beginning the driving test. In the non-sleep deprivation condition, testing took place during the daytime. In the sleep deprivation condition, the tests were performed between six o'clock and 10:00 o'clock in the morning after staying awake the preceding night. The order of the sleep deprivation and non-sleep deprivation conditions was counterbalanced across participants. In the sleep-deprived condition, the participants spent the night in groups of two to four at a time at the facilities of the University of Turku. A young participant in each group was given an extra fee for controlling that all group members stayed awake. The participants were offered a light meal in the evening and in the following morning. During the sleep deprivation night, no caffeine was allowed. The participants were allowed to watch TV, DVD films, and play video games. The safety of the participants was ensured: they could contact the supervising researcher, university security, and/or emergency center at any time during the night. Each driving test took one hour with preparations due to the EEG measurements conducted at the same time (EEG results will be reported elsewhere).

Subjective evaluations

Before the driving test, the participant evaluated his subjective tiredness and driving ability on a numerical scale (tiredness 1–10, 1 = very alert and 10 = very drowsy; driving ability 1–10, 1 = very good, 10 = very poor).

Driving test

Instruments and stimuli. The NeuroCar driving simulation system based on a virtual headset (Hämäläinen *et al.*, 2017; Luimula, Hämäläinen Rashid Izullah *et al.*, 2017; Rashid Izullah, Hämäläinen Rashid Izullah *et al.*, 2016) was used in this study. Figure 1 shows the simple virtual scenery from the simulated driving task on a right-side driving system. The driving occurred on a 2-lane road with low curvature and no on-coming traffic. The speed of the car was a constant 100 km/h with no adjustment possibility. The main task of the participants was to stay within the lane borders and to respond simultaneously by button presses to visual and auditory stimuli. The visual stimuli were light-spots (duration 50 minutes) flashed either unilaterally or bilaterally in fixed locations in the peripheral visual field (Fig. 1). The auditory stimuli (sine wave bursts, duration 50 minutes, frequency 550 Hz, and an intensity of 66 dB) were presented via headphones. The intensity could be adjusted to compensate for possible hearing deficits. The inter-stimulus interval (ISI) for both visual and auditory stimuli varied randomly between 700 and 1200 minutes. During the 20 minutes of driving, visual and auditory stimuli, 210 left, 210 right, and 210 bilateral for each modality, were presented in random order. The participants responded to visual or auditory stimuli by pressing the two corresponding buttons attached to the driving wheel: left and right buttons to corresponding unilateral stimuli, and both to bilateral stimuli. Even though our spatial stimuli can only vaguely mimic the real stimuli in traffic, their efficacy in determining spatial perceptual and attentional capability has been demonstrated previously both in laboratory and virtual environment conditions (Hämäläinen *et al.*, 2017, 2018). Prior to the actual test, all participants had an introductory nine-minute training session: two min for only driving

Fig. 1. The virtual driving car and scenery with white light spots flashed in the periphery used as visual stimuli.

without stimuli, two min for only stimuli without driving, and five min for driving and stimuli. The training session was conducted only before the very first test.

The number of driving errors (crossing the lane borders), correct responses and reaction times to visual and auditory stimuli, erroneous responses, and response omissions were determined. Responses to the unilateral stimuli were considered correct if the corresponding button was pressed within 150–1000 ms after stimulus onset, and erroneous when a wrong button pressed. In bilateral stimulation, both left and right buttons had to be pressed within the time limit (150–1000 ms) for a correct response, and both button presses had to occur within 350 ms from each other. A response was considered omitted when it did not occur within the time window of 150–1000 ms after the stimulus onset.

Psychological tests

All participants were tested with Digit-Span and Coding (Wechsler, 2008), Trail Making Test-A (TMT-A), and Trail Making Test-B (TMT-B) (Bowie & Harvey, 2006), always in this order. These tests are commonly used in driving ability evaluations (e.g., Lafont, Marin-Lamellet, Paire-Ficout, Thomas-Anterion, Laurent & Fabrigoule, 2010). The Digit-Span task is an auditory working memory test, and the Coding Test targets visuomotor processing speed and it is considered to be a sensitive predictor of driving safety (Lafont *et al.*, 2010). The Trail Making Tests (A and B) are used in the assessment of visual processing speed, visual attention, and cognitive control (e.g., Bowie & Harvey, 2006), and have been previously applied for evaluating the usefulness of a driving simulator as a tool for predicting the safety of on-road driving (Bédard, Parkkari, Weaver, Riendeau & Dahlquist, 2010).

Statistical analyses

The statistical analyses (SPSS, version 25) were conducted with the repeated measures analysis of variance (ANOVA) test. The analysis of each dependent variable included Age (2: young, old) as a between-subjects factor and Sleep Deprivation (2: deprived vs. non-deprived) as a within-subject factor. In the case of visual and auditory stimulation during driving, the Stimulus Condition (2 or 3 levels: left, right, both) was also included as a within-subject factor. The order of the sleep deprivation conditions was always included as an additional between-subjects factor for reducing the variance generated by counterbalancing the order of sleep deprivation (Pollatsek & Well, 1995); hence, the effects of the order are not reported here. Whenever Mauchly's test for sphericity was violated, we reported the Greenhouse–Geisser corrected *p*-values. Fisher's least significant difference (LSD) test was used for pairwise comparisons when a statistically significant main effect or interaction involved a factor with three levels.

RESULTS

Driving errors

The repeated measures ANOVA on driving errors (Fig. 2) did not reveal any main effect for Age. Lane border crossings were more frequent when deprived ($M = 22.4$) than when non-deprived ($M = 15.1$), $F(1,40) = 17.07$, $p < 0.01$, $\eta_p^2 = 0.30$. Lane border crossings to the left ($M = 23.4$) were more frequent than to the right ($M = 14.0$), $F(1,40) = 10.20$, $p = 0.03$, $\eta_p^2 = 0.20$. No interactions between age and sleep deprivation were found.

Visual-spatial perception

Correct responses. The young made more correct responses ($M = 78\%$) than the old ($M = 41\%$), $F(1,40) = 68.53$, $p < 0.01$, $\eta_p^2 = 0.63$ (Fig. 3A). The number of correct responses was smaller in the deprived condition ($M = 55\%$) than in the non-deprived condition ($M = 64\%$), $F(1,40) = 18.21$, $p < 0.01$, $\eta_p^2 = 0.31$. The correct responses to the right side stimuli ($M = 61\%$) were more frequent than to the bilateral stimuli ($M = 57\%$), $p = 0.01$, $F(2,80) = 3.95$, $p = 0.02$, $\eta_p^2 = 0.09$. An interaction between the Stimulus Condition and Age, $F(2,80) = 4.35$, $p = 0.02$, $\eta_p^2 = 0.01$, revealed that the old had more correct responses to the right side stimuli ($M = 45\%$) than to the bilateral stimuli ($M = 36\%$), $p < 0.01$.

Reaction times

The old participants were slower ($M = 569$ ms) than the young ones ($M = 497$ ms), $F(1,40) = 36.33$, $p < 0.01$, $\eta_p^2 = 0.48$ (Fig. 3B). Reaction times (RTs) were longer ($M = 542$ ms) in the sleep deprived than in the non-deprived condition ($M = 525$ ms), $F(1,40) = 17.50$, $p < 0.01$, $\eta_p^2 = 0.30$. Response times were longer to the left side stimuli ($M = 543$ ms) than either to the bilateral stimuli ($M = 528$ ms), $p < 0.01$, or the right side stimuli

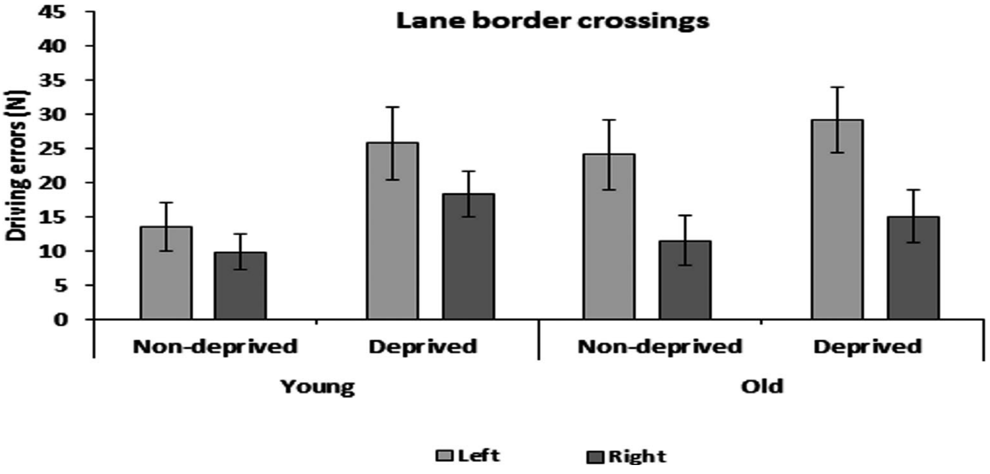

Fig. 2. Driving errors (lane border crossings) of both age groups in non-deprived and deprived sleep conditions. Error bars represent the standard error of the mean (SEM).

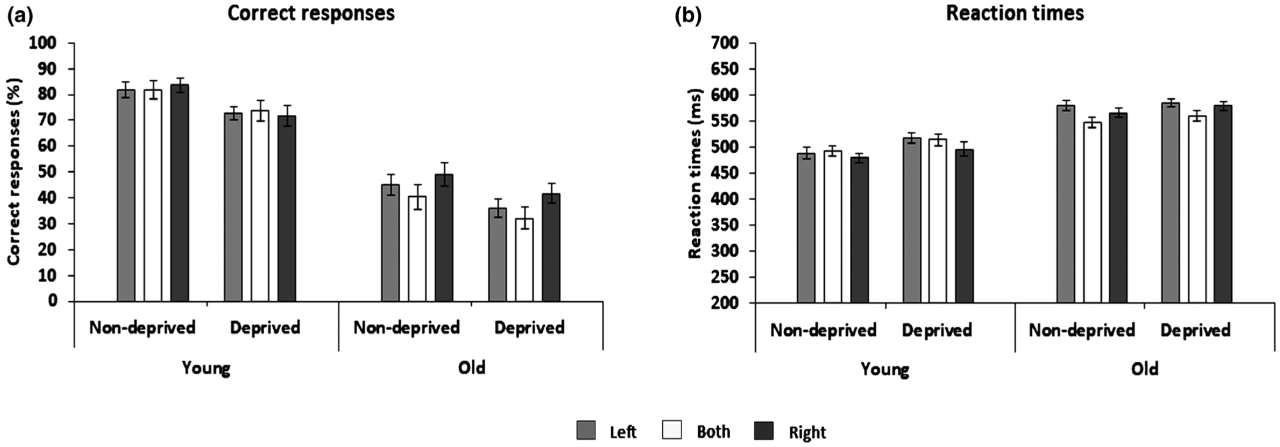

Fig. 3. (A) Correct responses and (B) reaction times to visual stimuli of both age groups in deprived and non-deprived sleep conditions. Error bars represent SEM.

(M = 530 ms), $p = 0.01$, $F(2,80) = 7.28$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.15$. An interaction between the Stimulus Condition and Age, $F(2,80) = 10.25$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.20$, revealed that the responses of the young participants were faster (M = 486 ms) to the right side stimuli than either to the left side (M = 502 ms), $p = 0.04$, or bilateral stimuli (M = 486 ms), $p = 0.03$. The old participants' responses were faster to bilateral (M = 554 ms) than either to the left (M = 584 ms), $p < 0.01$, or the right side stimuli (M = 574 ms), $p < 0.01$.

Erroneous responses. The young participants made fewer errors (M = 8%) than the old participants (M = 16%), $F(1,40) = 39.13$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.49$ (Fig. 4A). The participants in general made more erroneous responses to the bilateral stimuli (M = 20%) than either to the left (M = 7%) or the right side stimuli (M = 8%), $p < 0.01$, $F(2,80) = 61.74$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.61$. Sleep deprivation did not have any significant effect on the amount of the erroneous responses. An interaction between the Age and Stimulus Conditions, $F(2,80) = 13.53$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.25$, showed that the young participants responded erroneously more frequently to the bilateral (M = 12%) than either to the right (M = 6.4%), $p = 0.02$, or to the left stimuli (M = 5%), $p < 0.01$, and more frequently to the right than to the left stimuli, $p < 0.01$. Similarly, the old participants also made more errors when responding to the bilateral (M = 28%) than either to the left (M = 10%) or right side stimuli (M = 10%), $p < 0.01$. In the old participants group, there was no difference in the rate of errors between the left and the right side stimuli.

Response omissions. The old participants omitted more responses (M = 44%) than the young (M = 15%), $F(1,40) = 57.12$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.59$ (Figure 4B). The number of omitted responses was higher when deprived (M = 34%) than when non-deprived (M = 25%), $F(1,40) = 23.72$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.37$. Responses to the left side stimuli (M = 34%), $p = 0.04$, were omitted more often than responses to the right side (M = 31%) or bilateral stimuli (M = 24%), and fewer omissions were made in the bilateral stimulus condition than in the cases of either the left or right side stimuli, $p < 0.01$, $F(2,80) = 36.13$, $p < 0.01$, $\eta_{\mathrm{p}}^2 = 0.48$.

In both age groups, the number of response omissions was significantly larger compared to the total number of erroneous responses; the difference between error types was, however, larger in the old than the young participants (young: total erroneous

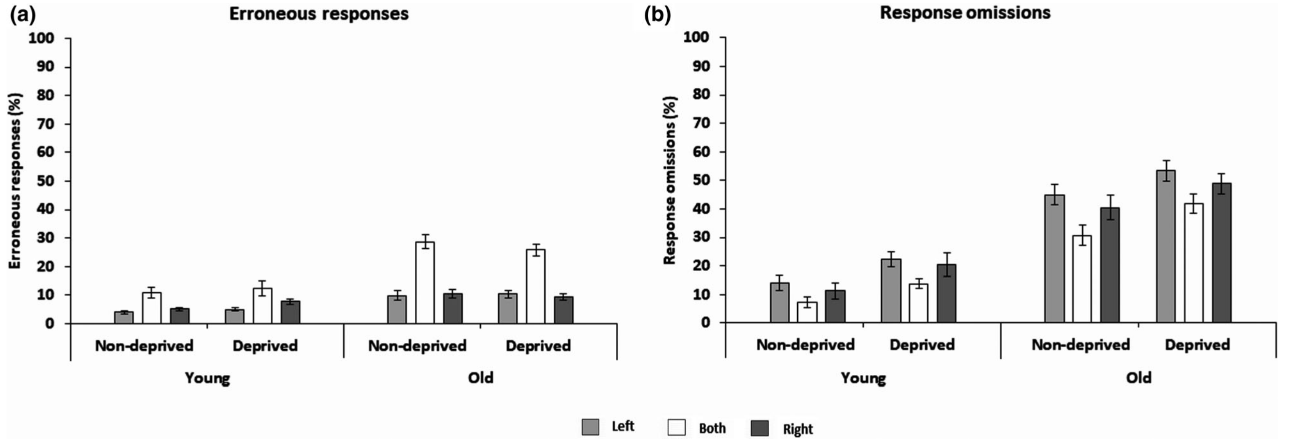

Fig. 4. (A) Erroneous responses and (B) omission of responses to bilateral visual stimuli of both age groups and in non-deprived and deprived sleep conditions. Errors bars represent SEM.

$M = 8\%$, total response omission $M = 15\%$, $p < 0.01$; old participants: total erroneous $M = 16\%$, total response omission $M = 44\%$, $p < 0.01$). Another interaction between Error Type and Sleep Deprivation, $F(1,40) = 22.42$, $p < 0.01$, $\eta_p^2 = 0.36$, showed that the number of response omissions was higher in the sleep deprived ($M = 33\%$) condition than in the non-deprived condition ($M = 25\%$), $p < 0.01$.

Auditory spatial perception

Correct responses. The young participants made more correct responses ($M = 75\%$) than the old participants ($M = 49\%$), $F(1,40) = 32.99$, $p < 0.01$, $\eta_p^2 = 0.45$ (Fig. 5A). Fewer correct responses were made in the sleep-deprived condition ($M = 59\%$) than in the non-deprived condition ($M = 65\%$), $F(1,40) = 15.72$, $p < 0.01$, $\eta_p^2 = 0.28$. More correct responses were made to the right side ($M = 69\%$) and left side stimuli ($M = 68\%$) than to the bilateral stimuli ($M = 49\%$), $p < 0.01$, $F(2,80) = 66.28$, $p < 0.01$, $\eta_p^2 = 0.62$. An interaction between Age and Sleep Deprivation, $F(1,40) = 5.33$, $p = 0.03$, $\eta_p^2 = 0.12$, showed that the performance of young participants was worse after sleep deprivation ($M = 71\%$) than without sleep deprivation ($M = 80\%$), $p < 0.01$. The performance of the old participants, however, was not affected by Sleep Deprivation (deprived $M = 48\%$, non-deprived $M = 50\%$). A two-way interaction between Age and Stimulus Condition, $F(2,80) = 6.73$, $p = 0.07$, $\eta_p^2 = 0.14$, revealed that for the young participants, the bilateral stimulus condition was the most difficult to react to correctly, compared to either the left- or the right-side stimuli (bilateral $M = 66\%$, left $M = 80\%$, right $M = 80\%$, $p < 0.01$). For the old participants, similar results were obtained (bilateral $M = 31\%$, left $M = 57\%$, right $M = 59\%$, $p < 0.01$).

Reaction times. RTs in the sleep-deprived condition were longer ($M = 626$ ms) than those in the non-deprived condition ($M = 615$ ms), $F(1,38) = 5.98$, $p = 0.02$, $\eta_p^2 = 0.14$ (Fig. 5B). RTs were longer in the bilateral stimulation ($M = 651$ ms) than either the left ($M = 603$ ms) or right side stimulation ($M = 606$ ms), $p < 0.01$, $F(2,76) = 29.57$, $p = 0.01$, $\eta_p^2 = 0.44$. An interaction between Age and Sleep Deprivation, $F(1,38) = 7.12$, $p = 0.01$, $\eta_p^2 = 0.16$, indicated that the young participants were slower in the deprived condition ($M = 629$ ms) than in the non-deprived condition ($M = 606$ ms), $p = 0.01$. Old participants' response speed did not differ between the two sleep deprivation conditions. Another interaction between the Sleep Deprivation and Stimulus Condition, $F(2,76) = 4.49$, $p = 0.03$, $\eta_p^2 = 0.11$, showed that responses were generally slower in the sleep-deprived condition than in the non-deprived condition to both the left (deprived $M = 610$ ms, non-deprived $M = 594$ ms, $p < 0.01$) and right side stimuli (deprived $M = 614$ ms, non-deprived $M = 594$ ms, $p = 0.01$).

Erroneous responses. The old participants made more erroneous responses ($M = 19\%$) than the young ones ($M = 12\%$), $F(1,40) = 7.89$, $p < 0.01$, $\eta_p^2 = 0.17$ (Figure 6A). The erroneous responses were more frequent in the deprived condition ($M = 16\%$) than in the non-deprived condition ($M = 14\%$), $F(1,40) = 6.33$, $p = 0.02$, $\eta_p^2 = 0.14$. More erroneous responses were made to the bilateral ($M = 25\%$) than either to the left ($M = 10\%$) or right side stimuli ($M = 11\%$), $p < 0.01$, $F(2,80) = 44.64$, $p < 0.01$, $\eta_p^2 = 0.53$. An interaction between Sleep Deprivation and Age, $F(1,40) = 6.28$, $p = 0.02$, $\eta_p^2 = 0.14$, was due to the young participants making more erroneous responses when sleep-deprived ($M = 13.9\%$) than in non-sleep-deprived condition ($M = 9.9\%$), $p < 0.01$, whereas for the old participants no such difference was found. Another interaction between Age and Stimulus Condition, $F(2,80) = 5.83$, $p = 0.01$, $\eta_p^2 = 0.13$, showed that the young participants made more erroneous responses to the bilateral stimuli ($M = 18\%$) compared to either the left ($M = 8\%$) or right side stimuli ($M = 9\%$), $p < 0.01$. Similar results were obtained for the old participants, but the difference between responses to the bilateral and unilateral stimuli was larger (bilateral $M = 32\%$, left $M = 12$, right $M = 12$, $p < 0.01$) compared to those of the young participants.

Response omissions. The old participants omitted more responses ($M = 32\%$) than the young participants ($M = 13\%$), $F(1,40) = 23.74$, $p < 0.01$, $\eta_p^2 = 0.37$ (Figure 6B). When sleep deprived, the participants omitted more responses ($M = 24\%$) than when they were not ($M = 21\%$), $F(1,40) = 5.12$, $p = 0.03$, $\eta_p^2 = 0.11$. Response omissions of the left side stimuli were more frequent ($M = 21\%$) than those of the right side ($M = 20\%$), and

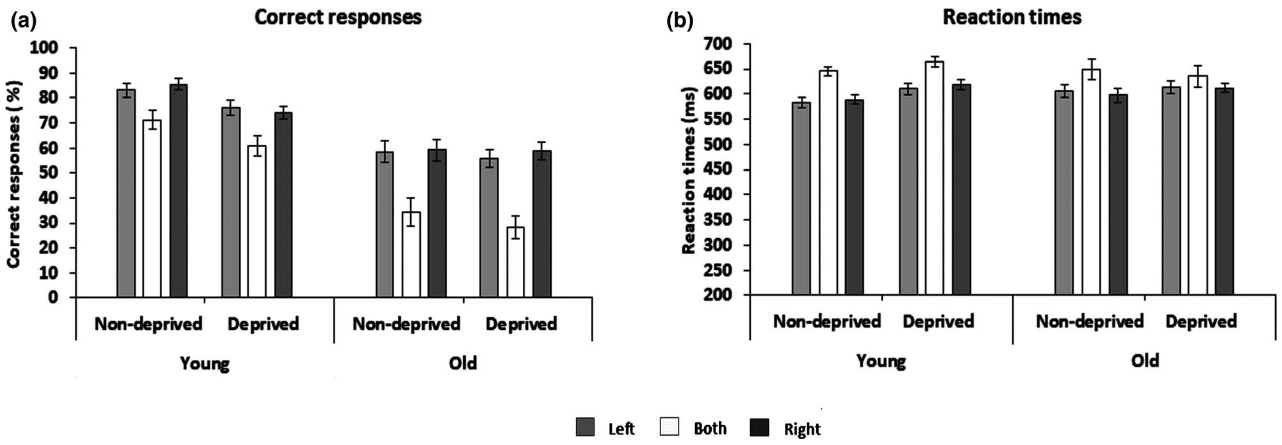

Fig. 5. (A) Correct responses and (B) reaction times to auditory stimuli of both age groups and in non-deprived and deprived sleep conditions. Error bars represent SEM.

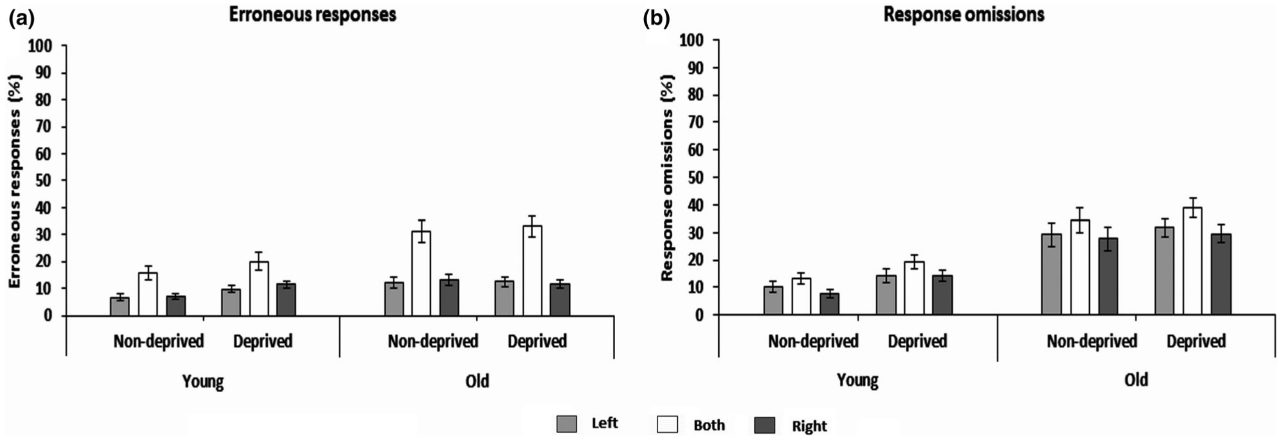

Fig. 6. (A) Erroneous responses and (B) omission of responses to bilateral auditory stimuli of both age groups and in non-deprived and deprived sleep conditions. Error bars represent the SEM.

more frequent in the bilateral ($M = 26\%$) than in the unilateral stimulus condition, $p < 0.01$, $F(2,80) = 34.09$, $p < 0.01$, $\eta_p^2 = 0.46$.

For the young participants, the difference between erroneous and omitted responses was not significant, whereas the old participants made significantly more omissions ($M = 32\%$) than erroneous responses ($M = 19\%$), $p < 0.01$. The young made more errors when sleep deprived ($M = 15\%$) than when non-sleep deprived ($M = 10\%$).

Subjective tiredness and driving ability

The young participants evaluated themselves as being more tired ($M = 5.0$) than the old participants ($M = 3.9$), $F(1,41) = 10.59$, $p < 0.01$, $\eta_p^2 = 0.21$ (Fig. 7A). Participants evaluated themselves as being more tired ($M = 6.1$) after sleep deprivation than after normal sleep ($M = 2.8$), $F(1,41) = 208.47$, $p < 0.01$, $\eta_p^2 = 0.84$. An interaction between Age and Sleep Deprivation, $F(1,41) = 25.65$, $p < 0.01$, $\eta_p^2 = 0.39$, revealed that after sleep deprivation, the young participants rated themselves as being more tired ($M = 7.2$) than the old participants ($M = 4.9$). With no deprivation, there was no difference in the subjective evaluation of alertness between the young ($M = 2.9$) and the old participants ($M = 2.8$). The driving ability after sleep deprivation was considered to be worse ($M = 5.8$) than that with no sleep deprivation ($M = 3.2$), $F(1,41) = 51.26$, $p < 0.01$, $\eta_p^2 = 0.56$ (Fig. 7B). No significant effect of Age was found.

Psychological tests

Figure 8A displays the performance scores on the Digit Span task by the two age groups in the sleep-deprived and non-deprived conditions. The young had a higher total score ($M = 27.8$) than the old participants ($M = 23.8$), $F(1,41) = 9.45$, $p < 0.01$, $\eta_p^2 = 0.19$. Sleep deprivation caused a marginal/slightly inferior performance ($M = 25.4$) compared to the non-deprived condition ($M = 26.2$), $F(1,41) = 3.94$, $p = 0.05$, $\eta_p^2 = 0.10$. Series of separate analyses were conducted for the subtask scores. These analyses revealed that only the main effects for Age were significant in Digit Span Backward, $p < 0.01$, Longest Digit Span Backward, $p < 0.01$, Digit Span Sequencing, $p < 0.01$, and Longest Digit-Span Sequencing, $p = 0.03$, the young participants outperforming the old ones. Sleep Deprivation had no effect on performance in the subtasks.

Figure 8B shows the performance scores of the Coding Test by both age groups in the sleep-deprived and non-deprived

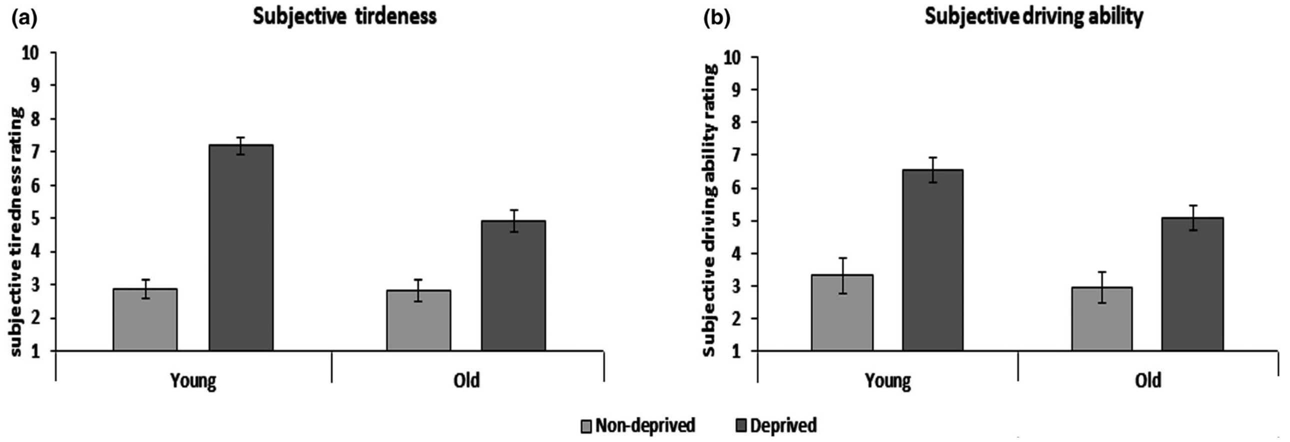

Fig. 7. (A) Subjective tiredness ratings (scale: 1 = extremely alert, 10 = extremely tired/drowsy), and (B) subjective driving ability ratings (scale: 1 = extremely good, 10 = extremely bad) of both age groups in non-deprived and deprived sleep conditions. Error bars represent SEM.

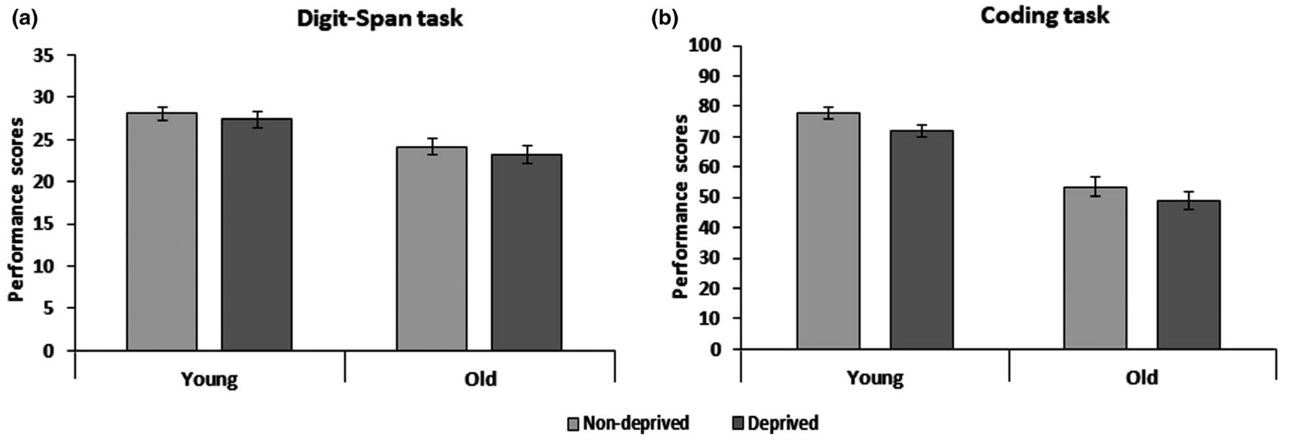

Fig. 8. (A) Total performance scores of the Digit-Span task and (B) performance scores of the Coding Test of both age groups in non-deprived and derived sleep conditions. Error bars represent SEM.

conditions. The young participants had higher scores ($M = 74.8$) than the old participants ($M = 51.2$), $F(1,41) = 42.67$, $p < 0.01$, $\eta_p^2 = 0.51$. The participants scored lower in the deprived condition ($M = 60.5$) than in the non-deprived condition ($M = 65.5$), $F(1,41) = 29.41$, $p < 0.01$, $\eta_p^2 = 0.42$.

Figure 9A and B show the performance time of the Trail Making Test-A and the Trail Making Test-B by both age groups in the sleep-deprived and non-deprived conditions. In TMT-A, the young participants were faster ($M = 21.7$ s) compared to the old ones ($M = 39.1$ s), $F(1,41) = 25.21$, $p < 0.01$, $\eta_p^2 = 0.38$. Similarly, in TMT-B, the young participants were faster ($M = 46.1$ s) than the old participants ($M = 103.1$ s), $F(1,41) = 14.28$, $p < 0.01$, $\eta_p^2 = 0.26$. Sleep Deprivation had no effect on the results of either TMT-A or TMT-B.

DISCUSSION

In a virtual VR headset environment, aging did not affect driving errors. Sleep deprivation increased the amount of driving errors in general with the left side lane border crossings outnumbering the crossings to the right side. Age and sleep deprivation both impaired visual and auditory spatial perception with the young being on average more affected by sleep deprivation than the old, as hypothesized by us. As regards to driving, our hypotheses were not verified, and indeed an unexpected but quite strong bias in driving errors to the left was found (i.e., crossings of the left lane border). The amount of driving errors was independent of age, but sleep deprivation increased them. A general spatial perceptual rightward bias was found without any relation to age. The subjective tiredness evaluation was influenced by aging and sleep deprivation, in agreement with corresponding objective measures. The driving ability was subjectively considered to be weaker in the sleep deprivation condition by both age groups. In the conventional psychological tests, the effect of age was more evident than that of sleep deprivation.

Driving, age, and sleep deprivation

Virtual driving errors were deteriorated by sleep deprivation but not by aging. This first of all shows that the virtual driving environment was not too unfamiliar to our old participants. The majority of the driving errors, especially in the sleep deprivation condition, were left lane border crossings. Lane border crossings are postulated to have linkage to attentional lapses (Jackson, Croft, Kennedy, Owens & Howard, 2013) and blink duration (Hallvig, Anund, Fors, Kecklund & Åkerstedt, 2014). This

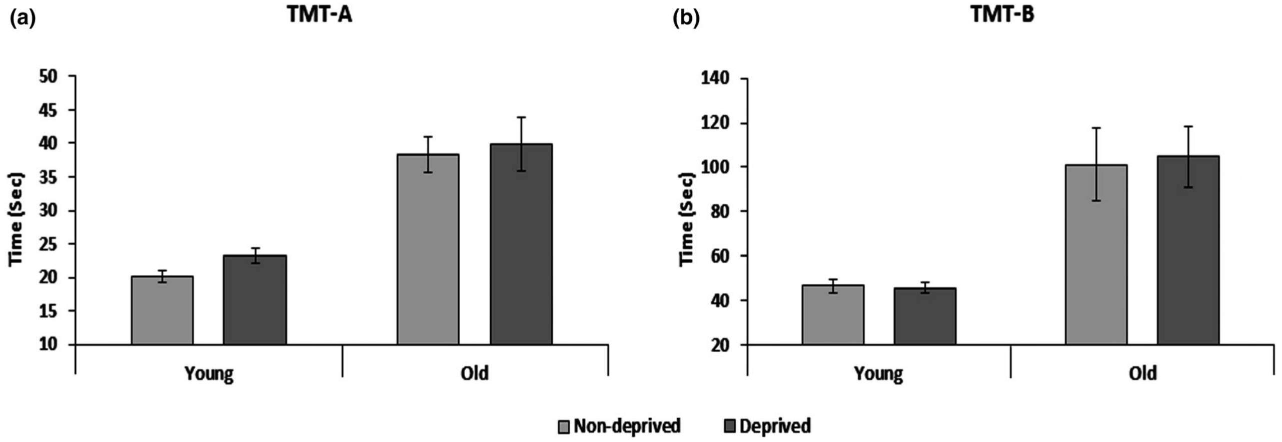

Fig. 9. (A) The time needed on the Trail Making Test-A and (B) Trail Making Test-B tasks by both age groups in non-deprived and deprived sleep conditions. Error bars represent SEM.

tendency toward the left side in driving navigation has been found in several other situations. In their walking navigation study, Hatin, Sykes Tottenham, and Oriet (2012) found a leftward collision tendency that was relatively age-independent. Benedetto, Pedrotti, Bremond and Baccino (2013) reported that in their right-side driving simulation study, drivers' attention was biased to the left side of the road. Left side accidents in general seem to be more prominent in comparison to right side ones. Indeed, in an actual on-road accident study, Friedrich, Elias and Hunter (2017) found that, in the right-side traffic system, drivers collided far more with cars situated to the left than to the right in relation to their own vehicle. It has been reported that both healthy subjects and neglect patients leave relevant stimuli unnoticed more often in the left hemispace than in the right hemispace in complex, stimulus-rich settings (Buxbaum, Palermo, Mastrogiovanni *et al.*, 2008). Interestingly, Learmonth, Märker, McBride, Pellinen and Harvey(2018), in their left-side driving system simulating study, have found biased positioning of the vehicle to the right side of the lane. Thus, the findings of the current study and the mirroring findings of Learmonth *et al.* (2018) indicate a relationship between the side of the driving system and tendency for driving biases.

Spatial perception, age, sleep deprivation, and spatial bias

Age impaired visual-spatial perception capacity measured as an increased number of erroneous responses, prolonged response times, and increased number of response omissions. For the auditory spatial perception, similar results were obtained with the exception that aging did not influence response times. Aging-induced general slowing of perceptual processes is a common observation (for reviews, see, e.g., Hugdahl *et al.*, 2009; Klencklen *et al.*, 2012; Pichora-Fuller & Singh, 2006). However, it does not seem to be general across all modalities and settings (e.g., Abel & Armstrong, 1992; Laurienti, Burdette, Maldjian & Wallace, 2006). Peiffer, Mozolic, Hugenschmidt and Laurienti (2007), for example, have found that in multisensory processing the response speed of the old may even exceed that of the young. Interestingly, in the current study, error type, that is, response omissions, also varied as a function of aging. The ratio of total response omissions by the old participants compared to their erroneous responses was almost three to one. The young had a similar response trend, but the ratio was less than two to one. In the auditory test, the old participants made more total response omissions than total erroneous responses, the ratio being almost two to one, while there was no such difference in the young participants' performance.

Sleep deprivation adversely affected visual perception measured as a decrease in the number of correct responses, increased response omissions to the unilateral and bilateral stimuli, and prolonged reaction times. More generally, sleep deprivation increased the total number of errors. The effects of sleep deprivation on auditory perception, in general, were similar to those in the visual domain. Sleep deprivation decreased the number of correct responses, increased the reaction times, and increased the number of response omissions. The young participants were significantly affected by sleep deprivation. The young had slower reactions, increased number of erroneous responses and response omissions, while the old participants did not show any similar pattern. The fact that the young participants' responses to auditory stimulation were affected by sleep deprivation more and differently than the old participants is in line with previous findings (e.g., Philip *et al.*, 2004). The differing effects of sleep deprivation in the two age groups may reflect differences in performance strategy (Lemaire, 2010). The young may act with full effort prone to fatigue, whereas the old rather play it safe in all conditions. This feature can be seen in actual traffic behavior by the old as safe choosing of routes and times of day for driving (Keeffe, Jin, Weih, McCarty & Taylor, 2002).

Age did not induce any spatial bias to either side when measured as correct responses to the visual stimuli during driving. Bilateral stimulation induced the highest cognitive load and hence caused the most erroneous responses in both age groups. Left side response omissions were age-independent and in general significantly more frequent compared to the right side ones. The participants missed the left side stimuli more than the right side ones, and driving errors were more frequently crossings of the left lane border than of the right side one. Also, Nagamatsu, Carolan, Liu-Ambrose and Handy (2011) reported that the old made significantly more response errors and had longer RTs to stimuli in the left visual field than in the right side. In the present study, both age groups were slower in responding to the left side visual stimuli than to those applied to the right hemispace.

In our study, leftward auditory spatial inattention bias was observed. Response omissions of the left side auditory stimuli were more frequent than those of the right side, but this effect did not depend on age or sleep deprivation. This is in accordance with previous findings on leftward auditory spatial inattention bias in normal healthy drowsy subjects (Bareham, Manly, Pustovaya, Scott & Bekinschtein, 2014).

Comparison between visual and auditory perception

In both visual and auditory modalities, age and sleep deprivation reduced the number of correct responses. In visual tasks, reaction times in the old group were slower, while in the auditory tasks both age groups were as fast in their responses. In the visual tasks, sleep deprivation slowed down both age groups equally, whereas in the auditory task only the young were slowed down. This difference probably reflects the difficulty of spatial perception in these two modalities. The auditory bilateral condition was considered difficult by all participants. Thus, the old group did worse also in the non-sleep deprivation condition and no sleep deprivation effect was found for them.

Psychological tests vs. virtual driving

In the psychological tests, the effect of age was evident (cf. Bowie & Harvey, 2006; Wechsler, 2008). The young outperformed the old in all tests except in some Digit Span subtests. These age differences, in general, are comparable to other age differences obtained in the current study. In contrast, the impairing effect of sleep deprivation on test performance was detected only by the Coding Test and by the total performance scores of the Digit Span task.

Our virtual driving and spatial perception test system thus appears to be ecologically valid and more sensitive to factors affecting driving and perceptual capability than the psychological tests. In the assessment of on-road driving skills of the aging population, Vaucher, Herzig, Cardoso, Herzog, Mangin and Favrat (2014) have found that TMT is a poor indicator of the actual driving skills, albeit a good indicator of driving-related cognitive status. Psychological tests, after all, assess only the cognitive prerequisites to driving. The interplay of perceptual-cognitive processes and driving performance is context-dependent and therefore cannot fully be accounted for by out-of-context tests (e.g., Wood, Anstey, Kerr, Lacherez, & Lord, 2008).

Both age groups rated themselves as being more tired/less vigilant after a night of sleep deprivation than after a night of normal sleep. The old participants, in general, reported being less tired after sleep deprivation and also commented less on tiredness during the sessions than did the young participants (see also Fig. 7A). This subjective evaluation of the effect of sleep deprivation corresponded to the objective measurements with our virtual VR-based test. The sleep-deprived young participants, particularly in auditory perception, made more response errors and responded more slowly compared to the non-sleep-deprived condition, while the old participants did not show any similar trend. Similar age-related effects of sleep deprivation have also been reported by Philip *et al.* (2004; for review, see also Shekari Soleimanloo, White, Garcia-Hansen & Smith, 2017) in driving.

CONCLUSION, IMPLICATIONS FOR DRIVING, AND LIMITATIONS

The amount of driving errors was not affected by aging, whereas it was significantly increased by sleep deprivation regardless of age. Lane crossings occurred more often to the left than to the right side. Aging impaired almost all measures of spatial perception. There was a clear imbalance unfavoring left side stimuli which were more frequently omitted, more notably in the sleep deprivation condition. The left side response times were clearly longer than the right side ones. Subjective evaluations by the age groups were, in general, in correspondence with objective measures in the virtual driving test. Psychological tests captured mainly the effects of aging but not those of sleep deprivation.

In relation to our promising results and to the fact that driving simulators, in general, are now accepted as a valid driving evaluation tool (Bédard *et al.*, 2010; Meuleners & Fraser, 2015; Philip, Sagaspe, Taillard *et al.*, 2005), and have proven to be effective in the training of real driving skills (Casutt, Theill, Martin, Keller & Jäncke, 2014), the interpretation of the present results, obtained via VR-based virtual driving, warrants caution. Driving simulation by definition is only a simulation with its own limitations (for review, see Kemeny & Panerai, 2003; see also Hallvig *et al.*, 2013; Meuleners & Fraser, 2015; Philip *et al.*, 2005). Therefore, a VR-based assessment can be considered only as one of the indicators of driving ability, but not as a full assessment of that ability.

The study had certain limitations. Participants were only males, for this reason, our results can be safely generalized only to males. Further investigation of heterogeneous samples is warranted. The fact that sleep-deprived and non-sleep-deprived tests were conducted in different daytime hours may have influenced the results. The effects of sleep deprivation in our study correspond to the situation in which a person starts driving in the morning after a sleep-deprivation, as compared with daytime driving after normally slept night. Hence, future investigations should take this possible confounding factor into consideration. The virtual driving results were not compared to on-road driving performance. Although previously the validity of virtual driving results has been established through this type of comparison (e.g. Aksan, Hacker, Sager, Dawson, Anderson & Rizzo, 2016; Bédard *et al.*, 2010; Casutt, Martin, Keller & Jäncke, 2014; Lee, Cameron & Lee, 2003), in future it would be important to test the validity of this particular VR-system against on-road driving performance.

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CONFLICT OF INTEREST

No conflict of interests to be declared.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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