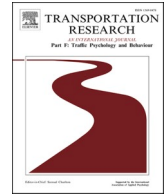


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Aging and sleep deprivation affect different neurocognitive stages of spatial information processing during a virtual driving task – An ERP study

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ABSTRACT

We have previously shown that aging deteriorates detection of spatial visual and auditory stimuli and prolongs reaction times measured during a virtual driving task. Sleep deprivation affected the young more than the old. Here we determined the effects of age and sleep deprivation on ERPs elicited by spatial visual and auditory stimuli during virtual driving. Participants were 22 young (18–35 years) and 19 old (65–79) healthy males. Experiments were run in normal daytime condition and after a night of sleep deprivation. Aging shortened the peak latencies of the early P1 and N1 but increased the P3 latency. Sleep deprivation slowed down and diminished the N1 peaks of the young. General right-side preference was seen in latencies. Thus, the effects of aging could be seen in decision making and working memory related processes (P3), whereas those of sleep deprivation could be found in alerting and orienting functions (N1) in the young.

1. Introduction

Aging and sleep deprivation are increasing risks in today's traffic. Behavioral and neural evidence for the adverse effects of aging and sleep deprivation on cognitive functioning, cognitive control, visual and auditory perception is accumulating (for reviews; see, e.g., Durmer & Dinges, 2005; Kléncklen, Després, & Dufour, 2012). The negative effects of aging and sleep deprivation on divided and selective attention, essential in traffic behavior and specially driving, have been frequently reported (for reviews, see Alhola & Polo-Kantola, 2007; Durmer & Dinges, 2005; Zanto & Gazzaley, 2014).

The present study focused on the effects of aging and sleep deprivation on detection of spatial visual and auditory stimuli during a virtual driving task, by utilizing the event-related potential (ERP) technique which has been extensively employed in research of perception and attention (for reviews, see, e.g., Luck, Woodman, & Vogel, 2000; Sokhadze et al., 2017). ERP components P1 and N1 reflect early stages of perceptual processing of a stimulus, and can be modulated by attention (Mangun & Hillyard, 1991). P1 reflects the early processing of sensory information, for example in auditory or visual cortical areas, whereas N1 has been associated with stimulus discrimination, alerting and orienting processes (Kaufman, Sozda, Dotson, & Perlstein, 2016; Neuhaus, Urbanek, Oppen-Rhein, Hahn, & Ta, 2010; Vázquez-Marrufo et al., 2014; Vogel and Luck, 2000). P2 manifests normally with auditory stimuli and is elicited by both attended and unattended stimuli (Crowley & Colrain, 2004). P3 reflects higher order cognitive processing and occurs

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when a stimulus is attended to and its features are discriminated from other simultaneous non-target features (Herrmann & Knight, 2001; Kok, 2000). Its shorter latency and larger amplitude have been associated with superior cognitive performance and efficient attentional processing (Sur & Sinha, 2009). The amplitude of P3 is affected by the attentional resource allocation to the target stimuli, whereas the latency of P3 reflects the time taken to evaluate the stimulus (Polich, 2007). The latency of P3 has been suggested to reflect processing between the detection of and reaction to a stimulus (for reviews, see Polich, 2007; Verleger, 1997; Verleger, Jaśkowski, & Wascher, 2005), and can thus be associated with decision making and working memory (Saliassi, Geerligs, Lorist, Maurits, 2013; Nieuwenhuis, Aston-Jones, & Cohen, 2005). Saliassi et al. (2013) also reported that effective working memory functioning in the young is associated with larger parietal P3 responses compared to those of the old. Previously, the association between longer latency, smaller amplitude posterior P3 responses and aging has been reported (Fjell & Walhovd, 2001). To summarize, we will use the following categorization for the different ERP components measured in the present study: The early P1 deflections reflect the early sensory/perceptual processes, the N1 peaks reflect the alerting/orienting to the stimuli and discrimination of the stimuli, and the P3 deflections are associated with later attention-demanding cognitive functions such as working memory and decision making processes. Both N1 and P3 are sensitive to attention effects.

The neurocognitive effects of aging have been widely studied with ERPs (for reviews see, Kok, 2000; Friedman, 2008; Onofrij, Thomas, Iacono, D'Andrea Matteo, & Paci, 2001; Polich, 1996), whereas to a lesser degree as regards to sleep deprivation (see, however, Corsi-Cabrera, Arce, Del Río-Portilla, Pérez-Garci, & Guevara, 1999; Lee, Kim, & Suh, 2003; Mograss, Guillem, Brazzini-Poisson, & Godbout, 2009; Qi et al., 2010; Trujillo, Kornguth, & Schnyer, 2009). So far there are no studies utilizing ERP measures to evaluate the effects and mechanisms of aging and sleep deprivation together in a driving context. However, Jackson et al. (2008) found that, for example, early sensory/perceptual processes of professional drivers are less affected than P3 by sleep deprivation, whereas reaction times (RTs) and response omissions induced by sleep deprivation were not associated with the early ERP components. These results suggest that sleep deprivation has its influence on relatively late higher cognitive processes rather than on the early sensory ones.

The electrophysiological data of the present article were obtained together with a behavioral study (Rashid Izullah et al., 2021), where simultaneously both visual and auditory spatial perception and driving behavior were assessed in a virtual headset-based driving environment. The study found that aging affected visual and auditory perceptual processes by reducing the amount of correct responses, increasing the amount of response errors, especially response omissions, and prolonging the RTs. Sleep deprivation in visual modality had effects comparable to those of aging, and more pronounced on the young than the old participants especially in the auditory spatial perception. In addition, spatial perception was biased toward the right hemispace, but this effect did not depend on age or sleep deprivation.

In the present study, our aim was to examine and evaluate the electrophysiological correlates of aging and sleep deprivation during a virtual task requiring responses to spatial visual and auditory stimuli while driving in a virtual environment. We hypothesized, on the basis of the aforementioned behavioral findings, that: First, aging should slow down and reduce brain responses to visual and auditory stimuli. Second, sleep deprivation should slow down and reduce some ERP components; prolonged latencies of auditory ERPs should be particularly seen in the young. Third, the right-side bias in spatial perception should be observed also in ERPs, that is, the electrophysiological responses to the right-side stimuli should be faster and possibly larger in amplitude than those to the left-side stimuli. Finally, our core interest was to test in which ERP components the possible effects of aging and sleep deprivation are to be observed, and whether they occur in sensory/perceptual, alertness/orienting or higher-level working memory/decisions making cognitive ERP components, which are relevant to spatial perception and attention and decision making, correspondingly. Each of these cognitive levels are necessary in demanding cognitive tasks such as driving, and the present study aims to reveal at which levels the effects of aging and sleep deprivation occur.

2. Methods

The study was approved by the Ethics Committee of the University of Turku.

Forty-one healthy right-handed young (18–35 years, $N = 22$) and old (65–79 years, $N = 19$) male participants with valid driver's license participated in the study. For inclusion criteria, see Rashid Izullah et al. (2021). Each participant signed a form, which explained the content of the study, and the participant's right to withdraw from the study at any point.

Participants were tested twice, after one-night of sleep deprivation and after a night of normal sleep. Tests after normal sleep were conducted in the working daytime, while sleep deprivation tests were performed between 6 and 10 o'clock in the morning following the sleep deprivation night. The order of non-sleep deprivation and sleep deprivation tests was counterbalanced across the participants. Caffeine intake was forbidden in the sleep deprivation night. In the sleep deprived condition, the participants spent the night in groups of two to four at a time at the facilities of Turku University. Safety and convenience of the participants was assured (see Rashid Izullah et al., 2021).

During the driving tests, in both sleep deprivation and non-sleep deprivation conditions, the participants drove a head-set and steering wheel-based virtual car (Luimula et al., 2015; Rashid Izullah et al., 2016) on a two-lane road with no oncoming traffic for 20 min. Their primary task was to stay within the lane borders. In addition, they had to respond to the auditory and visual stimuli with two buttons (left and right), attached to the driving wheel. While driving, visual (light spots, 50 ms) and auditory (sine waves, 50 ms) were randomly ($ISI = 700\text{--}1200$ ms) presented to them. The stimuli were presented either unilaterally to the left or right hemispace, or bilaterally simultaneously to the left and right hemispaces (210 stimuli/stimulus side condition). That is, the total number of stimuli presented during each trial was 630 as follows: 210/left, 210/right, and 210/bilateral. Prior to the first test, all participants had an introductory nine-minute training session involving two min driving without the stimuli, two min for responding to the stimuli without

driving, and five min for both driving and responding to the stimuli.

The participants wore an EEG cap with eight ring electrodes attached according to the international 10/20 sites, Fp1, Fp2, C3, C4, P3, P4, O1, O2, referenced to the nose and with the Cz as ground. Due to the application of VR-glasses and headphone, a limited number of recording sites could feasibly be used. Vertical and horizontal eye movements were measured with two electrodes attached next to the left eye. EEG was measured with Neurone amplifier (Bittium, Finland) with band pass 0.16–125 Hz, sampling rate 500 Hz, and electrode impedance maintained under 5 kΩ.

The data from each participant was visualized individually in order to determine the exact site of peaks for amplitude and latency measurements. As Table 1 shows, this was not possible especially for some of the old participants due to flattening and noisiness of the average responses. The peak latencies and amplitudes of three ERP components, P1, N1, and P3 were determined (see Fig. 1) in responses to correctly detected visual stimuli, and the same parameters were measures from the three ERP components, N1, P2, and P3, in responses to correctly detected auditory stimuli (Fig. 2).

Data analyses were conducted with Brain Vision Analyzer (Brain Products GmbH, Germany) on EEG data obtained from recording sites P3-P4 and C3-C4 in which the most distinct ERPs to visual and auditory stimuli, respectively, were observed. Baseline correction was based on EEG of 100 ms duration prior to the onset of the stimuli. Trials with amplitudes beyond ±70 μV were filtered out as artifacts. Eye movement correction was based on the logarithm by Gratton, Coles, and Donchin (1983). The data was filtered offline using low cut-off of 0.1 Hz and high cut-off of 30 Hz.

Due to the large age variation of our participants, and the occasionally rather devastating effects of sleep deprivation on the responses, there was a considerable variation in the peak latencies of the different ERP components. For visual ERPs the latency ranges were: P1: 74–272 ms, N1: 104–324, and P3: 298–802 ms, and for auditory ERPs N1: 184–288, P2: 268–472, and P3: 414–906 ms.

2.1. Statistical analyses

The statistical analyses were applied to the ERPs data from the electrode sites contralateral to the stimulus side and only the data from the unilateral (i.e., left, right, but not bilateral) stimuli were included in the analysis. “The statistical analyses were conducted with the mixed model of repeated measures analysis of variance (ANOVA): Age (2: young, old) was a between-subjects factor and Sleep Deprivation (2: deprived, non-deprived) and Stimulus Side (left, right) were within-subject factors. We explored the data also with the order of the sleep deprivation conditions (Condition Order: deprived vs. non-deprived as the first condition) as an additional between-subjects factor. Because Condition Order had significant effects only in the analyses of auditory P3’s latency and amplitude, and because these effects did not change the results relating to Age, Sleep Deprivation, and Stimulus Site (the original significant p-values remained statistically significant and no new statistically significant effects appeared), we report the analyses of auditory P3 with Sleep Deprivation Order as a factor only in Supplementary Materials. Whenever Mauchly’s test for sphericity was violated, Greenhouse-Geisser corrected p-values were reported.

3. Results

3.1. Visual

Fig. 1 shows the P1, N1, and P3 components of visual ERPs in response to correctly detected stimuli by the young and the old participants.

Table 1
Number of participants with reliable component parameter determination included in the ERP analyses and grand average responses in Figs. 1 and 2.

Visual ERP components		Non-deprived		Deprived	
		EEG channels			
		P3	P4	P3	P4
P1	Young	21	20	22	21
	Old	15	14	14	13
N1	Young	21	22	22	21
	Old	16	15	14	13
P3	Young	21	22	22	22
	Old	16	17	14	14
Auditory ERP components		Non-deprived		Deprived	
		EEG channels			
		C3	C4	C3	C4
N1	Young	22	22	22	22
	Old	19	19	19	19
P2	Young	22	22	21	22
	Old	19	19	18	19
P3	Young	18	20	18	19
	Old	12	13	12	14

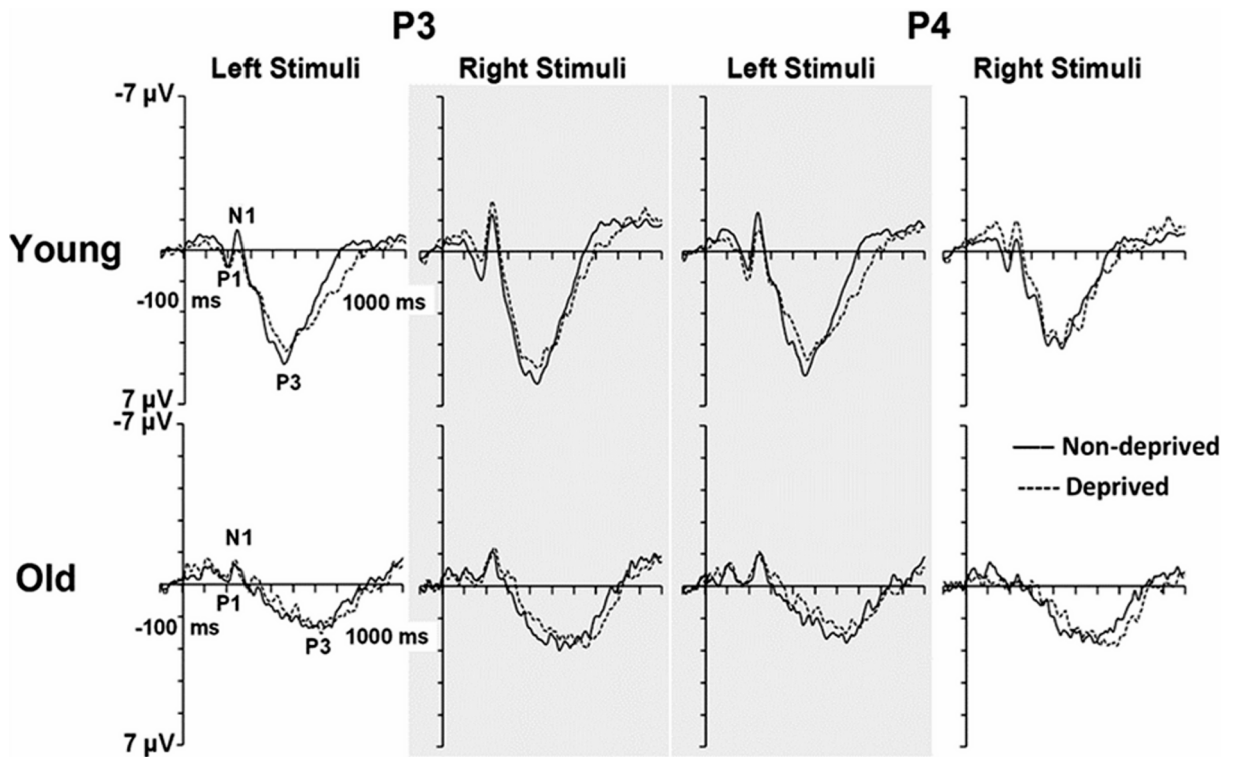


Fig. 1. Visual ERPs with P1, N1, and P3 components in responses to correctly detected left- and right-side visual stimuli determined from P3 and P4 electrode sites for both age groups in non-deprived and deprived sleep conditions. The statistical analyses involved the ERPs from the electrode sites contralateral to the stimulus side, which is indicated by gray shading.

3.1.1. P1

Sleep Deprivation did not have any effects on P1 peak latency. The P1 peaked earlier in responses to the right-side ($M = 156$ ms) than to the left-side stimuli ($M = 182$ ms), $F(1,21) = 22.55$, $p < 0.01$, $\eta_p^2 = 0.52$. In the old, P1 peaked earlier ($M = 155$ ms) than in the young ($M = 183$ ms), $F(1,21) = 20.66$, $p < 0.01$, $\eta_p^2 = 0.50$.

The general ANOVA for P1 amplitude did not reveal any statistically significant effects for Age, Sleep Deprivation, or Stimulus Side.

3.1.2. N1

The N1 latencies in the old were shorter ($M = 220$ ms) than those in the young ($M = 237$ ms), $F(1,25) = 5.13$, $p = 0.03$, $\eta_p^2 = 0.17$. The N1 peak latencies in response to the right-side stimuli were shorter ($M = 222$ ms) than those to the left-side ones ($M = 235$ ms), $F(1, 25) = 16.64$, $p < 0.01$, $\eta_p^2 = 0.40$. There were no significant effects of Sleep Deprivation.

The general ANOVA on N1 amplitudes did not show any significant effects for Age, Sleep Deprivation, or Stimulus Condition.

3.1.3. P3

The P3 peaked earlier in the responses by the young ($M = 455$ ms) than in those of the old ($M = 590$ ms), $F(1,30) = 33.88$, $p < 0.01$, $\eta_p^2 = 0.53$. Sleep Deprivation did not influence P3 latency. The peak latencies to the right-side stimuli were shorter ($M = 501$ ms) than those to the left-side stimuli ($M = 545$ ms), $F(1,30) = 20.33$, $p < 0.01$, $\eta_p^2 = 0.40$.

The amplitude of P3 was larger for the young ($M = 6.8$ μ V) than that for the old ($M = 4.69$ μ V), $F(1,30) = 12.27$, $p < 0.01$, $\eta_p^2 = 0.29$. Sleep Deprivation and Stimulus Side did not have any effect on P3 amplitudes.

3.2. Auditory

Fig. 2 shows ERP components N1, P2, and P3 in responses to correctly detected left and right auditory stimuli by the young and the old.

3.2.1. N1

N1 peak latencies of the old were shorter ($M = 227$ ms) than those of the young ($M = 239$ ms), $F(1,39) = 6.48$, $p = 0.02$, $\eta_p^2 = 0.14$, and the latencies in the non-deprived condition were shorter ($M = 231$ ms) than in the deprived one ($M = 234$ ms), $F(1,39) = 5.92$, $p =$

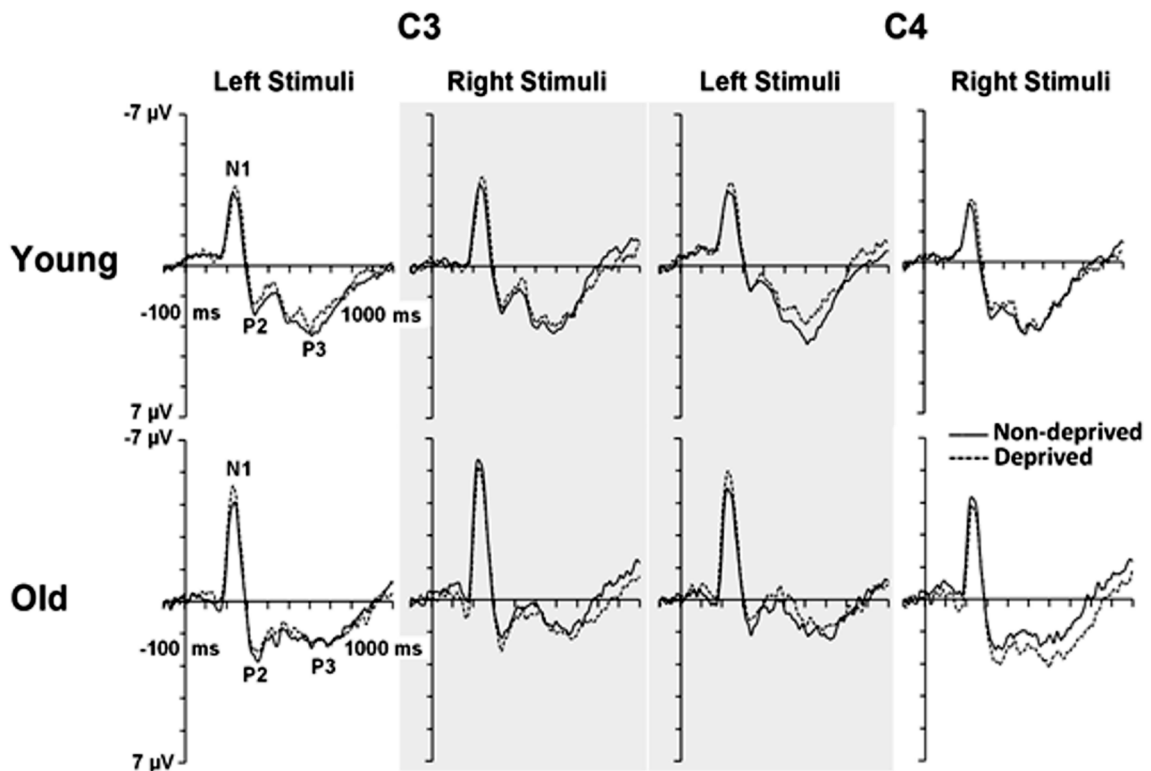


Fig. 2. Auditory ERPs with N1, P2, and P3 components in responses to correctly detected left- and right-side auditory stimuli determined from C3 and C4 electrode sites for both age groups in non-deprived and deprived sleep conditions. The statistical analyses involved the ERPs from the electrode sites contralateral to the stimulus side, which is indicated by gray shading.

0.02, $\eta_p^2 = 0.13$. An interaction between Age and Sleep Deprivation was also found, $F(1,39) = 6.34$, $p = 0.02$, $\eta_p^2 = 0.14$. Separate ANOVA on the young group's results showed that the N1 peaked earlier in the non-deprived condition ($M = 234$ ms), compared to the deprived condition ($M = 243$ ms), $F(1,21) = 12.97$, $p < 0.01$, $\eta_p^2 = 0.38$. In the old, no effects of Sleep Deprivation or Stimulus Side were found.

The N1 amplitude of the old was larger ($M = -6.33$ μV) than that of the young ($M = -4.46$ μV), $F(1,39) = 7.53$, $p < 0.01$, $\eta_p^2 = 0.16$. No significant effects were found for Sleep Deprivation or Stimulus Side.

3.2.2. P2

P2 peak latencies did not show any significant effects of Age, Sleep Deprivation, or Stimulus Side, and separate analyses for each age group did not reveal any significant effects, either.

The general ANOVA on P2 amplitude did not reveal any effects for Age or Sleep Deprivation. The P2 amplitude elicited by the right-side stimuli was larger ($M = 2.7$ μV) than that by left-side stimuli ($M = 1.9$ μV), $F(1,37) = 7.84$, $p < 0.01$, $\eta_p^2 = 0.18$.

3.2.3. P3

The P3 peak latencies of the young were significantly shorter ($M = 603$ ms) than those of the old ($M = 690$ ms), $F(1,23) = 7.65$, $p < 0.01$, $\eta_p^2 = 0.25$. Sleep deprivation did not have any effect on the P3 latency. The right-side stimuli elicited shorter LP peak latencies ($M = 634$ ms) than the left-side stimuli ($M = 659$ ms), $F(1,23) = 4.33$, $p < 0.05$, $\eta_p^2 = 0.16$.

The general ANOVA for P3 amplitudes did not reveal any significant effects for Age, Sleep Deprivation, or Stimulus Side.

4. Discussion

We measured the ERPs to spatial visual and auditory stimuli during driving in a virtual environment in order to evaluate the neurocognitive mechanisms underlying the effects of age and sleep deprivation on spatial perceptual abilities during driving. We hypothesized, on the basis of our previous (Rashid Izullah et al., 2021) behavioral findings, that: First, aging should affect, possibly by slowing down, brain responses to visual and auditory stimuli. Second, sleep deprivation should slow down some ERP components, and more effects on ERPs should be seen in the young than the old. Third, the right-side bias in perception should be observed also in ERPs, i.e., the brain responses to the right-side stimuli should be faster and possibly larger than those to the left-side stimuli.

The main findings related to the hypotheses were that: First, aging affected both early perceptual and alerting ERP components and the late P3. As expected, the effects were seen in latencies rather than in amplitudes. Aging in general had a dual effect on component latencies, it shortened the peak latencies of the earlier visual P1 and visual and auditory N1 components, but increased the P3 latencies. Second, the effects of sleep deprivation were more pronounced and differently manifested in the young than in the old, and were seen as longer peak latencies in the young. Third, spatial bias was evident in latencies of all visual ERPs components with right-side bias being evident as shorter latencies in general and larger auditory P2 amplitude and shorter auditory P3 latency being measured to right-side stimuli.

Aging, quite unexpectedly, shortened the latencies of the visual P1 and visual and auditory N1 components, but again, expectedly, increased the latencies of the P3 components. Aging did not affect the amplitudes of earlier P1 and N1 components, but larger visual P3 amplitudes were obtained for the young than the old. Early sensory/perceptual N1 components were in line with previous studies showing either no effect, or even enhancing and accelerating these components by aging (Brown, Marsh, & LaRue, 1983; De Sanctis et al., 2008). These changes are thought to be due to recruitment of wider neuronal networks to compensate for aging-induced inefficiency of brain functions related to perception, attention and cognitive control (Li, Gratton, Fabiani, & Knight, 2013; Grady, 2012).

Corresponding to our behavioral findings (Rashid Izullah et al., 2021), visual P3 components in the old were longer in latency and smaller in amplitude compared to those of the young, and the auditory P3 latency in the old was longer than that in the young. We may therefore conclude that aging slows down the processes reflected by P3, that is, attention, decision making, and working memory processes.

Sleep deprivation did not have any general effects on the ERPs, but its effects were different in the two age groups. The ERPs of the young were more affected by sleep deprivation than those of the old. Deprivation did not influence P1 components in either group. It slowed down the N1 in the young, but did not affect N1 latency in the old. Visual and auditory P3 latencies were not affected by sleep deprivation.

Finally, our aim was to evaluate on the basis of the ERPs, at which level in neurocognitive processing the behavioral effects of aging and sleep deprivation in spatial perceptual abilities during driving are to be found. Thus, the question is, whether they occur in early perceptual, or later endogenous higher level cognitive ERP components, which are relevant to spatial perception, decision making and working memory, correspondingly. Behavioral findings (see Rashid Izullah et al., 2021) demonstrated the distinct reduction of the number of correct responses and slowing down of the correct responses due to aging.

In the present ERP measurements, latencies of visual and auditory N1 were shorter in the old compared to those in the young. The amplitude of auditory N1 was larger in the old than in the young. Therefore, the behavioral effects of aging cannot be explained by the processes reflected by the early sensory/perceptual P1-N1 findings, which are rather contradictory to the behavioral ones (longer RTs vs. shorter peak latencies). Instead, the effect of aging on latencies and amplitudes of P3 components confirmed our hypothesis; aging both slowed down and reduced the amplitude of these deflections which correspond to the slowing down of response speed as a function of aging.

Our previous behavioral findings (Rashid Izullah et al., 2021) demonstrated that sleep deprivation had more adverse effects on the spatial perceptual capabilities of the young than the old. Sleep deprivation prolonged the N1 latency in the young. Therefore, the deteriorating effect by sleep deprivation on the performance of the young can only be correlated to that of changes in N1 deflection, referring to impaired alerting and orienting functions in the young due to deprivation. Boksem, Meijman, and Lorist (2005), for example, found that fatigue affected both discrimination- and reorienting-related effects seen in N1 deflections in young males, thus deteriorating the difference between orienting to relevant and irrelevant stimuli. No effects of sleep deprivation could be observed in the old. As a matter of fact, as hypothesized by Rashid Izullah et al. (2021) in their previous behavioral report, the fact that the old do not demonstrate any distinct effects of sleep deprivation behaviorally or in ERPs, indicates a difference in strategy, i.e. the old “play it safe” regardless of the condition.

Laterality biases were expected on the basis of the previous behavioral findings (Rashid Izullah et al., 2021). As a matter of fact, shorter peak latencies of visual P1 and N1 components were obtained in responses to the right than the left-side visual stimuli, whereas such bias was not found in the early brain responses to auditory stimuli. Laterality bias in auditory P2 amplitude, and in visual and auditory P3 latencies but not amplitudes was observed. The P2 in our study possibly is the auditory P3a described by Escera et al. (1998) in context with acoustic novelty and involuntary attention. It may thus reflect the fluctuations and bias in spatial attention in the test situation. We may therefore conclude that the spatial bias seen behaviorally to visual stimuli (Rashid Izullah et al., 2021), could be seen in both early and late ERP components, that is, at all levels of cognitive processing covered by our ERP measurements.

Our present results showed that aging slowed down and reduced the amplitudes of the visual P3 and also slowed down the auditory P3. The auditory P3 latency has been found to be a more consistent and sensitive indicator than its amplitude to detect the cognitive processing differences between normal age groups (Brown et al., 1983) and between normal participants and patients (Goodin, Squires, & Starr, 1978). Further, in relation to cognitive control and aging, delays in ERP latencies as a result of aging have consistently been found, but the findings on amplitude have been less consistent (Kropotov, Ponomarev, Tereshchenko, Müller, & Jäncke, 2016). Finally, we refer to Table 1 showing the number of participants from whom reliable components could be extracted for calculations and statistics. The table demonstrates rather clearly that the data loss was especially due to the old subjects' P3 deflections being too vague after sleep deprivation for determining the P3 peak or latency. These cases were dropped from further P3 analyses. The data loss in the old reflects the well-known aging-induced losses in the morphological complexity of ERP waveforms (Dustman, Snyder, & Schlehuber, 1981). Therefore, even though no distinct differences between the two groups' P3s could be detected on average level, some of the old participants demonstrated rather dramatic effects of sleep deprivation on this late P3 component.

This study used a within-participants design in which all the participants performed the tasks in both deprived and non-deprived conditions. The order of the deprivation and non-deprivation conditions was counterbalanced across the participants. Unfortunately,

we did not include any control groups without any sleep deprivation condition to control for possible practice or order effects. However, we studied the order effects by repeating the ANOVAs with the order of the sleep deprivation condition as an additional between-participant variable. The order of sleep deprivation vs. non-deprived condition influenced only auditory P3 latency and amplitude (see [Supplementary Materials](#)), but the significant main effects and interactions related to age, sleep deprivation, and laterality (reported in section 3.2.3) remained statistically significant and no new statistically significant effects appeared. Thus, these analyses did not imply any changes to the interpretation of the results.

5. Conclusion

Thus, we may conclude that, during driving simulation, the effects of aging on responding to spatial visual and auditory stimuli can be quite unequivocally observed in late, decision making and working memory related processes, whereas those of sleep deprivation can be found only in the young and related to alerting and orienting functions. The spatial perceptual biases could be seen at all levels from sensory processes to decision making and working memory, depicted as ERP responses in our study. These findings on different neurocognitive processes being affected by sleep deprivation in different age groups call for attention regarding traffic safety and education. Finally, we want to emphasize that the driving simulator system with spatial stimuli used in this study was designed to be as simple as possible in order to measure cognitive capacity in a multitasking situation combining driving and simultaneous simple spatial perception. This approach allows us to observe the cognitive capacity for this multitasking without any further confounding factors. While we now have demonstrated the effectiveness of this simple system, it is then safe to move over to more natural, i.e., ecologically valid sceneries and events in the virtual driving task.

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CRedit authorship contribution statement

Faramosh Rashid Izullah: Project administration, Resources, Investigation, Formal analysis, Writing – original draft, Visualization. **Mika Koivisto:** Writing – review & editing, Formal analysis, Supervision. **Valtteri Nieminen:** Investigation, Writing – review & editing. **Mika Luimula:** Methodology, Software. **Heikki Hämäläinen:** Conceptualization, Methodology, Project administration, Funding acquisition, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.trf.2022.07.001>.

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