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Effects of All-Night Driving on Selective Attention in Professional Truck Drivers: A Preliminary Functional Magnetic Resonance Study

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Abstract: Fatigue affects multiple aspects of cognitive performance among drivers. However, even after fatigue builds up, some are still able to maintain the level of behavioral performance. To evaluate these adaptations on the neural network level, we utilized functional magnetic resonance imaging (fMRI). Seventeen male professional drivers underwent two fMRI sessions, once while rested and once in a fatigued condition after 10-h of overnight driving. The cognitive task used in the study involved the detection of visual feature conjunctions, namely the shape and the color. There were no significant differences in the task performance between the conditions except for longer reaction times in the fatigued condition. However, we observed substantial differences in the activation patterns during the cognitive task involving selective attention between the conditions. On the global level, we observed a general decrease in activation strength in the fatigued condition, which appeared to be more pronounced in the left hemisphere. On the local level, we observed a (spatially) extended activation of the medial prefrontal regions in the fatigued condition, which reflected increased cognitive control mechanisms compensating for the diminished efficiency of mechanisms involved in meeting task demands.

Keywords: fatigue; selective attention; functional brain imaging

1. Introduction

Driving a car is a complex behavior that requires diverse abilities, including perceptual, attentional, decision-making, and motor skills [1]. All-night driving leads the buildup of fatigue. Driver's fatigue is related to about 10% of the total number of accidents, and about 25% of single-vehicle accidents [1]. The impact of fatigued driving in the EU is significant: social costs (including healthcare) of all road accidents leading to injuries and fatalities are at least EUR 100 billion per year [2].

Fatigue is a cumulative process. It is related to a sustained activity and often results in impaired performance. The main symptoms are: difficulty in maintaining alertness and focus of selective attention, vigilance, and staying awake [3]. Understanding the mechanisms that modulate selective attention in fatigued subjects may provide implications for accident prevention, as this information may help with management of human errors and minimization of number of accidents and injuries [4]. For this reason, non-invasive measurements of brain activity can play a role in understanding the neural basis of driving ability [5].

The ability to attend to one's surroundings is of utmost importance to safety in an environment with competing stimuli; failure to perceive relevant stimuli due to decreased attentional control can result in accident and injury [4]. Alertness and selective attention are closely intertwined but separable dimensions of attention. Both play an important role in ensuring driving safety. According to the salience effort expectancy value (SEEV) attention allocation model, 90% of attention used to operate a vehicle has visual character [6]. Visual selective attention plays a special role in driving behavior/control, since each driver is confronted with a plethora of competing stimuli that must be recognized and processed quickly to ensure the coordinated responsiveness to all the environmental events occurring while driving a car. Inadequate allocation of attention was identified as one of major factors leading to road accidents [7].

According to feature integration theory [8], visual selective attention is based on two linked levels of representation. On the first level, visual features such as color or shape are represented in separate feature maps. The second level of representation, the master map of locations, encodes the current site of the attentional focus. The attentional selection works on the second level by binding visual features present in the site of attentional focus. Thus, the attentional selection of visual objects requires not only the correct registration of their features, but also their proper integration [9]. Earlier fMRI studies identified the nodes of the underlying neural network using feature and conjunction search tasks [10]. An object defined by multiple features is simultaneously processed by functionally specialized systems in the brain. Cognitive processes of visual short-term memory (color, shape, and their conjunctions) were shown to activate (in a load-dependent manner) the bilateral superior parietal lobule (Brodmann area 7), close to intraparietal sulcus [11]. The posterior parietal cortex was sensitive to visual short-term memory load for color and shape [11]; in particular, it was sensitive to feature and visual working memory load manipulations. Other studies found greater activity in the right parietal cortex at the junction of the intraparietal cortex and transverse occipital sulcus during a conjunction search, as compared to a single-feature search [9,12]. On the other hand, the prefrontal regions were sensitive to visual working memory load manipulation, but relatively insensitive to feature differences [13].

Acknowledging the complexity of the factors contributing to driver's fatigue and ensuing decrease in driving performance, in this study we focused on the modulatory influence of the fatigue on the attentional system of the brain. While the brain networks underlying alertness have been shown to be sensitive to fatigue, less is known about its influence on selective attention. We used a feature conjunction detection task in which the participants were required to respond to a specific combination of color and shape. Such a task specifically addressed the domain of attentional control, since feature integration in target detection tasks involves this type of top-down attentional processing. In our study, all participants performed the task in the fMRI scanner twice—in a fatigued condition, following substantial sleep deprivation during the preceding 24 h period, and in a rested condition, after several hours of ceaseless sleep. We predicted decreased neuronal activity in the nodes of the attentional control network associated with the fatigued condition, irrespective of the task performance.

2. Materials and Methods

This study was part of a larger project to detect early signs of fatigue to improve the safety of driving. Qualification for participation in the project was preceded by general medical, neurological, and ophthalmological examinations. Seventeen male, right-handed [4], professional drivers with a current medical examination to qualify for professional driving, aged 32.9 ± 4.4 years, with work experience in the profession of 12.6 ± 5.6 years, without self-reported chronic conditions that impaired sensory and cognitive functions and could lead to sleepiness during driving [2,3], took part in the randomized cross-over functional MRI examination. The sex of the participants reflected the fact that this profession is rarely chosen by females. Their body mass index (BMI = 28.7 ± 3.3) was above the recommended values [14]; only three participants had a proper body weight, eight were overweight, and six were obese. Nine participants had a higher education, five completed secondary school, two had vocational training, and one had junior high school). Their average number of working hours per month was 220 ± 36.

Each participant underwent fMRI scanning session twice; i.e., according to randomized, control trial methodology: (1) after a normal night of rest for the driver, and (2) after a 10 h, overnight period of driving under normal working conditions. The median interval between both sessions was seven days (range from one day to 98 days). In order to minimize the impact of the so-called learning effect (interfering variable) on the results, seven of the drivers were first tested at rest, while for the remaining 10, the first fMRI was after the 10 h driving period. All the tests were performed during morning hours to eliminate the influence of circadian rhythms on physiological functions.

All the procedures were approved by the Bioethics Committee of the Military Institute of Aviation Medicine, Warszawa, Poland (Decision No. 11/2015) and were performed in accordance with the ethical standards as laid down in the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. Prior to the study, all the participants gave written informed consent to all procedures and personal data processing for scientific purposes. All data was defaced and anonymized before analyses.

2.1. *Assessment of Sleep Deprivation*

Before the fMRI examinations, all participants completed a questionnaire inquiring about the length of sleep the previous night, the amount of time elapsed since last waking up, the number and length of naps in the last 24 h prior to the fMRI, and potential problems with maintaining awareness during the fMRI scanning session. The effects of sleep deprivation and drowsiness were assessed using the Sleep Deficiency Effects Scale (the CHICa scale) [15]. This self-report tool enables the measurement of four components of an individual's fatigue resulting from sleep deprivation, and its results are grouped into four subscales; i.e., impaired thermoregulation (cold subscale), disrupted appetite (hunger subscale), affective problems (irritation subscale), and decreased level of cognitive functioning (cognitive attenuation subscale). Finally, the symptoms of fatigue were also assessed using the Polish version of the Japanese Questionnaire (named as the Assessment of the Current Well-Being) [16,17]. This questionnaire evaluates the symptoms of fatigue based on three groups of symptoms; i.e., (1) decreased activity (e.g., sleepiness, weariness, heaviness of the body), (2) weakened motivation (e.g., irritability, inability to concentrate, apathy), and (3) physical fatigue (e.g., trembling of the limbs, back pain), as well as a general score indicating an overall level of fatigue.

2.2. *fMRI-Visual Stimuli*

The visual stimuli were pairs of filled line drawings of geometric figures (squares, triangles, circles) presented on an LCD screen (see Figure 1). Each figure was filled with one of four possible colors (red, green, yellow, or blue). Stimuli were presented over a grey background (RGB: 64,64,64). A fixation point was presented in the center of the screen (white-filled circle, diameter = 3 pixels). The stimulus consisted of a pair of geometric figures, which were shifted 150 pixels to the left or to the right in regard to the fixation point; this horizontal deflection subtended ±4.5 degrees of visual angle relative to the center of the screen. The LCD screen resolution was 1920 × 1080 pixels (InroomViewingDevice, NordicNeuroLab, Bergen, Norway). The stimuli were back-projected on the screen and viewed through a system of mirrors mounted inside the head coil. Each stimulus pair was presented for 200 ms. Following the presentation of the stimulus pair, the short irregular inter-trial interval of varying duration of 1300 ms to 2300 ms occurred. During this period, only the fixation point was visible.

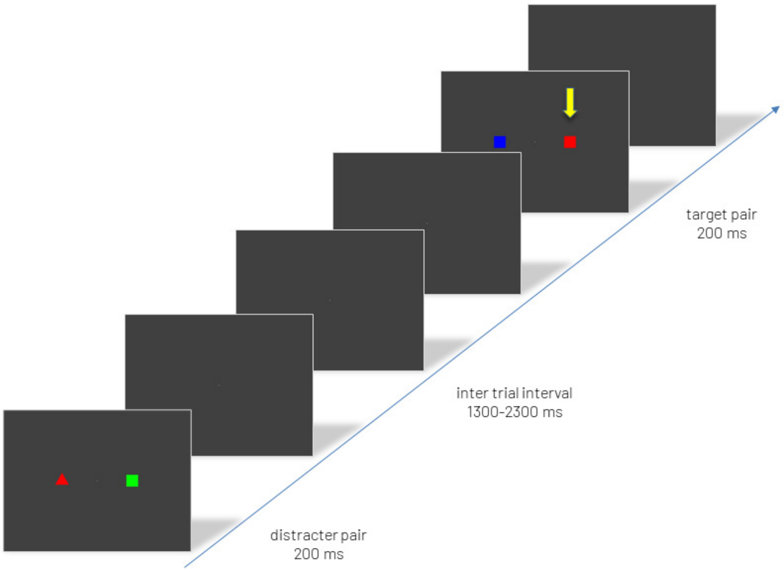


Figure 1. An outline of the cognitive task with two example trials separated by the inter-trial interval. In the actual experiment, 15 trials were presented during each 30 s block. The yellow arrow (not shown during the actual experiment) indicates the target stimulus. The relative size of the stimuli has been enlarged for illustrative purposes. Participants were instructed to respond with the left index finger to each instance of the distracter stimulus, and with the right index finger to each instance of the target stimulus.

2.3. Cognitive Task

The cognitive task used in the study involved the detection of visual feature conjunctions, namely the shape and the color. The study protocol was based on a blocked design, with each block lasting for 30 s. There was one type of an active block (repeated 6 times during the scanning session), which was interspersed with baseline blocks (7 repetitions). The functional scanning session always began and ended with the baseline block. All participants practiced the task before the scanning session (with three active blocks).

During the active block, 15 pairs of filled geometric figures appeared on the screen, presented on the left or the right side of the fixation point. Each active block was preceded with an instruction screen shown for 2000 ms containing the prompt “Detect the red square” in the center of the screen, displayed in yellow font. The volunteers had to detect the target stimulus in each pair, which was a specific combination of color and shape—a red square (see Figure 1 for the cognitive task outline). The participants had to react to this stimulus with right index finger using an NNL ResponseGrip (NordicNeuroLab, Bergen, Norway). They were instructed to respond with their left index finger to all other combinations of features and shapes, called distracter stimuli; for example, blue squares, red circles etc. Participants were required to respond in each trial.

To decrease participants’ expectations about the probability of the target, the proportion of pairs containing the target stimulus varied in each block. In two blocks, the target probability was set to 0.8, in another two, it was decreased to 0.2, and in the remaining two blocks, it was 0.5. The order of the blocks was random. During the so-called baseline blocks, the participants’ task was to keep their eyes on the fixation point.

The task difficulty was set to equalize the task performance during both the rested and fatigued conditions. In this way, detected differences between the rested and fatigued conditions could indicate modulation of task-related neural processing evoked by the alteration in tiredness, and not the confounding effects of varying subjective task difficulty.

2.4. Image Acquisition and Processing

The study was performed with a GE DISCOVERY MR750w with a 3.0 T field. For the presentation of the stimuli, an LCD screen with a horizontal angle of 24° was used, which was viewed by the participants through a system of mirrors in the head coil. The initiation of the procedure was synchronized with the first scanner TR by NNL SyncBox (NordicNeuroLab, Bergen, Norway https://nordicneurolab.com/product/responsegrips/ (accessed on 20 August 2021)). The participants responded with NNL grips (NordicNeuroLab, Bergen, Norway) by pressing the buttons under the index fingers of the left and right hand.

An 8-channel coil was used in all tests. Structural images were acquired with a 3D Fast Spoiled Gradient Echo (FSPGR BRAVO) sequence (TR = 8.496 ms, TE = 3.26 ms, TI = 450 ms, matrix 256 × 256 × 124, single voxel size: 0.9375 mm × 0.9375 mm × 1.2 mm). Functional images within the fMRI task used the echo planar (EPI) sequence with the following parameters: TR = 2000 ms, TE = 30 ms, 64 × 64 × 35 matrix, single voxel size: 3.125 × 3.125 × 3.5 mm, 196 repetitions, 4 dummy scans at the beginning of each scanning session.

2.5. Data Analyses

2.5.1. Behavioral Data

Behavioral data were compared between conditions (fatigued vs. rested) using paired *t*-tests. All tests were performed with IBM SPSS Statistics software.

2.5.2. Imaging Data

Imaging data analysis was performed using FSL 5.09, FEAT Version 6.0 [18]. Standard pre-processing steps were performed: correction of head movements with the MCFLIRT tool, and removal of non-brain voxels from images with the BET tool. Global intensity normalization of images with a single factor and a Gaussian-weighted least-squares straight line fitting, with sigma = 45.0 s, was performed. Registration and normalization results were visually inspected for each participant. Level 1 analysis was performed using the FILM tool with local autocorrelation correction. The main effect of active blocks was examined. The $Z > 3.1$ threshold was applied with the use of clusters and the corrected cluster significance threshold $p < 0.05$. Level 2 analysis was performed in the mixed-effects model, with a participant as a random factor; the significance of stimuli was determined by threshold $Z > 3.1$ with the use of clusters and adjusted significance threshold $p < 0.05$. The whole-brain main effects analyses were intended to reveal level 2 group means for each condition separately (i.e., the difference between active and baseline blocks). The correlations of the activations with reaction times were evaluated separately for each condition. The effect of condition was tested with a T-statistics contrast between conditions. We analyzed contrasts fatigued > rested as well as rested > fatigued.

3. Results

3.1. Behavioral—Fatigue Symptoms

The average sleep length during the night preceding the study was 1.7 ± 1.1 h (min = 0 h, max = 3 h) in the fatigued condition, as compared to 6.8 ± 1.1 h (min = 4 h, max = 9 h) in the rested condition. As some of the participants reported napping, we also measured time since last waking up. In the fatigued condition, the time was on average 8.2 ± 6.6 h (min = 2.5 h, max = 26 h), whereas in the rested condition, the times were the following: 2.9 ± 1.0 (min = 2 h, max = 5 h). The drivers had significantly more symptoms of sleepiness and fatigue in the fatigued condition than in the rested one, which confirmed the successful manipulation of their state (see Tables 1 and 2).

As shown in Table 1, the drivers participating in the study were more tired, and consequently reported more severe symptoms of fatigue in the assumed fatigued condition than in the rested one. Significant differences between these two experimental conditions were obtained in three subscales, as well as in the general score in the Japanese Questionnaire.

The results in Table 2 show that the reduced level of self-reported cognitive functioning of the drivers was the most symptomatic (the highest score on the cognitive-attenuation subscale in the fatigued condition compared to other subscales).

Table 1. Severity of fatigue symptoms reported in the Japanese Questionnaire (lower score = more severe reported symptoms). The general score was defined as the sum of the results from three subscales. All $p < 0.001$.

Symptoms	Fatigued Condition	Rested Condition
Decreased activity	3.1 ± 4.3	19.6 ± 7.3
Weakened motivation	1.3 ± 2.1	12.8 ± 6.9
Physical fatigue	1.4 ± 2.6	10.4 ± 7.9
General score	5.8 ± 7.3	42.8 ± 18.9

Table 2. Measures of sleep deprivation in rested and fatigued conditions on the CHICa subscales. All $p < 0.001$.

Fatigue Components	Fatigued Condition	Rested Condition
Impaired thermoregulation	3.1 ± 2.4	0.5 ± 1.0
Disrupted appetite	4.3 ± 2.5	0.8 ± 1.2
Irritation	5.4 ± 4.0	0.5 ± 1.5
Cognitive attenuation	10.3 ± 4.1	1.5 ± 2.4

3.2. Behavioral—Task Performance

There were no significant differences in the level of task performance between the fMRI sessions. The percentages of correct answers were 97 ± 3% for the rested condition and 95 ± 5% for the fatigued condition ($p = 0.06$). However, there were noted differences in the response speed. The mean response time was 13% longer for the fatigued condition; particularly for the right hand, the average response time increased from 644 ± 44 ms to 731 ± 130 ms ($p = 0.01$); whereas for the left hand, the mean response time for the rested condition was 657 ± 42 ms, while for the fatigued condition, the mean response time was 743 ± 113 ms ($p = 0.004$).

3.3. Imaging Results (Analysis Level 2)

3.3.1. Main Effects of the Task in Both Conditions

The results are displayed in Figures 2 and 3, as well as presented in Tables 3 and 4. In both conditions, we observed a mostly overlapping pattern of activations in the lateral frontal, lateral parietal, and medial frontal regions. In both conditions, we also observed overlapping clusters in the left lateral temporo-occipital regions. There were marked differences between both conditions. In the rested condition, the general extent of suprathreshold activation was notably wider and more bilateral than in the fatigued condition. The strongest effects of task in the rested condition were observed in the posterior parietal cortex, as well as in the premotor cortex, extending into the dorsolateral cortex, mainly in the right hemisphere. Bilateral activations were also observed in the anterior insulae and in the medial frontal regions (SMA). In contrast with the fatigued condition, we observed bilateral activations in the polar visual cortex, as well as in the fusiform gyrus.

Table 3. Main effects—rested condition. The table lists the approximate anatomical details of the suprathreshold clusters. Z-score represents the maximum Z value within the given cluster. X, Y, and Z values denote MNI coordinates of the maximum Z-value voxel. Cluster volume is given as a voxel count. Anatomical labels were identified using the Harvard-Oxford Cortical and Subcortical Atlases, Juelich Histological Atlas, and Talairach Daemon Labels as provided by FSL software (https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/Atlases (accessed on 20 August 2021)). The characters within parentheses accompanying the anatomical labels indicate the hemisphere—left or right.

Anatomical Label	Cluster Volume	Z-Score (Maximum)	X	Y	Z
Supplementary motor area (L/R), medial frontal gyrus (L/R), inferior parietal lobule (R), postcentral gyrus (R)	9708	6.31	−2	4	52
Lateral occipital cortex (L), fusiform gyrus (L)	1425	4.74	−44	−70	−14
Inferior parietal lobule (L), postcentral gyrus (L)	1411	4.77	−32	−56	44
Putamen (R), thalamus (R), caudate (R)	1185	5.2	20	12	2
Anterior insula (L)	385	4.98	−36	14	14
Occipital pole (L)	327	4.24	−20	−100	−12
Thalamus (L), caudate (L)	300	4.66	−16	−8	16
Middle frontal gyrus (L), precentral gyrus (L)	292	4.82	−46	6	36
Occipital pole (R)	291	4.45	22	−92	−14
Precentral gyrus (L), superior frontal gyrus (L)	291	4.29	−32	−10	52

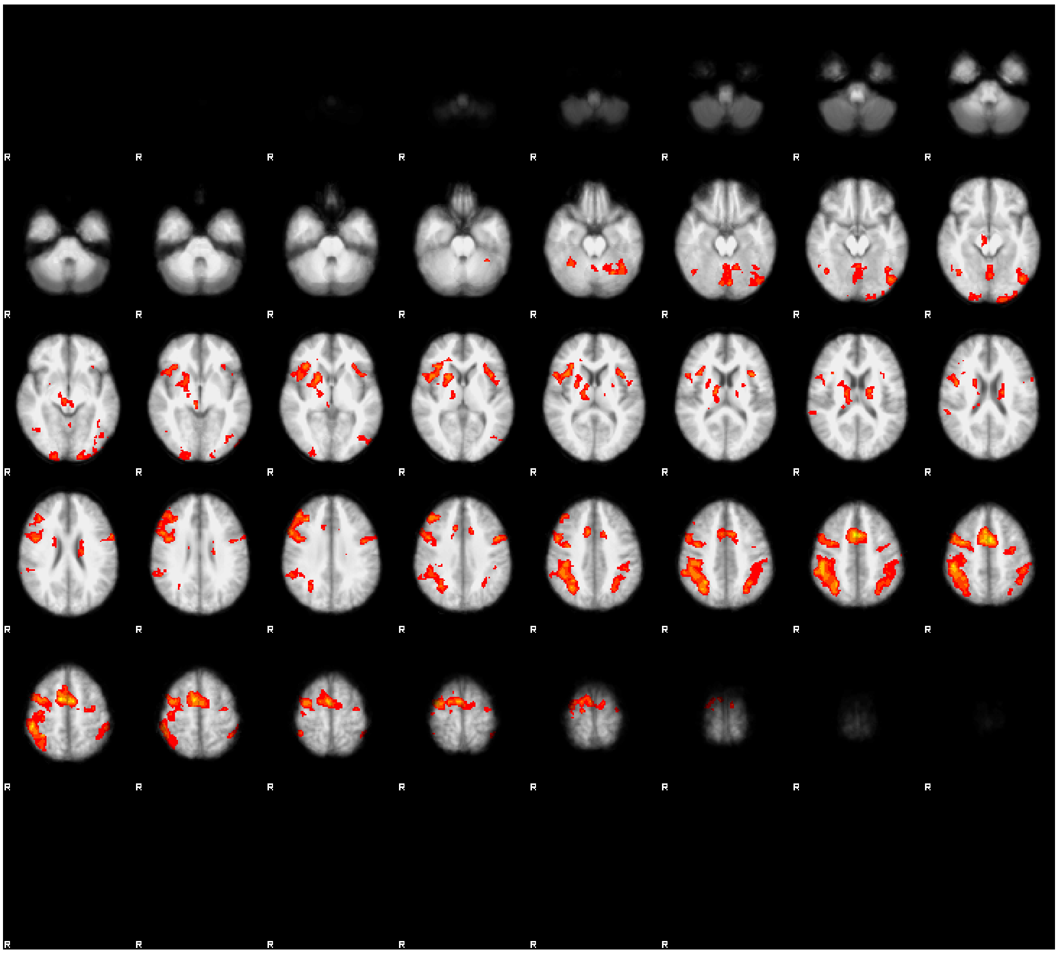


Figure 2. The main effects of the task in the rested condition. Images were thresholded at $Z > 3.1$. Note the extensive bilateral activation in the posterior parietal cortices, SMA, premotor cortex, and dorso-lateral prefrontal cortex. Activation in the middle temporal cortex was left-lateralized. The right side of the brain is denoted by letter R.

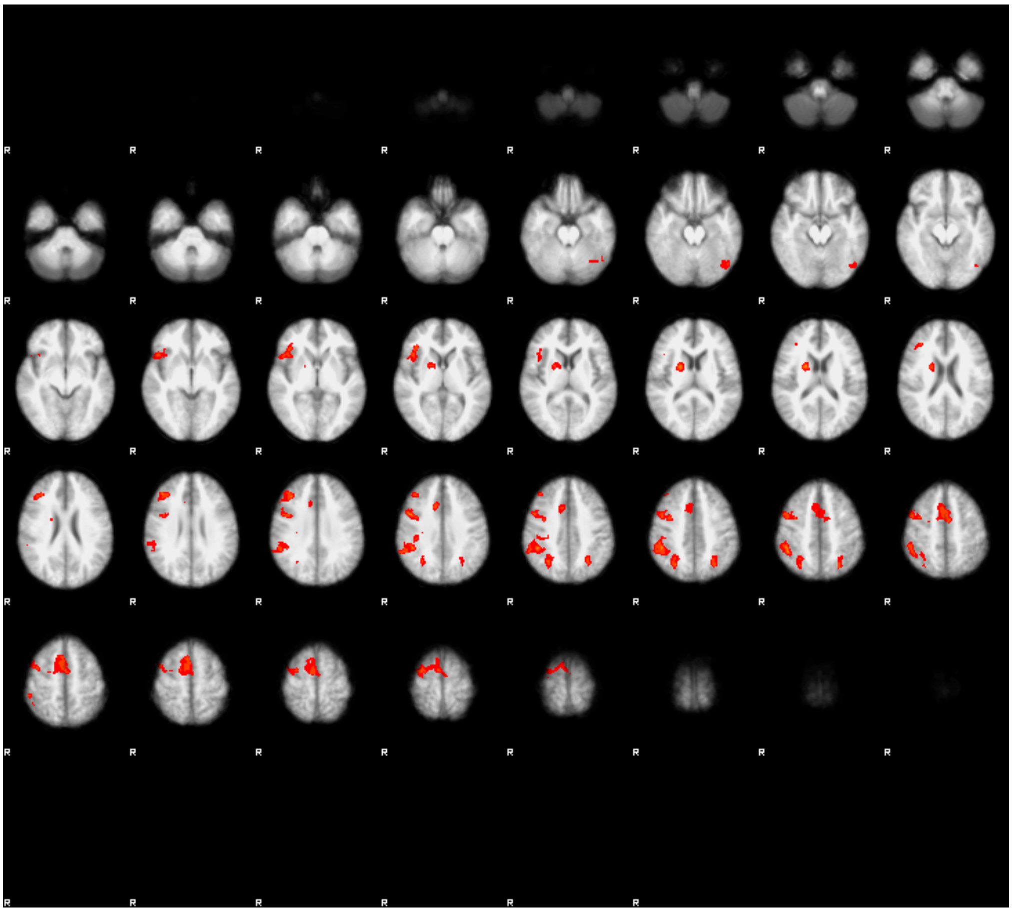


Figure 3. The main effects of the task in the fatigued condition. Images were thresholded at Z > 3.1. Note the more extensive activations in the right hemisphere of the brain (denoted by the letter R) in the posterior parietal cortices, supplementary motor area (SMA), premotor cortex, and dorso-lateral prefrontal cortex in comparison to the rested condition (see Figure 2). Activation in the middle temporal cortex maintained its lateralization in the left hemisphere.

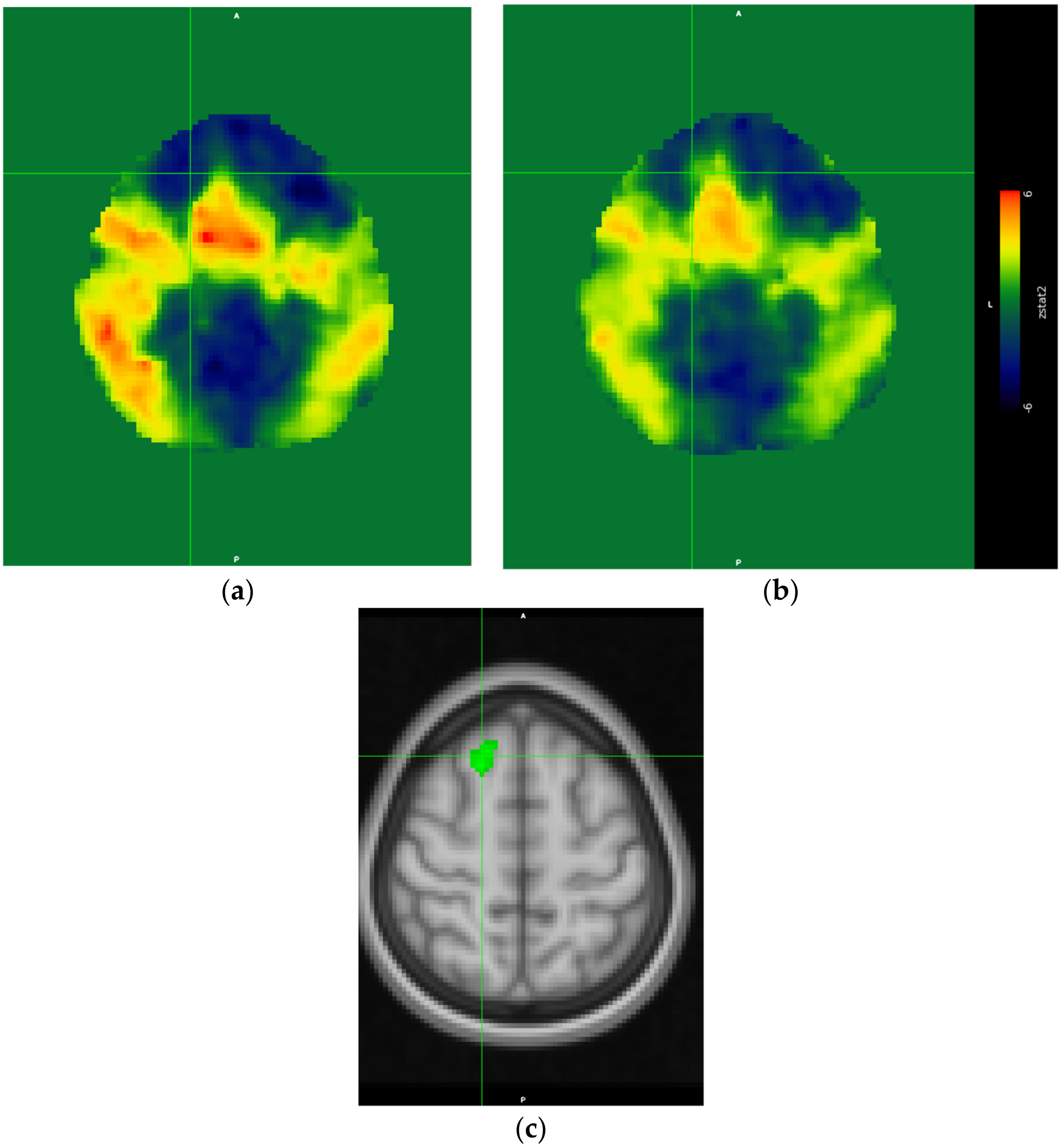
Table 4. Main effects—fatigued condition. The table lists the approximate anatomical details of the suprathreshold clusters. Z-score represents the maximum Z value within the given cluster. X, Y, and Z values denote MNI coordinates of the maximum Z-value voxel. Cluster volume is given as a voxel count. Anatomical labels were identified using the Harvard-Oxford Cortical and Subcortical Atlases, Juelich Histological Atlas, and Talairach Daemon Labels as provided by FSL software. The characters within parentheses accompanying the anatomical labels indicate the hemisphere—left or right.

Anatomical Label	**Cluster Volume**	**Z-Score (Maximum)**	**X**	**Y**	**Z**
Supplementary motor area (R), precentral gyrus (R), middle frontal gyrus (R), medial frontal gyrus (R)	2348	4.57	46	6	34
Inferior parietal lobule (R)	967	4.85	48	−42	46
Inferior frontal gyrus (R)	372	4.45	40	30	2
Middle frontal gyrus (R)	358	4.41	40	34	34
Superior parietal lobule (R)	356	4.56	28	−66	44
Putamen (R)	286	4.72	22	2	16
Superior parietal lobule (L)	216	4.32	−28	−68	46
Fusiform cortex (L)	150	4.02	−48	−66	−20

In the fatigued condition, the extent of the suprathreshold clusters was notably smaller. Bilateral activations were seen only in the parietal regions, while in the frontal regions, the activations were mainly observed in the right hemisphere. In neither condition were the activations correlated with the reaction times.

3.3.2. Contrast Results

Direct contrast between both conditions revealed a suprathreshold cluster only in the contrast fatigued > rested. The cluster was located in the right superior frontal gyrus (see Figure 4c). Interestingly, this region did not exceed the Z = 3.1 threshold in either condition, and it appeared in the fatigued > rested contrast because of the negative Z values in the rested condition (see Figure 4a showing the unthresholded Z values) and positive Z values in the fatigued condition (Figure 4b shows the unthresholded Z values). Thus, the difference of activation of this region in both conditions was caused by low response of this region in the rested condition and the moderately elevated response in the fatigued condition.



(a) (b) (c)

Figure 4. Unthresholded Z-statistics image of rested condition results (**a**), unthresholded Z-statistics image of the fatigued condition results (**b**). Note the larger extension of activations in the rested condition (**a**) as compared to the fatigued condition (**b**). The region of statistically significant differences; i.e., the contrast fatigued > rested conditions thresholded at Z > 3.1 (**c**). The crosshairs indicate the same voxel at the center of the suprathreshold cluster in the right superior frontal gyrus (MNI coordinates: x = 18, y = 26, y = 56, cluster volume = 136, Z-score (maximum—4.53)).

4. Discussion

In this study, we assessed the susceptibility of the networks involved in selective attention to the fatigue state induced by sleep restriction in professional truck drivers. In order to engage these networks, the visual feature detection cognitive task was used, in which the participants responded to the conjunctions of color and shape of visual stimuli. The difficulty level of the cognitive task was adjusted to ensure a commensurate performance in both arousal states.

Our manipulation of fatigue level via sleep deprivation proved successful. Both the CHICa scale and the Japanese Questionnaire revealed significant changes in self-reported arousal level due to the 10 h of overnight driving under normal working conditions. The results of the CHICa demonstrated that the reduced level of cognitive functioning in the fatigued condition was accompanied by the symptoms of impaired thermoregulation, disrupted appetite, and irritation. These results were consistent with the data obtained by the authors of this questionnaire themselves [15], according to which the symptoms of cognitive attenuation; i.e., problems with concentration, memory, logical thinking and understanding, lack of energy, and decreased accuracy at work, seemed to be the most characteristic and specific subjective manifestations of the sleep-deprivation state. It should also be noted, however, that while some physiological symptoms of sleep deprivation may be unpleasant for the driver (cold, hunger), they can be easily modified and fixed; whereas coping with emotional and cognitive problems is much more difficult, and consequently, they can endanger driving safety by influencing, for example, the driver's situational awareness in road traffic, as well as his sense of control behind the wheel [15].

The increase in response time in the fatigued condition was consistent with other studies [4,19,20]. The changes in response time can be interpreted as indicators of lowered alertness, accompanied by slowed processing of relevant stimuli without affecting the accuracy.

Regarding the whole-brain fMRI results in each condition, we observed a widespread activation spanning across the whole cortical mantle. The activated clusters in the rested condition were located in the regions consistently observed in the task involving selective attention (dorsal frontal areas, posterior parietal areas, medial frontal regions, and basal ganglia) [9–12]. Moreover, the additional suprathreshold clusters were observed in regions related to the visual ventral stream in the fusiform gyrus, as well as regions related to willed action in the anterior insula [21]. The fact that a similar pattern of activated regions involved in attentional selection was observed in both conditions suggests that in both situations, participants recruited basically the same brain networks. This observation was also supported by the lack of significant brain response differences in those networks as revealed by the direct contrast between the conditions.

However, at the same time we observed a notable decrease of the extent of activation in the fatigued condition, indicating a less-consistent brain response to the experimental task across participants. Interestingly, we observed a more lateralized pattern of activation in the fatigued condition, with the majority of clusters located within the right hemisphere. We surmised that this effect might be associated with lowered brain metabolism in the state of sleep deprivation [22]. Of course, this does not mean that truck driver's brain resembles a brain of a dolphin, yet it points to a lowered energy capacity of the fatigued brain, which can affect each hemisphere in a different manner [23]. The direct contrast between conditions revealed only one suprathreshold cluster, obtained in the fatigued > rested contrast. The reverse contrast did not reveal any significant differences. The cluster was located in the dorsal part of the prefrontal cortex. Interestingly, this region did not cross the significance threshold in any of the main effect contrasts for both the rested and fatigued conditions. However, a close inspection of the unthresholded images revealed that in the rested condition, this cluster was strongly deactivated, and in the fatigued condition, the response was positive, yet below the significance threshold. The inspection also revealed that the region discovered in the fatigued > rested contrast was a part of the larger cluster encompassing the medial frontal cortex—covering the SMA, pre-SMA, and parts of the superior frontal gyrus (see Figure 4). Previous research on the effects of cognitive working memory and attentional training research suggested that this region is a part of the cognitive control network, which is engaged in executive control over ongoing cognitive activity, and it is known that its responsiveness becomes significantly decreased over a training period [24,25]. Thus, in our case, the heightened activity of this region might suggest that a relatively simple task we used, involving simple visual feature conjunction detection, in the fatigued condition with lowered metabolic capacity due to sleep deprivation became a task that required more cognitive control resources in order to maintain the performance level. Thus, our results suggested that the influence in the arousal state of drivers on the cognitive level manifested as an increased demand for controlled attentional processing.

Although visually apparent, there were no statistically significant differences in activation of Brodmann area 7. An earlier study by Muto and colleagues [26] demonstrated that in young, healthy participants, there were no effects of one night of total sleep deprivation on attention; however, orienting and conflict resolutions were associated with significantly larger thalamic responses during sleep deprivation than during rested wakefulness. They concluded that sleep deprivation influenced different components of human attention non-selectively by affecting the structures maintaining vigilance or ubiquitously perturbing neuronal function. They further concluded that compensatory responses can counter these effects transiently by recruiting thalamic responses via that supporting thalamocortical function.

According to Johns [27], there is a continuous inhibitory interaction between a wake drive and a sleep drive, each of which involves integrated action of several different neuronal centers in the brain. At any time, the state of sleep or wakefulness depends on the comparative strengths of the total wake drive and the total sleep drive. Under the circumstances of fatigued driving, the driver can stay awake only by maintaining or increasing the secondary wake drive. Long-haul truck drivers are known to have developed methods to increase their wake drive, such as chewing gum, singing, or making frequent changes to their sitting position [27]. In our task, no behavioral influences on the wake drive were possible, as they would result in deterioration of data quality, which was not the case in our study. Therefore, the differences in brain activation between the rested and fatigued conditions reflected the adaptation mechanism involving increased cognitive control over task execution—in this case, voluntary focusing of attention on the incoming stimuli and the response selection.

Our research had certain limitations. The study was performed while the subjects were lying on a scanner table—a posture (position) that is known to increase subjective perception of sleepiness [27]. Therefore, some interactive effects of this position could not be excluded. Moreover, the small sample might have obscured smaller differences between experimental conditions. Furthermore, caffeine is known to have short-term effects on basal cerebral blood flow, and thus the activation strength of the brain [28]. Similarly, being sleepy was associated with lower cerebral perfusion than during normal functioning [23,29]. Therefore, future studies should evaluate cerebral perfusion to properly account for this phenomenon.

5. Conclusions

In conclusion, our research showed that the state of decreased arousal associated with sleep deprivation substantially changed the activation patterns during a cognitive task involving selective attention. When comparing the rested and fatigued conditions, these changes were twofold. On the global level, we observed a general decrease of activation strength in the fatigued condition that was more pronounced in the left hemisphere. On the local level, we observed an extended activation of the medial prefrontal regions in the fatigued condition that reflected an increased contribution of cognitive control mechanisms compensating for the diminished efficiency of mechanisms involved in selective attention and response selection.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Data are available upon request from the authors.

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