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Early Alpha Reactivity is Associated with Long-Term Mental Fatigue Behavioral Impairments

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Abstract

The quantitative analysis of electroencephalogram (qEEG) is a suitable tool for mental fatigue (MF) assessment. Here, we evaluated the effects of MF on behavioral performance and alpha power spectral density (PSD) and the association between early alpha PSD reactivity and long-term behavioral MF impairments. Nineteen right-handed adults (21.21 ± 1.77 years old) had their EEG measured during five blocks of the visual oddball paradigm (~ 60 min). A paired t-test was used to compare first and last block values of cognitive performance and alpha PSD. The sample was divided into high (HAG) and low alpha group (LAG) by early alpha PSD median values. The behavioral performance of the HAG and LAG was compared across the blocks by a two-way ANOVA with repeated measures (groups and blocks). MF impairs general behavioral performance and increases alpha PSD. The HAG presents more behavioral impairment when compared to LAG across the task. Simple linear regression between early alpha PSD and behavioral performance across the task can predict 19 to 39% of variation in general behavior impairment by MF. In conclusion, MF induction impairs general behavioral and increases alpha PSD. The other finding was that higher alpha PSD reactivity is associated to higher long-term behavioral impairments of MF. This work contributes to existing knowledge of MF by providing evidence that the possibility of investigating early electrophysiological biomarkers to predict long-term MF impairments.

Keywords Mental fatigue · Alpha rhythm · Electroencephalogram · Cognitive impairment · Applied physiology

Introduction

Mental Fatigue (MF) refers to the effects that people experience during prolonged mental effort (Boksem et al. 2005; Hopstaken et al. 2015; Lal and Craig 2001, 2002). Prolonged mental effort is associated with decreased motivation, drowsiness, and cognitive impairment (Boksem et al. 2005; Faber et al. 2012; Kato et al. 2009; Lin et al. 2012; Melo et al. 2017a, b; Ting et al. 2008; Wascher et al. 2014). Psychometric Likert scales (i.e., NASA-TLX scale) are already widely established methods to assess MF, but the exclusive use of self-perception measures has some limitations (Hart and Staveland 1988; Hart 2006). First, subjective bias (i.e., hating the job position) can provide data that does not reflect the individual's actual performance (Horrey et al. 2009). Second, interrupting work to complete the scale does not allow real-time mental state measurements (Matthews et al. 2015). Finally, using the same Likert scale multiple times creates a learning bias in workers' responses. The development of other methods to assess MF impairments is

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interesting to prevent workplace accidents. (Borghini et al. 2014; Matthews et al. 2015; Paxion et al. 2014; Young et al. 2014).

Cognitive neuroscience research uses an experimental model of prolonged mental effort to induce MF while electroencephalogram (EEG) equipment records simultaneous nervous system activity (Borghini et al. 2014; Wijesuriya et al. 2007). The main findings of research using EEG during MF induction suggest that low-frequency rhythms (4–12 Hz) increase during MF induction (Wascher et al. 2014; Zhao et al. 2012). An increase in low-frequency rhythms is an indication of decreased alertness, corroborating with behavioral impairment of MF induction (Klimesch et al. 1998; Makeig et al. 2000). The evaluation of MF using EEG requires the placement of electrodes and a pattern recognition algorithm for classification. Therefore, electrophysiological biomarkers have less influence of subjective bias, can be performed in real-time and are not susceptible to spontaneous learning (except through techniques such as neurofeedback), being a viable alternative for Likert scales used for MF assessment (Borghini et al. 2014; Lal and Craig 2001; Parasuraman et al. 2008).

MF induction is associated with a specific increase in alpha power spectral density (PSD) (8–12 Hz) at posterior EEG sites (Boksem et al. 2005; Borghini et al. 2014; Eoh et al. 2005; Lal and Craig 2002; Trejo et al. 2015; Wascher et al. 2014; Zhao et al. 2012). High mental effort tasks have a higher alpha PSD compared to low mental effort tasks (Borghini et al. 2014). Wascher et al. (2014) reports that alpha PSD increases continuously across a prolonged cognitive task (3 h). Machine learning algorithms using EEG measures based on alpha PSD classify MF with a 91 to 100% accuracy (Trejo et al. 2015). So, alpha PSD is associated with mental effort and MF. Alpha rhythm represents the cortical-thalamocortical feedback loop (Hughes and Crunelli 2005; Schreckenberger et al. 2004). Synapses from the thalamus to cortical areas are responsible for information processing, implicating several cognitive processes such as attention, memory and processing speed (Fama and Sullivan 2015; Van Der Werf et al. 2001). A better comprehension of the potential of alpha PSD modulation for cognitive performance prediction during MF may provide some insights for workplace accident prevention strategies.

Most studies that have already shown that alpha PSD is suitable for MF classification compares data from the first to the last block of the task (Borghini et al. 2014; Trejo et al. 2015). The last block of the task is the best period to induce MF, but these results may not be applied to workplace accident prevention. The last block of data represents the greatest performance impairment period. The classification of the highest performance impairment during MF may be too late for preventive strategies in the real workplace routine. Also, there are impaired behavioral performance without significant physiological changes (Melo et al. 2017a, b) and baseline values of physiological measures can be associated to emotional impairment of mental workload (Melo et al. 2020). Some studies suggest that alpha PSD increases consecutively across a prolonged cognitive task, perhaps alpha PSD values from the previous task blocks that can predict the long-term behavioral impairments of MF. This study aims: (a) To compare the first and last block values of alpha PSD and behavioral data (self-reported measures and cognitive performance) to evaluate the effects of mental fatigue; and, (b) To verify the reliability of first block alpha PSD to predict the long-term behavioral impairments of MF.

Material and Methods

Participants

Nineteen right-handed adults (men = 9, women = 10), aging between 18 and 24 (21.21 ± 1.77) years old were recruited from student population of Federal University of Santa Catarina, Brazil. All participants had a normal or corrected-to-normal vision. The exclusion criteria were: (a) neurological or psychiatric diagnose; (b) drug abuse history; (c) previous caffeine or alcohol consumption and intense physical activity for at least 3 h before the experiment; and (d) sleep restriction or deprivation in the previous night from the experiment. Local Ethics and Research with Human Beings Committee of the Federal University of Santa Catarina approved this study (CAAE number: 44053615.4.0000.0121).

Procedures and Experimental Setting

Data collection occurred between 9:00 and 16:00 h in a bright (250 lx), quiet (external sound noise between 35 and 45 dB) and grounded room. The participants signed the consent form and were placed in front of an LCD monitor (21"), approximately 90 cm from the screen. The following instructions were provided: "*press the left button to the green stimuli and the right button to the red stimuli*". All participants trained before data collection (≅ 2 min). The participants would have to answer questions about their self-perception of attention (SPA), drowsiness (SPD) and motivation (SPM) (using a Likert scale model with scores from 1 to 10) every 250 trials (≅ 12-min). A 5-min baseline was recorded, followed by the task with 1250 trials (5 blocks with ≅ 60-min duration).

Electroencephalographic Assessment

Mitsar® amplifier was used for EEG recordings using 19 channels EEGCap Ag/AgCl electrodes (10–20 system positioning) at the sites: Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T6, T7, P3, Pz, P4, T8, O1 and O2. All electrodes were referenced by monopolar earlobe references (A1 and A2). The ground electrode was located at FCz. The electrooculogram (EOC) was also recorded for ocular movement artifacts correction using the independent component analysis (ICA) (as described by Jung et al. 2000). The electrodes impedance did not exceed 10 kΩ. All physiological signals were sampled at 500 Hz with a 0.1–70 Hz band-pass filter and notched at 60 Hz.

Cognitive Task

The experimental task was a visual oddball paradigm. The stimulus is composed of a red or green circle (2 cm) presented in the screen center (200 ms). Before the stimulus presentation, there is a fixation cross (200 ms) followed by a black screen (800 ms). After the stimulus presentation, there is an interval of 800 ms for response (black screen). Each task block had 250 trials with 80% of non-target stimuli (green circle) and 20% of target stimuli (red circle), 1250 trials in total (~60-min duration). At the end of each task block, the participant should answer questions about their self-perception of attention (SPA), drowsiness (SPD) and motivation (SPM) using a Likert scale (scores from 1 to 10).

Data Extraction

The following behavioral data were obtained for each task block: (a) Target Stimulus Reaction Time (TRT); (b) Non-Target Stimulus Reaction Time (NTRT); (c) Commission Errors Number (CE; "press the wrong button"); (d) Omission Errors Number (OE; "don't press any button"); (e) Self-Perception of Attention (SPA); (f) Self-Perception of Drowsiness (SPD) (g) Self-Perception of Motivation (SPM). Only responses between 200 and 800 ms after the stimulus presentation were considered correct answers for reaction time measures (TRT and NTRT).

The signal processing and EEG power spectral analysis was conducted on EEGLab toolbox 13.5.4b (Delorme et al. 2011) using MATLAB (version 2014a). The EEG data were filtered off-line by 0.5–35 Hz bandpass filter and the ocular artifacts corrected by the ICA method (Jung et al. 2000). For each task block, the alpha (8–12 Hz) power spectral density (PSD) was extracted from 1-s epochs by Fast Fourier Transform using the Hanning Window (50% of overlap). To obtain alpha reactivity for each block all participants EEG data during cognitive task were corrected using the participant's baseline.

Statistical Analysis

A paired t-test was used to verify the effect of mental fatigue on behavioral and electrophysiological variables (first and last block values comparison). The sample was divided into two groups (by median) according to the first block alpha reactivity values, composing the High Alpha Group (HAG; values > median, n = 9) and Low Alpha Group (LAG; values < median, n = 10). ANOVA with repeated measures was used to compare the effects of alpha reactivity (LAG versus HAG) on cognitive impairment by time-on-task effects (delta of cognitive performance across the task blocks, each block was corrected by the first block values). The ANOVA with repeated measures was composed of two factors: (a) between-subjects comparison "Group" (LAG versus HAG) and (b) within-subjects comparison "Blocks" (five blocks repeated comparison). The Pearson correlation and simple linear regression (for each block individually) were performed to verify the association between early alpha reactivity and behavioral data across the task. All statistical tests were initially performed with alpha PSD at the Pz electrode. The analysis was replicated in other midline electrodes that shared the same dipole (Cz and Fz) to avoid statistical type II error (false-positive result). The statistical analysis was conducted in Stata (Version 14; StataCorp LLC, Texas, USA). The significance for all tests was $p < 0.05$.

Results

Table 1 shows the comparison between first and last block values of alpha PSD and behavioral data. The paired t test shows that MF increases alpha PSD (Fig. 1) at Fz, $t(18) = 3.98$, $p = 0.0009$, Cz, t $(18) = 4.46$, $p = 0.003$ and Pz, $t(18) = 3.74$, $p = 0.001$ electrodes, showed a significant increase (Fz = 57.7, Cz = 58.6 and Pz = 58.6) in the last

Table 1 The comparison between the variables in the first and last blocks indicates that FM induction is associated with an increase in alpha PSD and impaired behavioral performance

Variable (n = 19)	First Block mean ± sd	Last Block mean ± sd	*t*	*p*
SPA*	6.94 ± 1.74	3.05 ± 1.95	8.11	0.0001
SPD*	5.15 ± 2.24	7.68 ± 1.33	4.48	0.0001
SPM*	6.52 ± 2.45	2.73 ± 2.35	7.34	0.0001
TRT*	375.21 ± 52.88	399.73 ± 47.82	3.46	0.004
NTRT*	301.89 ± 49.69	275.73 ± 36.83	3.01	0.043
OE*	2.94 ± 3.86	6.94 ± 8.99	2.40	0.027
CE	0.73 ± 1.44	1.10 ± 2.51	0.53	0.60
Alpha PSD at Fz*	56.85 ± 2.39	57.78 ± 2.80	3.98	0.0009
Alpha PSD at Cz*	57.69 ± 2.47	58.66 ± 2.70	4.46	0.0003
Alpha PSD at Pz*	57.62 ± 2.34	58.66 ± 2.78	3.74	0.001

SPA self-perception of attention, *SPD* self-perception of drowsiness, *SPM* self-perception of motivation, *TRT* target reaction time, *NTRT* non-target reaction time, *OE* omission errors, *CE* commission errors

*$p < 0.05$

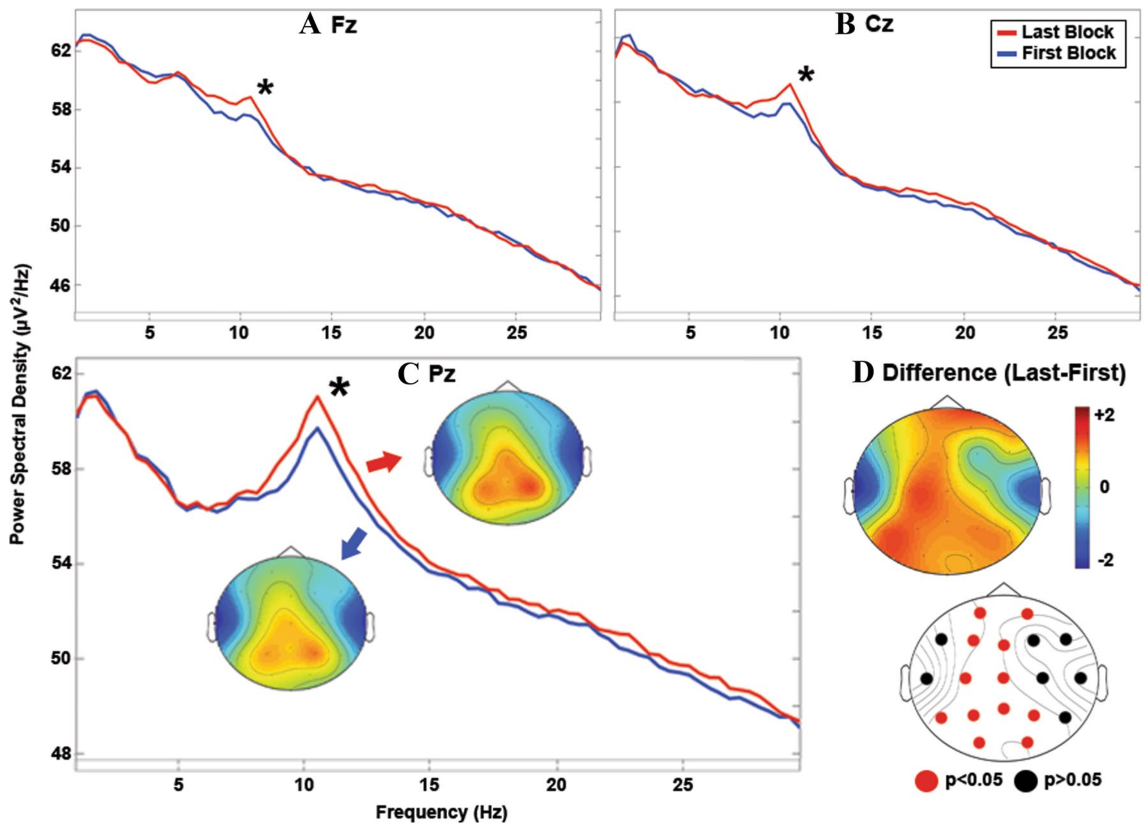

Fig. 1 Mental fatigue increase alpha (8–12 Hz) PSD. In the figure, the comparison between Fz (**a**), Cz (**b**) and Pz (**c**) electrodes. The difference between first and last block for all sites in topographical representation is seen in "**d**". The asterisks in **a**–**c** represents $p<0.05$ for paired t-test

block when compared to the first block values (Fz = 56.8, Cz = 57.6 and Pz = 57.6. Behavioral variables showed a significant increase in the first and last block comparison the SPD, $t(18)=4.48$, $p=0.0001$, TRT, $t(18)=3.46$, $p=0.004$, and OE, $t(18)=2.40$, $p=0.02$, when the SPA, $t(18)=8.11$, $p=0.001$, SPM, $t(18)=7.34$, $p=0.0001$, NTRT, $t(18)=3.01$, $p=0.04$, exhibited a significant decrease during mental fatigue period.

Table 2 contains the comparison of behavioral performance between the LA and HA group across the task blocks. HA group presents an increased delta of SPA, F from 3.75 to 5.56, $p<0.05$, SPD, F from 2.33 to 5.73, $p<0.05$, SPM, F from 3.23 to 5.32, $p<0.05$, TRT, $F=2.54$, $p=0.02$ and decreases delta of NTRT, F from 2.19 to 3.49, $p<0.05$, when compared to LA group (Fig. 2). These differences between HA and LA groups were more prominent at posterior sites (Cz and Pz) and during the last block, although some variables present significant differences since the second block (i.e., delta of SPD).

Table 3 describes the Pearson correlation results between alpha PSD and behavioral variables across the task blocks show that delta of SPA presents higher r coefficients at Cz and Pz, showing significant negative relation, r values from -0.259 to -0.600, $p>0.05$, starting at the third block. For the delta of SPD, the Pz presents the best correlation coefficients, r values from 0.46 to 0.57, showing significant positive associations, starting at the second block. The delta of SPA showed best r values, from -0.36 to -0.55, at Cz site, where a negative correlation for each block across the task. The delta of reaction time measures (TRT and NTRT) showed a positive correlation (more prominent at Cz and Pz) with alpha PSD, r values from 0.36 to 0.46, $p<0.01$ to the delta of TRT and r values from 0.42 to 0.62, $p<0.05$ for NTRT, both at Pz site. The simple linear regression with alpha PSD reactivity showed that alpha PSD data explains 19–36% of behavioral scores delta during the time-on-task effect (R^2 from 0.19 and 0.36 for $p<0.05$ models).

Discussion

This study reports that prolonged mental effort (60-min. of visual oddball task) impairs general behavioral performance (SPA, SPD, SPM, TRT, NTRT, and OE) and increases alpha PSD, causing similar effects of MF induction. The comparison of behavioral performance across the task blocks between groups LAG and HAG suggests that higher alpha reactivity at the first block is associated

Table 2 Comparison of behavioral performance between HA and LA groups across the task blocks

Variable	Alpha PSD at Fz			Alpha PSD at Cz			Alpha PSD at Pz		
	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)
Δ of SPA									
Second	− 1.00	− 1.00		− 1.10	− 0.9		− 0.88	− 1.10	
Block	± 1.80	± 1.76		± 1.83	1.72		± 1.96	± 1.5	
Third	− 2.11	− 2.60		− 1.77	− 2.90		− 1.66	− 3.00	
Block	± 1.34	± 1.34	3.75#	± 1.98	± 1.28	5.38*#	± 1.93	± 1.24	5.56*#
Fourth	− 2.72	− 3.5	(0.001)	− 2.38	− 3.80	(0.0001)	− 2.38	− 3.80	(0.00001)
Block	± 2.04	± 1.43		± 2.05	± 1.13		± 2.05	± 1.13	
Fifth	− 3.88	− 3.9		− 3.00	− 4.70		− 3.00	− 4.70	
Block	± 2.47	± 1.79		± 1.73	± 2.11		± 1.73	± 2.11	
Δ of SPD									
Second	0.88	0.80		0.66	1.00		0.55	1.10	
Block	± 1.36	± 1.22		± 1.32	± 1.24		± 1.42	± 1.10	
Third	1.11	2.11		0.77	2.40		1.00	2.20	
Block	± 1.76	± 1.37	2.33*#	± 1.64	± 1.17	5.73*#	± 1.80	± 1.22	3.60*#
Fourth	1.33	2.66	(0.03)	0.88	3.00	(0.00001)	1.11	2.80	(0.002)
Block	± 2.00	± 1.64		± 1.76	± 1.41		± 1.90	± 1.54	
Fifth	1.66	3.30		1.00	3.90		1.33	3.60	
Block	± 2.73	± 2.00		± 2.23	± 1.79		± 2.44	± 2.01	
Δ of SPM									
Second	− 0.88	− 1.00		− 0.55	− 1.3		− 0.77	− 1.10	
Block	± 1.53	± 1.33		± 1.33	± 1.41		± 1.39	± 1.44	
Third	− 1.77	− 1.90		− 1.22	− 2.40		− 1.22	− 2.40	
Block	± 1.64	± 1.66	3.23#	± 1.64	± 1.42	5.32*#	± 1.64	± 1.42	4.77*#
Fourth	− 2.77	− 3.00	(0.005)	− 1.88	− 3.80	(0.0001)	− 2.00	− 3.70	(0.0002)
Block	± 2.48	± 2.16		± 2.20	± 1.98		± 2.17	± 2.11	
Fifth	− 3.88	− 3.70		− 3.00	− 4.50		− 3.11	− 4.40	
Block	± 2.42	± 2.21		± 2.17	± 2.17		± 2.08	± 2.31	
Δ of TRT									
Second	3.00	15.70		6.55	12.50		3.33	15.40	
Block	± 31.80	± 15.54		± 32.94	± 15.57		± 27.60	± 21.71	
Third	6.22	26.60		6.55	26.30		8.33	24.70	
Block	± 26.36	± 34.10	2.00*	± 26.41	± 34.27	1.56*	± 29.99	± 32.54	2.54*
Fourth	5.44	36.40	(0.06)	5.88	36.00	(0.16)	1.55	39.90	(0.02)
Block	± 41.79	± 23.08		± 41.90	± 23.41		± 32.35	± 29.70	
Fifth	12.22	35.6		16.00	32.2		10.11	37.50	
Block	± 38.83	± 16.54		± 40.63	± 17.19		± 27.52	± 28.86	
Δ of NTRT									
Second	− 34.22	− 3.9		− 31.11	− 6.7		− 31.44	− 6.4	
Block	± 33.35	± 32.92		± 34.76	± 34.19		± 34.44	± 34.23	
Third	− 30.55	− 7.3		− 37.33	− 1.2		− 38.00	− 0.60	
Block	± 36.49	± 33.44	2.19*	± 34.68	± 28.81	3.19*	± 33.99	± 28.69	3.49*
Fourth	− 34.11	− 6.7	(0.04)	− 36.22	8.60	(0.005)	− 37.11	9.4	(0.003)
Block	± 39.58	± 27.34		± 38.87	± 24.82		± 37.81	± 24.64	
Fifth	− 37.00	− 16.40		− 42.66	− 11.30		− 43.33	− 10.7	
Block	± 45.16	± 28.59		± 46.50	± 20.33		± 45.72	± 20.85	
Δ of OE									
Second	0.66	1.40		2.22	3.60		1.11	1.00	

Table 2 (continued)

Variable	Alpha PSD at Fz			Alpha PSD at Cz			Alpha PSD at Pz		
	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)	LAG (n = 10) mean ± sd	HAG (n = 9) mean ± sd	*F* (*p*)
Block	± 1.80	± 2.50		± 1.78	± 5.10		± 2.31	± 2.16	
Third	3.44	7.40		3.44	4.50		4.00	6.90	
Block	± 4.33	± 7.91	2.76*#	± 2.29	± 4.69	1.89#	± 4.06	± 8.27	1.68#
Fourth	0.22	1.60	(0.01)	6.33	10.4	(0.08)	1.55	0.40	(0.12)
Block	± 2.10	± 3.97		± 4.94	± 12.79		± 3.12	± 3.37	
Fifth	1.22	6.50		2.88	4.80		3.77	4.20	
Block	± 3.63	± 8.88		± 2.08	± 4.21		± 3.92	± 9.56	
Δ of CE									
Second	0.11	− 0.10		0.11	− 0.10		0.11	− 0.10	
Block	± 2.08	± 1.10		± 2.08	± 1.10		± 2.08	± 1.10	
Third	0.00	− 0.60		0.00	− 0.60		0.00	− 0.60	
Block	± 2.00	± 0.84	0.19	± 2.00	± 0.84	0.21	± 2.00	± 0.84	1.14*
Fourth	0.55	0.30	(0.98)	0.66	0.20	(0.98)	1.66	− 0.70	(0.34)
Block	± 3.77	± 3.56		± 3.77	± 3.55		± 4.66	± 1.76	
Fifth	0.22	0.50		0.22	0.50		1.33	− 0.50	
Block	± 2.10	± 3.77		± 2.10	± 3.77		± 3.87	± 1.77	

SPA self-perception of attention, *SPD* self-perception of drowsiness, *SPM* self-perception of motivation, *TRT* target reaction time, *NTRT* non-target reaction time, *OE* omission errors, *CE* commission errors

The p values reported in table is related to complete model of repeated measures ANOVA

*$p < 0.05$ for "Group Effect"

#$p < 0.05$ for "Block Effect"

with more behavioral impairment across the task (SPA, SPD, SPM, TRT, NTRT, and OE). Simple linear regression shows that alpha PSD predicts 19 to 36% of the variation in the impairment of behavioral performance (SPA, SPM, SPD, TRT, and NTRT) across the task.

In accordance with the present results, previous studies have demonstrated that prolonged mental effort impairs general behavioral performance and increases alpha PSD (Boksem et al. 2005; Faber et al. 2012; Kato et al. 2009; Ting et al. 2008; Wascher et al. 2014; Zhao et al. 2012). The behavioral impairment observed in this study is consistent with the decreased accuracy that Wascher et al. (2014) reported after 4 h protocol to induce MF. Similarly to our experimental design, Kato et al. (2009) report that reaction times, premotor times, and motor times significantly increased with time on task after a 60-min of Go/NoGo task. Our study found a significant increase in errors at the last block that was not reported by Kato et al. (2009). This result can be explained by the fact that our task had a faster stimulus presentation and interval between stimuli, increasing task difficulty (greater error probability). So, probably the behavioral impairment observed in our last task block represents MF effects.

The increased alpha PSD after 60-min oddball task broadly supports the work of other studies in this area linking alpha PSD with the time-on-task effect (Boksem et al. 2005; Wascher et al. 2014; Zhao et al. 2012). Wascher et al. (2014) report that alpha PSD increases at the last block (after 4 h) compared to the first block and reaches maximal amplitude at 60-min. These results corroborate the findings of Zhao et al. (2012) that found an increase in alpha PSD after a continuous simulated driving task for 90-min. In the Go/NoGo experiment performed by Kato et al. (2009) there is no information about EEG spectral analysis. Our results support that the 60-min visual oddball task for MF induction increases alpha PSD. Kato et al. (2009) proposes that MF attenuates neural resource allocation for stimuli processing and delays evaluation latency producing slower reaction times. The increase of alpha PSD decreases regional cortical MRI signal at posterior and thalamic sites (Bazanova and Vernon 2014; Goldman et al. 2002), suggesting that cortical-thalamocortical feedback loop regulates alpha PSD (Hughes and Crunelli 2005; Schreckenberger et al. 2004). In addition, the administration of GABAergic receptor agonists decreases thalamic metabolism and alpha PSD (Schreckenberger et al. 2004). Thalamus synaptic network to cortical

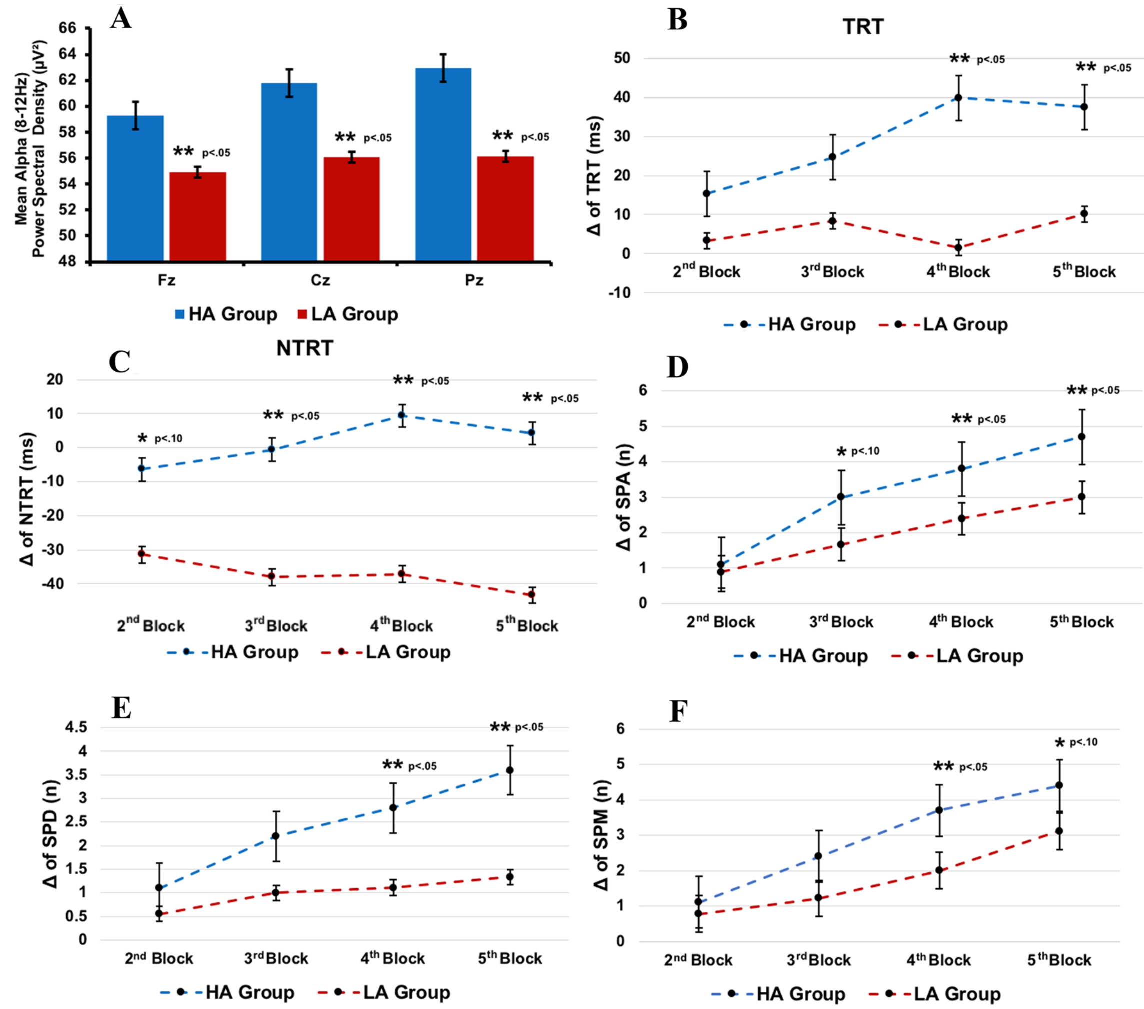

Fig. 2 The comparison between HAG and LAG alpha PSD (**a**) and the effect of early alpha reactivity (HAG versus LAG, at Pz site) on delta of TRT (**b**), NTRT (**c**), SPA (**d**), SPD (**e**) and SPM (**f**) across the task blocks. The single asterisk represents $p<0.10$ and the double $p<0.05$ for post-hoc "group" comparison (HA versus LA) on the task block. The error bars represent standard error for the respective mean values

areas are responsible for information processing implicating general cognitive performance (Fama and Sullivan 2015; Van Der Werf et al. 2001). Our results support the hypothesis of neural resource allocation (Kato et al. 2009), suggesting that cortical-thalamocortical feedback loop dysfunction is associated with the behavioral impairment of MF.

The relation between alpha PSD alpha and behavioral performance was noted in prior studies. Kirschfeld (2008), reports that alpha PSD suppression before stimuli presentation produces faster reaction times. Similarly, Melo et al. (2017a, b) show that greater alpha PSD at the resting state is correlated with slower reaction time during cognitive task. These results further support the idea of baseline alpha PSD could be associated to long-term behavioral performance. MF studies indicate that in the last task block occurs a simultaneous increase in alpha PSD and a decrease in behavioral performance (Borghini et al. 2014; Wascher et al. 2014; Zhao et al. 2012). So, these results suggest that alpha PSD can be a general indicator of behavioral performance in MF, but no data was found on early alpha reactivity to predict long-term MF behavioral impairments.

The comparison between groups LAG and HAG suggests that higher alpha reactivity at the first block is associated with more behavioral impairment across the task when compared to LAG. Behavioral performance and alpha PSD impair continuously along the task blocks in MF induction. So, the first block values can be considered an individual best overall performance on task. A possible explanation for this might be that alpha values will continuously increase across the task, the high alpha reactivity at the first block indicates that participants could be more influenced by the time-on-task effect, having a greater probability of long-term behavioral impairments. These results reflect those of Bazanova and Vernon

Table 3 Pearson correlation values and R^2 for simple linear regression analysis between first block alpha reactivity (at Fz, Cz and Pz) and delta of behavioral performance for each task block

Variable	Alpha PSD at Fz			Alpha PSD at Cz			Alpha PSD at Pz		
	r	R^2	*p*	*r*	R^2	*p*	*r*	R^2	*p*
Δ of SPA									
Second Block	0.067	0.004	0.78	0.010	0.001	0.96	− 0.244	0.059	0.31
Third Block	− 0.227	0.05	0.34	− 0.375	0.140	0.11	− 0.509*	0.259	0.02
Fourth Block	− 0.348	0.121	0.14	− 0.401	0.160	0.08	− 0.600*	0.361	0.006
Fifth Block	− 0.288	0.083	0.23	− 0.436	0.190	0.06	− 0.520*	0.271	0.02
Δ of SPD									
Second Block	0.179	0.032	0.46	0.045	0.002	0.85	0.462*	0.214	0.04
Third Block	0.160	0.025	0.51	0.360	0.130	0.12	0.558*	0.312	0.01
Fourth Block	0.255	0.065	0.29	0.256	0.127	0.13	0.576*	0.332	0.009
Fifth Block	0.260	0.067	0.28	0.478	0.229	0.03	0.508*	0.258	0.02
Δ of SPM									
Second Block	− 0.050	0.002	0.83	− 0.361	0.130	0.12	0.002	0.001	0.99
Third Block	− 0.147	0.021	0.54	− 0.443*	0.196	0.05	− 0.283	0.080	0.24
Fourth Block	− 0.351	0.123	0.14	− 0.664*	0.441	0.01	− 0.275	0.076	0.25
Fifth Block	− 0.228	0.052	0.34	− 0.556*	0.309	0.01	− 0.236	0.056	0.32
Δ of TRT									
Second Block	0.321	0.103	0.17	0.049	0.002	0.83	0.024	0.006	0.92
Third Block	0.173	0.030	0.47	0.130	0.017	0.59	0.178	0.031	0.46
Fourth Block	0.211	0.044	0.38	0.222	0.049	0.35	0.463*	0.214	0.04
Fifth Block	0.265	0.070	0.27	0.120	0.014	0.62	0.366	0.134	0.12
Δ of NTRT									
Second Block	0.502*	0.252	0.02	0.197	0.039	0.41	0.333	0.111	0.16
Third Block	0.352	0.124	0.13	0.464*	0.215	0.04	0.570*	0.324	0.01
Fourth Block	0.432	0.186	0.06	0.465*	0.216	0.04	0.623*	0.388	0.004
Fifth Block	0.268	0.072	0.26	0.358	0.128	0.13	0.426*	0.181	0.06
Δ of OE									
Second Block	0.142	0.037	0.56	0.019	0.004	0.93	0.259	0.067	0.28
Third Block	0.341	0.116	0.15	0.313	0.098	0.19	0.017	0.003	0.94
Fourth Block	0.084	0.007	0.72	0.190	0.036	0.43	0.152	0.023	0.53
Fifth Block	0.393	0.154	0.09	0.226	0.051	0.35	0.076	0.005	0.75

Table 3 (continued)

Variable	Alpha PSD at Fz			Alpha PSD at Cz			Alpha PSD at Pz		
	r	R^2	*p*	*r*	R^2	*p*	*r*	R^2	*p*
Δ of CE									
Second Block	0.083	0.006	0.73	0.151	0.023	0.53	0.214	0.046	0.27
Third Block	0.250	0.062	0.30	0.335	0.112	0.16	0.061	0.003	0.80
Fourth Block	0.049	0.002	0.84	0.175	0.030	0.47	0.183	0.033	0.45
Fifth Block	0.031	0.001	0.89	0.094	0.008	0.70	0.106	0.011	0.66

SPA self-perception of attention, *SPD* self-perception of drowsiness, *SPM* self-perception of motivation, *TRT* target reaction time, *NTRT* non-target reaction time, *OE* omission errors, *CE* comission errors

*$p < 0.05$

(2014) who also suggest that the alpha PSD reflects an idling state of cortical areas in terms of cognition. Also, our results suggest that early alpha reactivity to mental effort could provide insights about the long-term behavioral performance during higher mental workload.

Important to note, our sample was composed of healthy young college students. Age is an important covariate of alpha activity. Future studies should investigate the effect of age groups on alpha PSD during MF induction, especially in older adults that compose a most generalizable workers group. Probably, adding the age and other clinical and sociodemographic variables in the linear regressions models we should observe higher predictive values. In future investigations, it might be possible to use a more realistic paradigm to bring the experimental setting closer to a real workplace routine (i.e., simulators) and to verify that alpha PSD is associated with long-term impairments of more complex tasks. The association between early EEG measures with long-term effects of MF provides insights into the development of functional performance diagnostic methods based on electrophysiological biomarkers. For example, the early assessment of MF risk factors associated with workplace accidents contributes to mental workload redistribution strategies according to daily mental state. The present study encourages the use of EEG for the development of technologies for MF assessment because EEG is low-cost electrophysiological equipment (in comparison to other brain imaging methods), the existence of wireless data transmission (in some sample rates), and electrodes can be coupled to embedded systems on several workplaces (i.e., hardhat or headbands). In general, our study supports that MF monitoring by EEG biomarkers, such as alpha PSD, can be a suitable tool for the development of technologies to improve safeness in high-risk workplaces (i.e., aircraft pilots or operators).

Conclusion

This study has shown that 60-min of the visual oddball task impairs general behavioral performance, self-report data and increases alpha PSD, inducing similar experience of MF in participants. The other major finding was that higher alpha PSD reactivity to the first task block is associated with greater long-term behavioral impairments on the visual oddball task. A simple linear regression between alpha PSD reactivity and behavioral performance across the task suggests that alpha is correlated with 19 to 39% of general behavior impairment induced by MF. This work contributes to existing knowledge of MF by providing evidence that investigating early electrophysiological biomarkers can predict long-term MF impairments. Although the young health sample, this work offers valuable insights into MF research, but the results are not easily generalized to the real workplace. Further studies need to validate the alpha PSD long-term prediction of behavioral impairment on more complex tasks.

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Author Contributions Study conception and design: HMM, LMN. Acquisition of data: HMM, LMN, Analysis and interpretation of data: HMM, LMN, AAH, RW, ET. Drafting of manuscript: HMM, LMN, AAH, RW, ET. Critical revision: HMM, LMN, AAH, RW, ET.

Compliance with Ethical Standards

Conflict of interest The authors have no conflict of interest, source of funding or financial ties to disclose and no current or past relationship with companies or manufacturers who could benefit from the results of the present study.

Ethical Approval This research was approved by the local ethics committee (*Comitê de Ética e Pesquisa com Seres Humanos da UFSC—CEPSH*), which can be checked by CAAE: 44053615.4.0000.0121. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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