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Original investigations/commentaries

Effects of an *n*-back task on indicators of perceived cognitive fatigue and fatigability in healthy adults

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Abstract. Fatigue is a multidimensional concept with diverse physical and mental determinants. The aims of the present study are: to know the efficacy of a high attentional demand test to induce acute cognitive fatigue (ACF) and to document its effects on perceived cognitive fatigue (PCF - subjective symptoms) and fatigability (F- resting heart rate and eye blinks). A quasi-experimental repeated measures design with two non-equivalent groups was used (experimental G1, n= 16, age M = 33.50 years, SD = 6.94; control G2 n= 13; age M = 38.77, SD = 5.90). Participants were exposed to a cognitive deficit induction test (n-back test, G1) or exposure to a content-neutral video (SML, G2). ACF indices were assessed using a reverse digit retention test. The findings suggest a decline in cognitive performance post-experimental manipulation comparable to the neutral group, evidenced by a lower number of hits and longer response time for a digit retention test, suggesting the effectiveness of the n-back test as a method to induce acute cognitive fatigue. The post-performance effects of the n-back task were associated with statistically significant changes in all PCF assessments. These changes turned out to be non-significant for physiological aspects of fatigability. Implications for the operational feasibility of employing PCF measurements in the short-term assessment of acute mental fatigue are discussed.

Keywords: Cognitive fatigue, fatigability, resting-state heart rate, eye-blinks, flickering, n-back test, cognitive restoration.

Introduction

Fatigue is usually defined as a set of unpleasant cognitive, emotional and physical symptoms associated with fatigue not resolved by daily strategies of restoring psychophysiological resources (Mota & Pimienta, 2006). Fatigue proneness is a common problem nowadays in 24 hrs / 7 days society (Harrington, 2012). Approximately 5-9 % of the population experiences fatigue with a duration of at least 6 months (Pawlikowska et al., 1994). Its prevalence in different sectors varies from 4-45 % (Galland-Decker et al., 2019) with a higher recurrence in women than in men (female/male ratio 4:1) (Afari & Buchwald, 2003). It is characterized in terms of its duration as recent (< 1 month), prolonged (1-6 months) and chronic (> 6 months) (Cornuz et al., 2006). Depending on its duration and intensity, it can become a problem with adverse consequences on quality of life and work productivity (Lange et al., 2005). Its impact translates into some functional limitations (Avlund et al., 2003a), disability (Avlund et al., 2003b) and mortality (Moreh et al., 2010).

Fatigue is a multidimensional concept with diverse physical and mental determinants. There is a wide diversity of field studies in specific populations (Bültmann et al., 2002; David et al., 1990; Fuhrer & Wessely, 1995), is less studied in the general population and little explored its determinants (Galland-Decker et al., 2019).

The present study focuses on one of the components of fatigue: acute mental fatigue, which comprises a phenomenon associated with mental performance arising from sustained cognitive processing tasks (van der Linden, 2011). In this article, the concept of acute mental fatigue will be used interchangeably with the concepts of mental fatigue, cognitive fatigue, and/or acute cognitive fatigue (Bafna et al., 2021).

Cognitive fatigue takes into account the wear and tear of the attentional state associated with subjective states (subjective fatigue or FCP) or objective states (fatigability) that are due to a gradual and cumulative modification of a state of psychophysiological deficit resulting from the prolonged execution of tasks demanding sustained attention (DeLuca, 2005). This definition contemplates the complexity of acute mental fatigue, incorporating behavioral and perceptual aspects and physiological manifestations during and after a demanding cognitive activity (Mitchell et al., 2019).

This acute form of mental fatigue is distinguished from other chronic forms of fatigue or cognitive impairment associated with age and illness (van der Linden, 2011). PCF comprises those subjective feelings of tiredness, lack of energy, desire for rest, and reduced motivation that people may experience after or during prolonged periods of tedious or sustained attention-demanding cognitive activity (Hopstaken et al., 2015).

This condition is conceived as a feeling of extreme tiredness that is accompanied by an aversion to continuing with the task and a decrease in the level of engagement (Boksem, 2008). On the other hand, fatigability contemplates a series of physical and behavioral indicators related to cognitive fatigue, which in turn evidence a decrease in the levels of sustained attention and working memory (Faber et al. 2012). PCF, fatigability and physiological correlates are aspects of interest to be evaluated in the present study.

Experimental techniques of cognitive deficit induction (e.g., acute mental fatigue) are of interest to understand the determinants of mental fatigue and the promotion of strategies to optimize the psychological restoration of fatigue in healthy populations (Martínez-Soto & Gonzales-Santos, 2020). Under laboratory conditions, acute mental fatigue is induced by specific cognitive tasks. Among these those types are psychomotor vigilance (Dinges & Powell, 1985), continuous performance (Pageaux et al., 2015), visual search (Kong & Fougnie, 2019), digit transformation (Kahneman et al., 1969), decision-making tasks (Otani et al., 2017) and Stroop test (MacLeod & MacDonald, 2000). One of the most widely used tests for mental fatigue induction is the n-back test, (Chen et al., 2015; Tanaka et al., 2009), which is a test of high attentional demand, sustained attention, working memory and response inhibition (Li et al., 2020; Pageaux et al., 2013).

The n-back test consists of participants deciding whether a stimulus was previously presented under certain conditions. It can be manipulated as a function of workload by controlling the presentation of the current stimuli and the addition of previous stimuli (e.g., n-back with 1 stimulus load, or n-back = 2 or 3, in which case the stimulus is defined by any other stimulus that is identical to that presented two or three trials ago, respectively). According to Baddley (1986), such a test is not affected by learning or order effects.

Several investigations have accounted for the effects of the n-back test on mental fatigue induction and its effects on PCF and fatigability (by assessing the gold standard of mental fatigue assessment, i.e., assessment of cognitive task performance indicators; Guifang et al., 2017; Pergher et al., 2019; Tommasin et al., 2020; Watanabe et al., 2019).

The cognitive effects of deficit induction that account for a process resulting from acute cognitive fatigue include a decline in performance quality over time (e.g., error proneness, decreased number of successes, and increased reaction times; Petrut et al., 2020) that is evidenced by a reduced ability of the individual to respond effectively to various tasks (Cohen & Cohen, 1993). Other cognitive effects involved include a reduction in working memory, decreased ability to focus attention, vigilance and selective attention, as well as lapses in information processing (Faber et al., 2012).

In terms of PCF, the emotional effects of n-back testing on cognitive performance have been assessed using affective valence and its relationship to performance ratings, with more errors in test successes associated with negative valence and complex difficulty levels (Kopf et al., 2013). High vs. low levels of activation are associated with difficulties in n-back test performance (Han et al., 2013). Also, subjective states of fatigue that may exist even before attempting a task are denoted (Cohen and Cohen, 1993). Referring to the physiological components of fatigability, some physiological indicators evidence that an increase in heart rate is associated with cognitive processing that requires effort (Chung et al., 2007; Fallahi et al., 2016), which is congruent with the fact that cognitive processing, by requiring effort, is linked to cardiovascular autonomic regulation physiology (Turner & Carroll, 1985).

In addition to heart rate, fatigue-related mental overload or strain can be studied by eye movements associated with eye blinks (Takahashi et al., 1994). Eye blinks are modulated by external cognitive demands (Bristow et al., 2005). It has been suggested that levels of alertness and directed attention increase the levels of interblink intervals (Ryu & Myung, 2005). Blink frequency (the number of blinks per minute), has been employed as an index of cognitive processing information (Wascher et al., 2015). Other indicators include blink duration and blink rate (Horiuchi et al., 2018). A wider flicker frequency interval reflects greater attention agreed upon by subjects for a more difficult task (Ryu & Myung, 2005).

In general, the effects of fatigue on blinks are dependent on the type of visual task (simple, difficult) and task duration time. Fatigue induction tests report higher flicker frequency associated with the presentation of complex cognitive tasks (Horiuchi et al., 2018). High levels of flicker suppression have also been observed in cognitively overloaded tasks compared to those of low overload (e.g., Siegle et al., 2008; Van Orden et al., 2000). Some studies suggest that blink frequency may decrease during cognitive task presentation and increase after cognitive task presentation (Oh et al., 2012). Overall little is known about the effects of n-back concerning eye movements associated with blinks.

Alluding to the multidimensional nature, physical and mental variants in the systematic study of cognitive fatigue (Ackerman, 2011) and the contemporary relevance of documenting the psychophysiological determinants of the phenomenon of acute mental fatigue in the healthy population, in the present study we aimed to: a) learn about the efficacy of a high attentional demand test as a method of inducing acute cognitive fatigue and b) document the effects of such a test on indicators of PCF and fatigability.

The efficacy of an attentional stress test was established by applying the n back = 3 test, whose effects related to a cognitive deficit (acute mental fatigue) were analyzed in terms of reaction times and hits in a digit retention test. As fatigability variables, self-reports associated with the subjective perception of fatigue were considered. Other fatigue-related emotional constructs (emotional valence and arousal reactions; Ackerman, 2011) were also taken into account. The fatigability variables incorporated the effects of prolonged n-back test performance on physiological indicators: resting-state heart rate (resting-state HR hereafter) and blink frequency.

Overall, significant effects on FCP and F indicators associated with a deficit induction method are expected. Specifically, it is hypothesized that a high attentional demand task will induce greater acute mental fatigue (FCP and F components) compared to a control condition.

Design

A quasi-experimental repeated measures design with two non-equivalent groups (G1 = experimental group vs. G2 = control group) was used.

Method

Participants

Of a total of 38 people who agreed to participate, 29 adult males (age range 25-45 years; M = 36; SD = 6. 91) met the inclusion criteria (being physically and mentally healthy, being between 25 and 45 years old, having a normal or adjusted vision) and exclusion criteria (suffering from physical or mental illnesses diagnosed at the time of the study, sleep problems, some type of ocular disease, presenting any vital crisis that could modify their normal state, being under controlled pharmacological treatment and/or use of psychoactive substances that could influence the cognitive tasks of execution entrusted (Ackerman, 2011). Assignment to the experimental (G1 n= 16; age M = 33.50 years, SD = 6.94) and control (G2 n= 13; age M = 38.77, SD = 5.90) groups was randomized. The experimental protocol was approved by the State Bioethics Commission of the state of Nayarit (CEBN/05/2020).

Stimuli

Experimental treatment of cognitive fatigue induction

N-back test. A 43-min computerized version of the n-back continuous performance test with loads 0 to 3 was used. A review of the psychometric properties of the n-back test can be read in Gajewski et al. (2018). The advantages of using such versions contemplate (a) the possibility of parametric variation in task difficulty, (b) multimodal presentation, and (c) accurate measurement of performance characteristics (Jacola, et al. 2014). The computerized n-back test was designed at the Institute of Neurobiology at UNAM by one of the co-authors of the present article (LG-S). The electronic version was implemented in PsychoPy (Peirce & Macaskill, 2018).

Control treatment

The treatment involved watching a 43-minute documentary video "The Secret of the Mona Lisa" SML (Deutsche Welle, 2020). This video tells the story of the origin of Leonardo Da Vinci's paintings. The documentary was selected for having interesting content capable of maintaining neutral mood states as identified in a previous pilot study reported in Argüero et al. (2021). Previous studies in the area have employed passive (Marcora et al., 2009) or active (Pageaux et al., 2015) control treatments for baseline comparisons. Due to the variety of intervention conditions, in the present study, G2 was identified as the passive control group.

Subjective evaluations

Subjective fatigue

Subjective fatigue was assessed before and after the control and experimental group treatment periods. Assessments of PCF are approached from different forms and assessment strategies. In the present study, a multidimensional measurement of PCF comprised within the Subjective Symptoms of Fatigue Test (PSSF; Yoshitake, 2007) was used. The PSSF is a dichotomous (yes-no response) questionnaire of 30 items and three dimensions: dullness (10 items; e.g., "Feeling heaviness in the head"), difficulty concentrating (10 items; e.g., "Feeling difficulty paying attention"), and physical impairment (10 items; e.g., "Feeling headache"). Barrientos-Gutierrez et al. (2004) report an internal consistency index for the scale in the Mexican population of .89 for the overall test. To assess the magnitude of fatigue, the classification applied for each 10-item dimension was used, where 0 to 5 affirmative responses indicate no fatigue (coded as 0), 6 that it is mild (coded as 1), 7 to 8 that it is moderate (coded as 2) and 9 to 10 that it is intense (coded as 3).

Valencia and activation

Emotion dimensions were assessed using the Self-Assessment Manikin (SAM; Bradley & Lang, 1994). SAM consists of a pictorial assessment that employs sequences of humanoid-like cartoons that are graded in terms of intensity representing three bipolar affective dimensions: valence, arousal, and dominance. In the SAM scale, each subscale is represented by five graphic figures, with four intermediate points so that a nine-point scale is configured.

Affective valence, pleasure, and hedonism (SAM-Val), ranges from a smiling figure (highest score, 9) to an unhappy one (lowest score, 1). Activation or arousal (SAM-Act) ranges from a wide-eyed figure (highest score, 9) to a very relaxed one (lowest score, 1). The reliability of the SAM in the Mexican population shows high internal consistency indices >.90 (Martínez Soto et al., 2014). Some research has questioned the relevance of the dominance dimension to explaining people's affective self-evaluations (Russell et al., 1981), and for this reason, this dimension is not taken into account in the present study.

Acute cognitive fatigue assessment

t was assessed with a computerized version of the Reverse Digit Retention (RDI) test of the Wechsler Adult Intelligence Scale (WAIS-IV, Wechsler, 2008). That version was implemented with PsychoPy software (Peirce & Macaskill, 2018) at the Institute of Neurobiology of the UNAM by one of the co-authors of the present article (LG-S). The test consists of participants repeating increasing lengths of digit sequences in reverse order until they make two consecutive failures.

Such computerized versions have been applied in recent studies to assess attention span, short-term memory, and working memory (Li et al., 2016; Moller et al., 2014). Such a test records reaction times (amount of time elapsed between a stimulus and the response offered accordingly; Wechsler et al., 2008) and item recording hits. The number of hits refers to the number of correct responses of a person on a cognitive task, operationally it involves evaluating the number of correct responses on the reverse digit retention subtest, which can range from 0 to 14 (Wechsler et al., 2008).

Physiological evaluations

Eye Blinks (Flickering)

For flicker frequency, the NeuroSky Mind Wave headband was employed (Vivar et al. 2017) which is a single-channel EEG device. Given its accessibility and efficacy, the use of this type of EEG recording device has recently been documented in research on physiological stress (Umar et al., 2018) and attention (Sałabun, 2014). The device provides a single channel of EEG recording from an electrode placed in the frontal part (FP1 of the brain). The data are interpreted through eSense ™ which is NeuroSky's proprietary algorithm for characterizing EEG responses. To calculate eSense™, NeuroSky ThinkGear technology amplifies the direct brainwave signal, and eliminates ambient noise and muscle movement. NeuroSky's MindWave enables biometric recording of flicker frequency. A description of the processing and extraction procedures of eye recordings is described in Abo-Zahhad, et al. (2015). Operationally, flicker assessment refers to frequencies in ranges above 30 Hz (Gamma) that evidence brain electrical activity resulting from the movement of opening and closing the eyes when blinking (Abo-Zahhad et al., 2015).

HR at rest

It was captured using a device with photoplethysmography (FPG) sensors. Some research has evidenced that the efficacy of this type of device in recording resting state HR can be similar to that of other standard electrocardiographic monitoring methods (Perez et al., 2019; Shcherbina et al., 2017; Wallen et al., 2016). In the present study, a heart rate sensor, contained in a Finger Pulse Oximeter with OLED Display, Digital RR Respiration Rate Monitor and PR Heart Rate was employed. The resting state HR is defined as the number of consecutive heartbeats a person has in one minute (normal results 70 and 100 beats per minute), during periods of physical inactivity (Collins et al., 1991). It was evaluated using the interbeat intervals derived from the FPG sensor (Quer et al., 2020).

Procedure

Experimental G1 and control G2 treatments were conducted in a room with dimmed lighting and sound attenuation using the same computer and physiological recording devices. Participants were summoned through a social network. With the acceptance to participate, they were contacted to agree on the date and time of the application of the experiment, which was performed individually. Before the day of the intervention, written instructions were provided to sleep at least 8 hr. before the day of the evaluation, avoid cognitively demanding activities during the day of the test, and avoid consuming alcohol for 24 hr. and caffeine at least 12 hr. before the day of the evaluation (Craig et al., 2012).

In each session, the experimenter provided general instructions on the procedure to be followed (familiarization and test requirements, as well as brief explanations of the activities for the assessment of physiological measures). Before starting the intervention, each participant remained at rest for 10 minutes. Subsequently, the participants were placed at a standard distance of 60 cm in front of a 15-inch, high-resolution (900 x 400 pixels) flat screen monitor. Afterward, the FPG sensor, the Mindwave Neurosky headband and the basal recording of resting HR and the electroencephalographic recording of brain activity associated with flicker frequency were placed on the monitor. On par with the above measurements, for both experimental G1 and control G2 interventions, the performance components associated with acute cognitive fatigue (digit retention) and FCP (subjective fatigue symptoms test, valence and activation) were counterbalanced before and after at regular intervals following 43 minutes of cognitive (e.g., n-back) or control treatment (content-neutral video) tasks. Figure 1 illustrates the experimental scheme of the study.

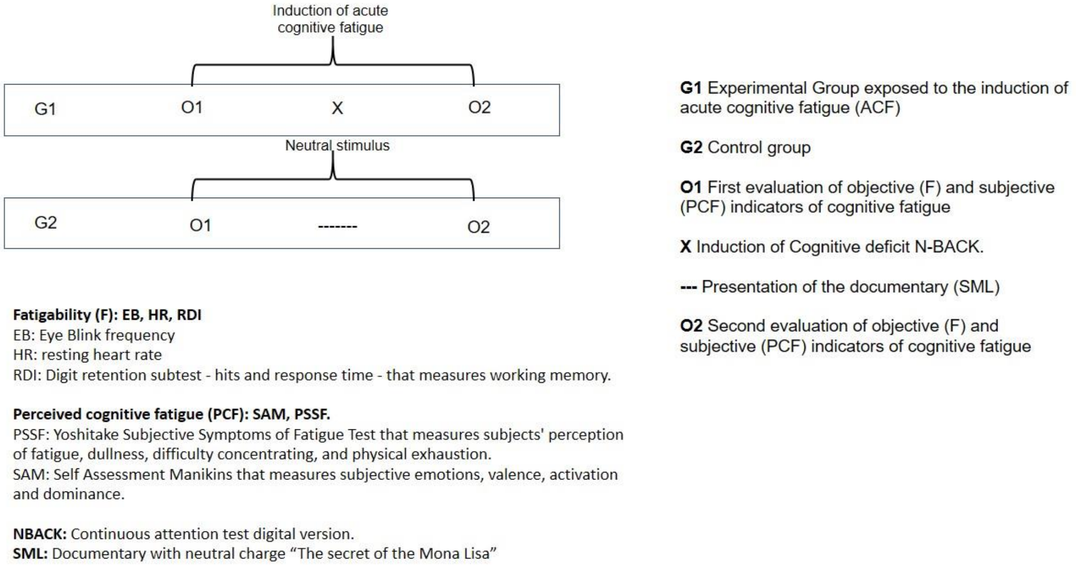

Figure 1. Experimental design of the acute cognitive fatigue induction protocol.

All individual intervention sessions (experimental G1 and control G2) were conducted in randomized order, considering three weeks. To avoid the effects of the daytime schedule (e.g., circadian rhythms) on cognitive fatigue (Smith et al., 2019) the sessions were conducted at the same time (between 4 and 6 p.m.).

Data analysis

Descriptive statistical analyses were performed to determine means and standard deviations. To evaluate the normality of the dependent variables, the Shapiro-Wilk test was used (considering that there were less than 50 observations). This test confirmed the absence of such a distribution, so the analyses were performed using nonparametric tests. Next, employing the Wilcoxon test, the intragroup scores were compared between the pretest and posttest. Additionally, through a set of Mann-Whitney U tests, intergroup pretests and posttests were compared. Finally, the effect size was calculated with Rosenthal's r. The accepted significance value was established. The accepted significance value was set at p<.05.

Results

Table 1 presents the means and standard deviations of both the experimental G1 and control G2. As can be seen, the nonparametric Mann-Whitney U independent measures test demonstrates the initial equivalence of the experimental group for the neutral group in terms of pretest measurements, indicating that these groups were comparable for the psychophysiological aspects of fatigue before starting the intervention. The effectiveness of the mental fatigue manipulation on FCP and fatigability indices is observed in the post-test measurements. When contrasting post measurements, significant differences were found in variables with effect sizes between medium and large, except for resting-state HR (Z=-.901, p=.368, r=.17) and blink frequency (Z=-.820; p=.412, r=.15) (see Table 1).

Table 1. Descriptive and inferential data for measures related to cognitive fatigue and PCF.

	T_1 (Pre-test)					T_2 (Post-test)				
	G_1	G_2				G_1	G_2			
Variable	*M (DE)* *Mediana*	*M (DE)* *Mediana*	*Z*	*p*	*r*	*M (DE)* *Mediana*	*M (DE)* *Mediana*	*Z*	*p*	*r*
HR at rest *Min*=70; *Max*=102	84.56 (9.50) 84.00	84.54 (10.38) 81.00	-.06	.94	.01	81.31 (8.70) 80.00	84.08 (8.91) 80.00	-.90	.36	.17
EB Flickering[a] *Min*=1; *Max*=3	1.56 (.72) 1.00	1.53 (.51) 2.00	-.17	.86	.03	1.43 (.62) 1.00	1.61 (.65) 2.00	-.82	.41	.15
RDI Hits *Min*=4; *Max*=9	7.25 (1.23) 7.00	7.31 (1.18) 7.00	-.15	.87	.03	4.88 (.88) 5.00	7.15 (1.06) 7.00	-4.18	.00	.78
RDI Time Min=4.20; M*ax*=12.08	6.14 (1.79) 5.88	6.06 (1.36) 6.00	-.08	.93	.02	7.49 (1.22) 7.15	5.85 (1.14) 5.61	-3.15	.00	.59
Valence *Min*=0; *Max*=3	1.69 (.79) 2.00	1.62 (.76) 2.00	-.21	.82	.04	.63 (.61) 1.00	1.69 (.75) 2.00	-3.37	.00	.63
Activation *Min*=0; *Max*=3	1.44 (.89) 2.00	1.46 (.87) 2.00	-.16	.87	.03	.38 (.50) .00	1.54 (.51) 2.00	-4.03	.00	.75
Blunting[b] *Min*=0; *Max*=3	1.06 (.44) 1.00	1.00 (.70) 1.00	-.26	.78	.05	2.06 (.57) 2.00	1.08 (.76) 1.00	-3.25	.00	.60
Difficulties[c] concentration *Min*=0; *Max*=3	1.06 (.92) 1.00	.92 (.64) 1.00	-.30	.75	.06	1.94 (.77) 2.00	1.23 (.92) 1.00	-2.16	.03	.40
Physical exhaustion[d] *Min*=0; *Max*=3	.63 (.71) .50	.69 (.63) 1.00	-.38	.69	.07	1.88 (.61) 2.00	.77 (.59) 1.00	-3.70	.00	.69

Note: G1 = Experimental group; G2 = Control group. a blinks per second; b,c,d mean scores of 0 indicate absence of any subjective symptomatology of fatigue, 1= mild symptomatology, 2= moderate, 3= intense symptomatology

To identify the differences between the groups concerning PCF and F, a Wilcoxon rank test was performed, where it could be observed that in the control G2 there were no differences, while in the experimental G1, the comparisons were significant and with effect sizes between medium and large except for flicker (Z= -.816, p=.414, r=.14). Table 2 shows these findings.

Table 2. Summary of Wilcoxon signed rank test for between-group comparisons

Variable	G1			G2		
	Z	*p*	*r*	*Z*	*p*	*r*
Heart rate	-2.45[b]	.01	.43	-1.29[c]	.19	.25
RC Blinks	-.81[b]	.41	.14	-.33[c]	.73	.07
RDI Hits	-3.54[b]	.00	.63	-.64[b]	.51	.13

RDI Time	-2.68^{c}	.00	.48	-1.01^{b}	.31	.20
Valencia	-3.15^{b}	.00	.56	$-.30^{c}$	.76	.06
Activation	-2.85^{b}	.00	.51	$-.26^{c}$	.79	.05
Dullness	-3.17^{c}	.00	.56	$-.57^{c}$	.56	.11
Concentration difficulties	-2.55^{c}	.01	.45	$-.96^{c}$	.33	.19
Physical wear and tear	-2.98^{c}	.00	.53	$-.26^{c}$	.79	.05

Note: G1 = Experimental group; G2 = Control group.

Discussion

The objectives of the present study were: a) to determine the efficacy of a test of high attentional demand as a method of inducing acute cognitive fatigue and b) to document the effects of such a test on indicators of PCF (subjective perception of fatigue, valence, and affective activation) and fatigability (physiological measurements of heart rate and flicker). It was hypothesized that compared to a control condition, the post-intervention effects of a high attentional demand task would produce statistically significant changes in indicators of PCF and fatigability.

Acute cognitive fatigue comprises attentional attrition associated with subjective and behavioral states related to a gradual, temporary and cumulative modification of a psychophysiological deficit linked to the prolonged execution of sustained attention demanding tasks.

This study proposed the implementation of a cognitive deficit induction method based on a sustained attention test (Sarter et al., 2001). As an acute mental fatigue induction technique, the n-back =3 test was employed, which is a high attentional demand test used to induce acute cognitive fatigue (Guifang et al., 2017; Pergher et al., 2019; Tommasin et al., 2020; Watanabe et al., 2019). With cognitive performance in cognitive tasks being "the gold standard" in the assessment of mental fatigue (Smith et al., 2019), the data yielded in the present study suggest a decline in cognitive performance post experimental manipulation comparable to a neutral group, evidenced by a lower number of hits and longer response time for a digit retention test (Table 1), accounting for the effectiveness of the n-back test as a method to induce acute cognitive fatigue (Petrut et al., 2020).

The above is congruent with previous research denoting increases in response times, errors in item hit, or both, as a result of increased cognitive task duration times (Boksem et al., 2005; Lorist et al., 2005).

Regarding the hypothesis statement of the research, the main finding of the present study refers that, compared to a control group, the 43-min post-performance effects of a high attentional demand task are associated with statistically significant changes in all FCP assessments (valence, arousal, blunting, concentration difficulties, and physical attrition). However, these changes turned out to be non-significant for the physiological aspects of fatigability: resting-state HR and blinks.

PCF refers to the individual experience associated with the depletion of mental energy; operationally, it is usually evaluated in terms of indicators of mental exhaustion, bodily discomfort, feeling of concentration difficulties and negative affect, among others (Kanfer, 2011). In congruence with the above, the results of the present investigation refer to a significant increase in the subjective symptoms of fatigue: dullness, difficulty concentrating and physical deterioration associated with the cognitive influences of the induction of cognitive fatigue (moderate effects according to the classification of Barrientos-Gutierrez et al., 2004), which coincides with previous research (Cohen and Cohen, 1993; Kanfer, 2011).

Likewise, such influences were documented in the affective aspects of valence and activation, with an affective response tending to be negative and with low levels of activation post-fatigue induction. The significant increase in negative valence levels is consistent with related research (Kopf et al., 2013). On the other hand, the low activation levels differ from that documented in other research where increases in activation levels are observed to be associated with greater performance difficulties during n-back tasks (Han et al., 2013). Given that the present study analyzes post-execution influences of n-back, a decrease in activation levels may be associated with residual effects of task fatigue (Matuz et al., 2021).

As can be seen in the present study, subjective fatigue assessments, or FCP measurements, can detect fatigue even when other types of objective indicators become impractical to implement (Christodoulou, 2005). Given that PCF precedes any decrement in cognitive performance (Kanfer, 2011), the above findings suggest the relevance of employing subjective measures of fatigue as appropriate methods of assessment when conservative indicators of mental fatigue are required.

Concerning physiological indicators of fatigability, cognitive influences of acute mental fatigue promoted by n-back were not found to be robust enough to confirm a significant difference in the aspects of fatigability namely resting state HR and blink frequency.

Several investigations have suggested a link between the physiology of cardiovascular autonomic regulation with cognitive processing, pointing to increased heart rate activity derived from the execution of tasks requiring mental effort (Chung et al., 2007; Fallahi et al., 2016). In the present study, a short-term index of cardiovascular autonomic activity such as resting-state HR was used. Such biomarker contemplates vagal control during that condition (Blons et al., 2019).

A connection between the function of vagal control and cognitive processes (Thayer & Lane, 2009) has shown mixed results associated with an acute phase response to cognitive tasks, either with an increased vagal response, thereby suggesting better attentional control (Blons et al., 2019) or a less active vagal response (Gianaros et al., 2004). According to Park et al. (2014), such responses may be modulated by context (e.g., how stressful the task is).

For the present study, the results denote that resting-state HR is not affected by a cognitive overload n-back 3 task, which is partly in agreement with other research (Penna et al., 2018). In the interest of contrasting the present findings, future research could incorporate different indices related to the assessment of long-term autonomic cardiovascular nervous autonomic activity (Lee et al., 2021).

Eye blinks have both physiological and cognitive functions. Cognitive function is related to attentional states and is significantly altered with fatigue states of the individual or by performing tasks that require a heavy cognitive load (Tapia, 2015). In this study, the recording of blink frequency was used as evidence of attentional overload associated with fatigue, and no statistically significant differences were found in the experimental vs. control condition in the pre-and post-test measures.

There are three types of blinks according to the degree of control the subject has over them: spontaneous, voluntary and reflex. The first ones occur regularly without the need for the presentation of any stimulus. Voluntary blinks are those executed by people consciously. The reflexes are those elicited by external stimuli, e.g., lighting (Espinoza et al., 2020). In the same way, there are different techniques employed for their recording (Espinosa et al., 2018; Roy et al., 2014; VanderWerf et al., 2003). Electrophysiological recordings of blinks, such as those reported in the present study, tend to report reflex blinks (Roy et al., 2014), while those of the spontaneous and voluntary types have been related to cognitive information processing (Eckstein, et al., 2017).

For the above, it could be considered that the findings found could have been due to a lack of attention to the registration of blinks sensitively related to cognitive information processing (Jongkees & Colzato, 2016). The above implies considering further methodological and technical robustness for its evaluation and processing in future research with cognitive deficit induction paradigms.

Conclusion

The findings demonstrated that the proposed protocol is effective in inducing acute cognitive fatigue. However, this situation is evidenced mainly in the PCF indicators, since most of the fatigability items showed inconsistencies, either because they did not show a significant difference between pre- and post-n-back measurements or because they were not sufficiently different to tie with a stimulus-neutral control group. In this sense, it would be worth considering the possibility of eliminating fatigability variables that have a small effect and a high operational complexity.

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