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RESEARCH ARTICLE

Measuring mental workload and heart rate variability of officers during different navigation conditions

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ABSTRACT

Mental workload (MWL) has a negative effect on the functional states of watchkeeping officers that ultimately causes collisions and groundings at sea. The aim of this study is to measure the MWL of officers during different navigation conditions. This study was conducted in a bridge simulator with 11 participants. Heart rate variability (HRV) measurements were taken during the 4 steps which have different difficulty levels and subjective assessments were taken at the end of each step by using NASA-TLX. The results of the measurements showed that different levels of navigation tasks caused significantly different levels of MWL and HRV values and MWL and HRV increased when task difficulty increased. Additionally, the correlation between MWL perceived by the participants and the heart rate variability values of the participants was found statistically significant. This study provides an example of predicting MWL for routine navigation operations by using physiological measures in maritime transportation.

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Introduction

While human error is the primary contributor of accidents where about 85% of all accidents were caused by human error (Kurt et al., 2016), it was stated that 16% of collisions, 30% of groundings were related to mental workload (MWL) of watchkeeping officers (Akhtar & Utne, 2015) in furtherance the determination that technology and automation have reduced the number of crew and increased the workload of officers (Louie & Doolen, 2007; Grech et al., 2008). This indicates that human element related issues will continue to be one of the major issues in marine transportation assets.

The workload is defined simplistically as a demand placed upon humans. Demand is specified by the aim of task performance. Therefore, the workload is the effect of demand on the individual in terms of stages used in energetics and information processing. More specifically, the workload is the amount of information processing capacity used for task

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performance (De Waard, 1996). Kahneman (1973) argued that in the cognitive system, difficult and complex tasks increase arousal levels, providing additional resources to cope with these tasks. In the light of this information, MWL can be monitored with the aid of physiological data collection in terms of autonomic nervous system activation. Kahneman (1973)'s approach, in terms of being measurable, was not considered sufficient alone but has been adopted by other researchers (De Waard, 1996; Young & Stanton, 2002).

MWL causes changes in human performance and behaviour that are nearly related to the physiological and biochemical changes in the body which are based on humoral regulation, nervous regulation and autoregulation (Lean & Shan, 2012). The cardiovascular reaction is one of these physiological changes. Heart rate variability (HRV) is a useful feature of cardiovascular activity and has successful classification accuracies in MWL and stress levels (Alberdi et al., 2016). HR increases when task demand increases (De Waard, 1996; Backs et al., 2000; Embrey et al., 2006; De Rivecourt et al., 2008), in multi task conditions (Fournier et al., 1999), during additional memory load (Finsen et al., 2001), when requiring problem solving (Splawn & Miller, 2013) or stressful condition increases (Sharma & Gedeon, 2012; Alberdi et al., 2016), HR increases and HRV decreases (De Waard, 1996; Embrey et al., 2006; Sharma & Gedeon, 2012; Alberdi et al., 2016). On the other hand, the increase of HRV was stated in high complexity tasks for longer durations (Fairclough et al., 2005; Gao et al., 2013). HRV metrics include the time-domain, frequency domain, time-frequency and non-linear analysis (Selvaraj et al., 2008; Ramshur, 2010; Aimie-Salleh et al., 2019). Frequency domain analysis has been mostly used in MWL studies. A decrease in mid (0.07-0.14 Hz) and high frequencies (0.15-0.50 Hz) is associated with an increase in mental effort and task demand (Veltman and Gaillard, 1998). The increase of LF/HF by the increase of LF (0.02 -0.06 Hz) together with the decrease of HF is associated with MWL (Lean & Shan, 2012) and stress (Sharma & Gedeon, 2012; Alberdi et al., 2016). However, the decrease of LF in high task difficulty was stated by authors (Delaney & Brodie, 2000; Lehrer et al., 2010; Splawn & Miller, 2013).

Mental workload measurement is not an issue widely studied in the maritime domain, compared to other industries such as aviation, railway, car driving etc. (Özsever & Tavacıoğlu, 2018). In maritime human factor research, there are several data collection methods related to mental workload or fatigue. These are physiological, physical (eye movement etc.), environmental measures, performance analysis in simulator environment, interviews, questionnaires, observations and logbooks, accident/incident analysis and computer-aided design/evaluations (Grech et al., 2008). Commonly, physiological-physical, subjective and performance measures have been used in workload measure studies (Embrey et al., 2006). The studies conducted in recent years have focused on the MWL measurements in some maritime-specific tasks. Wu et al. (2017) associated the EEG and the HRV data, obtained from 10 participants in engine control room simulator, with MWL as task difficulty increased. Orlandi & Brooks (2018) applied a similar method to ship pilots and reached similar results. Yan et al. (2019) used eye response measurement to predict MWL for engine department tasks.

This study aims to measure the mental workload of officers during different navigation conditions, adopting the self-reported and HRV measures. The following hypothesis of this study is mainly studied:

- Different levels of navigation tasks should draw out different levels of MWL and HRV values.

Methods

A total of 11 participants (5 female) were recruited to perform navigation scenarios in a bridge simulator in this study. At least, participants must have had an Oceangoing Watchkeeping Officer certificate and one contract sea experience as an officer in merchant ships. The mean age was 28.4 (SD=4.8) and the mean period of service of participants was 12.4 months (SD=7.9). The study was conducted in a bridge simulator (Figure 1) of Piri Reis University (İstanbul, Turkey) with navigation tasks based on the Malacca Straight passage (Figure 2).

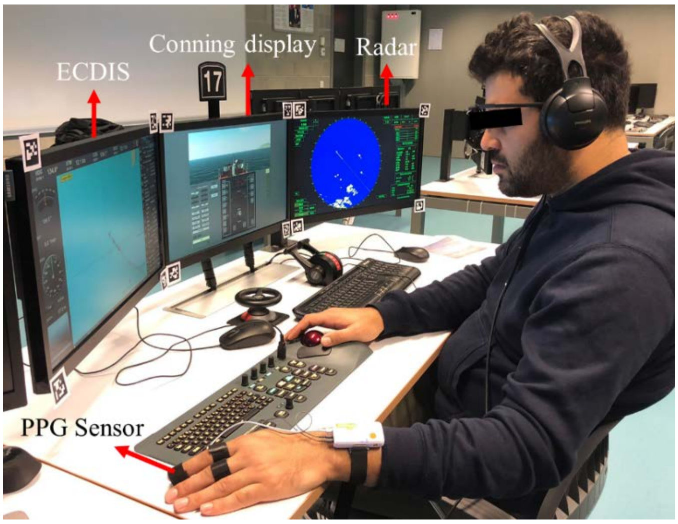

Figure 1. Bridge simulator

Navigation scenarios have been varied being used at different levels of difficulties in mostly visibility, traffic density and geography parameters. Gould et al. (2009) used the variables like geography, visibility and traffic density for

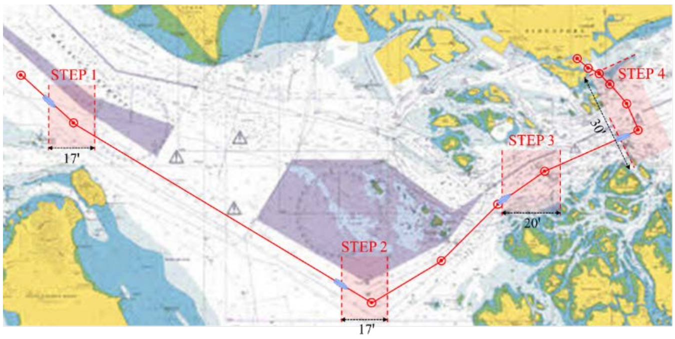

Figure 2. Navigation area used in the simulator with route legs and measurement areas as stated in steps. Image obtained from Admiralty Chart BA 3833

navigation scenarios with 4 different levels of difficulty Collision threat, target behaviour and traffic were used as variables for navigation scenario, which was conducted as 6 minutes and 18 times, in another study (Robert et al., 2003). Similar to the study of Gould et al. (2009), visibility, traffic density, geography, equipment condition and speed restriction were determined as difficulty variables in the study of Grabowski & Sanborn (2003). In this study, the difficulty level of the navigation scenario was gradually adjusted according to traffic density, visibility and geography by combining in 4 steps as:

- Step 1; high visibility, low traffic density, easy geography
- Step 2; high visibility, moderate traffic density, easy geography
- Step 3; moderate visibility, high traffic density, moderate geography
- Step 4; low visibility, high traffic density, hard geography

Heart rate measurement was taken from the participants during the navigation where measurement areas are stated in Figure 2. An optical pulse sensor was used in this study, which measures the photoplethysmogram (PPG) signal from a finger to estimate heart rate. This measurement is used to evaluate the PPG signal and to convert the PPG signal to heart rate. This unit contains electronics attached to a velcro cuff for a finger with a cable length of 9 inches (Figure 3a). The sampling rate was 128 Hz. The ConsensysPRO software was used to convert PPG data to heart rate and IBI (Interbeat interval) signal (Figure 3b) ("Optical Pulse Sensor User Guide," 2016).

The following HRV features to be used in statistical analysis have been extracted from the IBI signal:

- Standard deviation of NN intervals (SDNN) (Eq. (1)),
- Triangular interpolation of IBI interval histogram (TINN) (Eq. (2)),
- Poincaré plot standard deviation along the line of identity (SD2),
- Absolute spectral power of low frequency (0.04-0.15 Hz) (aLF), absolute spectral power of high frequency (0.15-0.4 Hz) (aHF) and the ratio of low frequency to high frequency (LF/HF) in time-frequency Lomb-Scargle Periodogram (Eq. (3)) domain.

$$\mathrm{SDNN} = \sqrt{\frac{1}{N-1}\sum_{n=1}^{N}[NN_n - mean(NN)]^2} \qquad (1)$$

$$\mathrm{TINN} = M - N \qquad (2)$$

where N is total window length and NN is the normal-to-normal time interval (Aimie-Salleh et al., 2019). M and N values represent the minimum and maximum values of a triangle which is shaped on the IBI histogram graphic, on the time axis (Ramshur, 2010).

Figure 3. Optical Pulse Sensor (a) and recording the PPG data (b)

Min-max normalization was applied in order to eliminate individual differences between the subjects and to observe the physiological change during the tasks. The equation (4) was performed for normalization;

To compare the HRV results of the participants with their MWL levels, NASA Task Load Index (NASA-TLX) was used at the end of each step of the navigation scenario by the participants.

Results

All statistical analysis has been performed in SPSS v24. The NASA-TLX scores of each step evaluated by the participants have been statistically analysed and summarized in Table 1. Figure 4 shows the boxplots of the distribution of total scores among 4 steps.

ANOVA has been also performed to show differences in the results of HRV features in different difficulty levels of navigation scenarios. Table 2 presents the ANOVA results of HRV features. Figure 5 shows the means plots of HRV features among 4 steps.

To analyse the relation between NASA-TLX scores and HRV features statistically, correlation analysis has been performed (Table 3). It is possible to observe how HRV features except LF/HF were positive significantly correlated with NASA-TLX scores of the participants.

Table 1. Analysis of variance (ANOVA) of NASA-TLX scores among 4 navigation steps

	Step 1 (*M* ± *SD*)	Step 2 (*M* ± *SD*)	Step 3 (*M* ± *SD*)	Step 4 (*M* ± *SD*)	*p*
Mental demands	3.57 ± 2.23	9.94 ± 4.11	13.88 ± 5.81	20.64 ± 6.27	<0.001**
Performance	5.90 ± 5.31	4.79 ± 2.76	6.30 ± 3.87	10.27 ± 5.19	0.031*
Temporal demands	1.00 ± 1.25	6.64 ± 7.39	9.70 ± 7.56	15.54 ± 10.40	0.001**
Efforts	3.47 ± 2.52	6.03 ± 3.83	9.39 ± 5.13	14.00 ± 5.35	<0.001**
Frustration	1.67 ± 1.29	6.27 ± 6.18	6.88 ± 5.43	12.12 ± 9.17	0.006**
NASA-TLX score	15.60 ± 8.93	33.67 ± 16.22	46.15 ± 14.28	72.58 ± 10.57	<0.001**

Note: * indicates significance level is 0.05; ** indicates significance level is 0.01.

Table 2. ANOVA of HRV features among 4 navigation steps

	Step 1 (*M* ± *SD*)	Step 2 (*M* ± *SD*)	Step 3 (*M* ± *SD*)	Step 4 (*M* ± *SD*)	*p*
SDNN	0.20 ± 0.24	0.45 ± 0.16	0.50 ± 0.16	0.56 ± 0.17	<0.001**
TINN	0.26 ± 0.22	0.46 ± 0.21	0.48 ± 0.16	0.54 ± 0.14	0.008**
SD2	0.20 ± 0.24	0.45 ± 0.15	0.49 ± 0.16	0.56 ± 0.17	<0.001**
aLF	0.18 ± 0.22	0.37 ± 0.11	0.40 ± 0.19	0.50 ± 0.12	0.001**
aHF	0.19 ± 0.23	0.39 ± 0.14	0.46 ± 0.17	0.47 ± 0.19	0.006**
LF/HF	0.33 ± 0.23	0.45 ± 0.14	0.41 ± 0.15	0.54 ± 0.11	<0.033*

Note: * indicates significance level is 0.05; ** indicates significance level is 0.01.

Table 3. Correlations between NASA-TLX scores and HRV features

		NASA-TLX	SDNN	TINN	SD2	aLF	aHF	LF/HF
NASA-TLX	Pearson Corr.	1	0.401**	0.321*	0.416**	0.390**	0.332*	0.221
	Sig. (2-tailed)		0.008	0.036	0.006	0.01	0.029	0.154
	N	43	43	43	43	43	43	43
SDNN	Pearson Corr.	0.401**	1	0.726**	0.997**	0.834**	0.841**	0.467**
	Sig. (2-tailed)	.008		0.000	0.000	0.000	0.000	0.002
	N	43	43	43	43	43	43	43
TINN	Pearson Corr.	0.321*	0.726**	1	0.740**	0.683**	0.595**	0.507**
	Sig. (2-tailed)	0.036	0.000		0.000	0.000	0.000	0.001
	N	43	43	43	43	43	43	43
SD2	Pearson Corr.	0.416**	0.997**	0.740**	1	0.837**	0.825**	0.490**
	Sig. (2-tailed)	0.006	0.000	0.000		0.000	0.000	0.001
	N	43	43	43	43	43	43	43
aLF	Pearson Corr.	0.390**	0.834**	0.683**	0.837**	1	0.789**	0.672**
	Sig. (2-tailed)	0.01	0.000	0.000	0.000		0.000	0.000
	N	43	43	43	43	43	43	43
aHF	Pearson Corr.	0.332*	0.841**	0.595**	0.825**	0.789**	1	0.391**
	Sig. (2-tailed)	0.029	.000	0.000	0.000	0.000		0.000
	N	43	43	43	43	43	43	43
LF/HF	Pearson Corr.	0.221	0.467**	0.507**	0.490**	0.672**	0.391**	1
	Sig. (2-tailed)	0.154	0.002	0.001	0.001	0.000	0.000	
	N	43	43	43	43	43	43	43

Note: * indicates significance level is 0.05; ** indicates significance level is 0.01.

$$P_{LS}(f) \equiv \frac{1}{2\sigma^2}\left\{\frac{\left[\sum_{n=1}^{N}(X(t_n)-\bar{x})cos(2\pi f(t_n-\tau))\right]^{2^\circ}}{\sum_{n=1}^{N}cos^2(2\pi f(t_n-\tau))}+\frac{\left[\sum_{n=1}^{N}(X(t_n)-\bar{x}_2)sin(2\pi f(t_n-\tau))\right]^{2^\circ}}{\sum_{n=1}^{N}sin^2(2\pi f(t_n-\tau))}\right\} \quad (3)$$

where $\tau \equiv tan^{-1}\left(\frac{\sum_{n=1}^{N}sin(4\pi f t_n)^\circ}{\left(\left(\sum_{n=1}^{N}cos(4\pi f t_n)^\circ\right)^\circ\right)}\right)$, $\bar{x}$ and σ^2 are the mean and variance of the time series (Ramshur, 2010).

$$\psi'_{j\_normalized} = \frac{\psi_{j,t}{'^\circ} - {}^\circ\psi_{j,min'}}{\psi_{j,max}{'^\circ} - \psi_{j,min'}} \quad (4)$$

where $\psi'_{j,min}$ and $\psi'_{j,max}$ are the minimum and maximum values of related extracted features within the measured data of the subject.

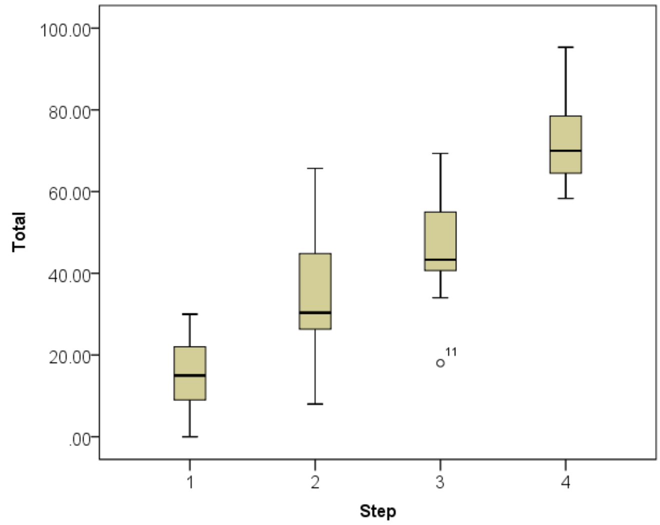

Figure 4. Boxplot of NASA-TLX total scores among 4 navigation steps

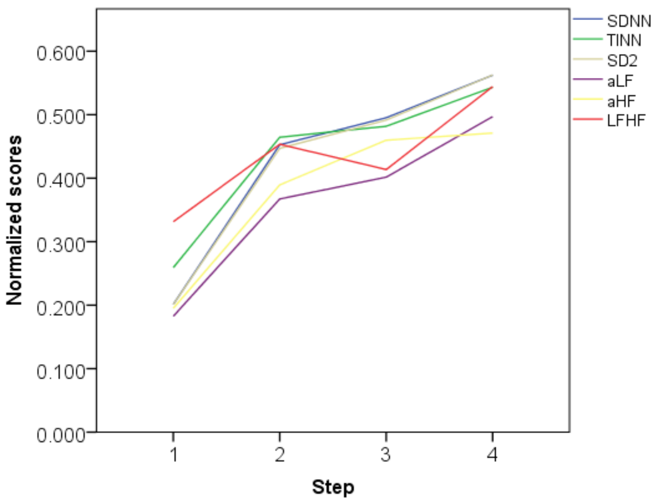

Figure 5. Means plots of HRV features among 4 navigation steps

Discussion

Different levels of navigation tasks caused different levels of MWL and HRV values. ANOVA results show that there are significant differences in the NASA-TLX scores of 5 different dimensions and in total, among 4 steps which have different difficulty levels, i.e., MD (p<0.01), P (p<0.05), TD (p<0.01), E (p<0.01), F (p<0.01) and total (p<0.01). It was observed that MWL perceived by the participants increased when task difficulty increased. It can be seen also that there are significant differences in the HRV features among 4 steps which have different difficulty levels, i.e., SDNN (p<0.01), TINN (p<0.01), SD2 (p<0.01), aLF (p<0.01), aHF (p < 0.01) and LF/HF (p<0.05). The increase of HRV features except aHF were found significant similar to the results of previous studies in that the increase of HRV was stated in high complexity tasks for longer durations (Fairclough et al., 2005; Gao et al., 2013). aHF was expected to decrease when task difficulty increased according to the studies in the literature.

The correlations between NASA-TLX and HRV features except LF/HF were also found significant. The reason that NASA-TLX scores were not correlated with LF/HF can be explained as increasing of aHF together with aLF. This result couldn't support the literature that increase of LF/HF by the increases of LF together with the decrease of HF is associated with MWL (Lean & Shan, 2012). However, LF/HF increased when task difficulty increased but this increase couldn't be found statistically significant when comparing the increase of NASA-TLX scores.

The increase of HRV time-domain features (SDNN, TINN) (this means the decrease of heart rate) in this study has been not observed in other maritime-related studies. Heart rate increased when task difficulty increased in ship manoeuvring (Orlandi & Brooks, 2018), heart rate increased and HRV time-domain features decreased when task difficulty increased in engine department tasks (Wu et al., 2017). On the other hand, the increase of LF/HF in this study was found similar to the results of the related studies in the literature. However, the change of all HRV features has not been found statistically significant in both maritime-related studies.

In general, the changes in NASA-TLX scores and time and frequency-based HRV features were found to be significant due to increased task load. The results of this study were found to be similar and significant to the results of the studies in the literature. Differently from other maritime-related studies in literature, the effect of increasing task load in routine navigation tasks on officers of the watch was shown with empirical data.

Conclusion

It is known that the human factor has a major effect on maritime casualties that cause great harm to the environment, economy and maritime sector. It was stated that while human error is the primary contributor to accidents, a good part of collisions and groundings were related to the mental workload (MWL) of watchkeeping officers. This study focused on the MWL measurement in routine navigation tasks instead of the studies conducted in recent years, which have focused the MWL measurements in the engine department and ship manoeuvring tasks. Therefore, the main aim of this study was to measure the mental workload of officers during different navigation conditions. The results of the measurements showed that different levels of navigation tasks caused significantly different levels of MWL and HRV values and MWL and HRV increased when task difficulty increased. Consequently, this study will contribute to the literature in terms of predicting

MWL for routine navigation operations by using physiological measures in maritime transportation.

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Compliance With Ethical Standards

Authors' Contributions:

BÖ: Taking the measurements, Data handling, Writing-original draft.

LT: Resources, Writing-review & editing.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethical Approval

This study was approved by the Medical and Engineering Sciences Human Research Ethics Committee of Istanbul Technical University.

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