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Review article

Measuring mental workload using physiological measures: A systematic review

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ABSTRACT

Technological advances have led to physiological measurement being increasingly used to measure and predict operator states. Mental workload (MWL) in particular has been characterised using a variety of physiological sensor data. This systematic review contributes a synthesis of the literature summarising key findings to assist practitioners to select measures for use in evaluation of MWL. We also describe limitations of the methods to assist selection when being deployed in applied or laboratory settings.

We detail fifty-eight peer reviewed journal articles which present original data using physiological measures to include electrocardiographic, respiratory, dermal, blood pressure and ocular. Electroencephalographic measures have been included if they are presented with another measure to constrain scope. The literature reviewed covers a range of applied and experimental studies across various domains, safety-critical applications being highly represented in the sample of applied literature reviewed. We present a summary of the six measures and provide an evidence base which includes how to deploy each measure, and characteristics that can affect or preclude the use of a measure in research. Measures can be used to discriminate differences in MWL caused by task type, task load, and in some cases task difficulty. Varying ranges of sensitivity to sudden or gradual changes in taskload are also evident across the six measures. We conclude that there is no single measure that clearly discriminates mental workload but there is a growing empirical basis with which to inform both science and practice.

1. Introduction

Mental workload (MWL) remains an important variable with which to understand user performance (Young et al., 2014). In this article we review the evidence base for measurement of MWL using physiological measures. This review is partly in response to the array of new sensor technologies available. This field is evolving quickly, and equipment is being developed constantly that makes physiological measurement easier and more mobile (Nixon and Charles, 2017). Cheaper, smaller technologies allow the collection and analysis of a variety of data associated with user physiology (Guzik and Malik, 2016). These data can be collected unobtrusively and in many cases without interference with the primary task. We suggest that understanding the links between user physiology and their experience of workload can generate exciting avenues for adapting and supporting complex cognitive work in response to real-time information about user response to a task (for example see Christensen and Estepp, 2013). We systematically review and present evidence that can assist scientists and practitioners alike to select physiological measures to assess MWL in an evidence based way. Many of the measures have limitations that preclude their use in certain tasks or applied settings and this review will help when selecting measures for a chosen task or experiment. Finally, we summarise the key findings of the review in a table which can be used to guide experimental design or to select measures for a particular task or application.

For a concept which is intuitively appealing, a plurality of understanding about the definitions and measurement of MWL exist (Young et al., 2014). This plurality was explored by a significant workshop hosted by Neville Moray and subsequent publication of the sessions in 1979 (Moray, 1979). Moray characterises the different attributes of operator workload from a variety of different perspectives throughout the system. More recently Pickup et al. (2005) detail the difficulties in distinguishing where the influence of workload and its measurement in the system is located. Workload is not only multidimensional in nature (Xie and Salvendy (2000) but is also experienced by the operator and imposed by the task as demand. Workload can be imagined as an input and an output, being both experienced by the user subjectively, demanded of the user by the work and expended by the user to do work.

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Abbreviations

ATC	Air Traffic Control
BP	Blood Pressure
ECG	Electrocardiogram
EDA	Electrodermal Activity
EDR	Electrodermal Reaction
EEG	Electroencephalogram
EOG	Electrooculogram
ERP	Event Related Potentials
HF	High Frequency
HR	Heart Rate
HRV	Heart Rate Variability
IBI	Interbeat Interval
LF	Low Frequency
MATB	Multi-Attribute Task Battery
MF	Mid Frequency
MWL	Mental Workload
N	Negative
NASA	National Aeronautics and Space Agency
NN	Normal Normal
P	Positive
PSD	Power Spectral Density
RMSSD	Root Mean Square Standard Deviation
RSME	Rating Scale of Mental Effort
SCR	Skin Conductance Response
SDANN	Standard Deviation of the Average Normal Normal [interval]
SDNN	Standard Deviation of the Normal Normal [interval]
SWAT	Subjective Workload Assessment Technique
TBV	Tissue Blood Volume
TLX	Task Load Index
ULF	Ultra Low Frequency
VACP	Visual Auditory Cognitive Psychomotor
VLF	Very Low Frequency

These different elements of workload are individually and interactively valid depending on the questions being asked and by whom. From a psychological background, mental workload may be framed using cognitive psychology in terms of task switching or allocation of attention (Wickens, 2008). A system designer may describe workload in terms of demand placed on the user by the system or what work is required of the operator. One user may experience workload very differently to another due to individual differences (Grassmann et al., 2017). Sharples and Megaw (2015) have updated the discussion placing operator workload at the centre of a framework which includes both the physical and cognitive task demands, the operator performance and other external or internal factors. The complex interactions suggested by the framework may give rise to challenges inherent in the measurement of workload and any theoretical framework used to underpin conclusions or make predictions in this space.

Diverse perspectives as to the nature of workload and its measurement may not be issues in themselves when an experiment or task is bounded. Internal validity may be claimed. Where trouble can emerge is through the formal comparison of studies employing different definitions, measurements or constructs relating to mental workload. It is for this reason that our original ambition to conduct a formal meta-analysis of the studies was rejected. Notwithstanding the power of meta-analyses to cope with differing methodologies, the diversity of theoretical treatments and task types we have observed would have rendered any conclusions unreliable at best. We suspect that the definition of MWL in research is sometimes so closely associated with its method of measurement that explicit definition is not considered and in many cases this is understandable (Matthews et al., 2015). Researchers or practitioners may satisfy themselves with the face or content validity of a reliable measurement instrument without needing to explore theoretical underpinnings.

To locate this review amid this diversity, we distinguish taskload and workload. Taskload can be defined as the work, for example the number of tasks, performed by a user. MWL encompasses the subjective experience of a given taskload. Factors such as time constraints, environment or experience can differentiate MWL between users for the same taskload (Sharples and Megaw, 2015; Wickens, 2008). It is possible to achieve a sense of the MWL by examination of taskload. At first glance it makes intuitive sense that the more a user must do, the higher their MWL. The higher the taskload, the higher the MWL (Colle and Reid, 1998). However, MWL is mediated by many factors, taskload being just one. A repetitive simple task may not be cognitively challenging, but if temporal pressure is added MWL may increase affecting performance (Young et al., 2014). Conversely, a complex task may at first be perceived as challenging, and MWL experienced may be high, but through practice and experience the MWL experienced may decrease even though the taskload has not changed (see Matthews et al., 2015). In this review we treat MWL as a subjective experience in response to a taskload, which can be modified by a variety of performance shaping factors.

The last review of multiple physiological measures of MWL was conducted by Kramer (1990). Jorna also reviewed heart rate as an index for workload (Jorna, 1992). Roscoe (1992) published a review focussing specifically on pilot workload. Lean and Shan (2012) present a review focussing on electrocardiogram (ECG) and related measures, and electroencephalogram (EEG). More recently, Young et al. (2014) present a concise summary of physiological measures associated with MWL measurement. In this review we expand the range of measures considered and review the recent evidence base for measurement of mental workload using major physiological measures reported in the peer-reviewed literature across multiple domains. We systematically explore the evidence base for each measure and consider the limitations

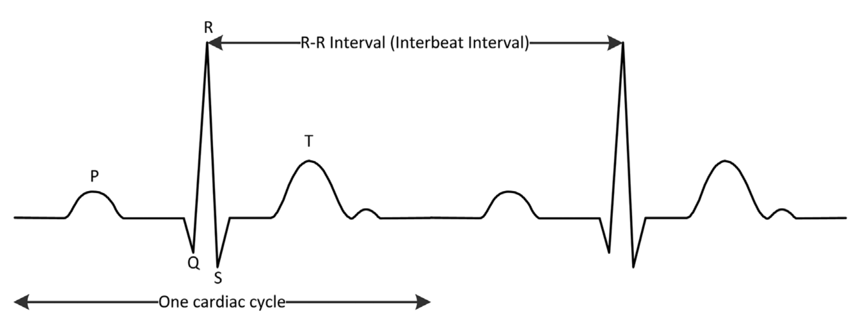

Fig. 1. The cardiac cycle.