Automation and its Effects on Mental Workload in Industrial Sectors

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Abstract

Automation technology has profoundly changed modern life and promises further advances in safety and efficiency. However, it is also fundamentally changing the dynamics of work, particularly in the maritime sector, where automation is increasingly prevalent. The maritime context differs significantly from other industries in terms of working conditions and challenges, placing unique demands on personnel and operations. This dissertation investigates how automated systems impact mental workload and human-technology interactions in maritime contexts. By adapting a framework based on cognitive load theory, it analyzes predictors (e.g., automation, system design, level of autonomy, individual differences) of mental workload through systematic reviews and experimental studies. Key challenges include recruiting specialized maritime participants and deploying equipment in operational settings. By addressing these challenges, the dissertation aims to enhance understanding and implementation of automation, offering practical insights for optimizing human-technology interfaces in maritime automation.

CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**.

Keywords

Human-Machine Interaction, Mental Workload, User Experience, Autonomy; Maritime, Robots

1 Introduction

Advances in automation technology have transformed nearly every aspect of modern life. With the growing power of intelligent machines, we can expect even more profound changes in the future. While it is not yet fully known how exactly these advances will shape our future, it is already clear that automation is making many areas of life safer, easier, and more efficient - for example, by preventing traffic accidents, automatically parking cars, and keeping them in their lanes [1]. The literature defines automation as "a device or system that accomplishes (partially or fully) a function that was previously or conceivably could be, carried out (partially or fully) by a human operator" [10, 287]. However, despite rapid development and enthusiasm for these technologies, it is often forgotten that automation has profoundly changed and will continue to change the way people work. Initially, the focus was on automating routine tasks due to their predictability, but continued maximization of system capacity and advanced machine learning algorithms will enable automation systems to perform more complex decisions largely autonomously [3, 7, 10]. Despite this progress, most highly automated systems still require human interaction for control and monitoring, leading to changes in operator roles, reduced understanding of tasks, decreased ability to predict future events, and a reduced ability to regain manual control after using automation [1, 5, 8].

The maritime sector is undergoing significant change with the continued advancement of technology and automation on ships, in ports, and throughout offshore operations. This transformation places new cognitive demands on maritime workers, who are now required to process and monitor large amounts of data from various automated systems [17]. Factors such as extreme environmental conditions, isolation from external support, and the high-stakes nature of navigation and safety make the maritime context unique in terms of mental workload. These challenges increase cognitive demands as maritime workers must remain vigilant and responsive in an ever-changing and often unpredictable environment. While research suggests that well-designed systems can mitigate mental workload by streamlining operations and reducing cognitive overload [2, 18], human error remains a leading cause of maritime incidents, accounting for 54% of accidents [4]. This underscores the critical need for effective automation and support systems to improve safety and operational efficiency in the maritime sector.

This dissertation aims to explore the transformative effects of automation on the mental workload of maritime industry workers. By analyzing these dynamics, the dissertation sheds light on the complexity of human-technology interaction, especially in the maritime sector. It investigates how highly automated systems affect operators' behavior, decision-making processes, and mental workload. These findings are relevant for future human-centered design and implementation of automated systems and for understanding the new demands faced by workers in maritime environments.

2 Mental Workload

Mental workload is a concept rooted primarily in the field of Human Factors, representing a complex and multidimensional construct for which no uniform definition currently exists. In this dissertation, I adopt the understanding that mental workload represents the amount of cognitive capacity allocated to perform a task in a specific context [20]. The concept has evolved from measuring the mental effort required to perform a task to a nuanced understanding

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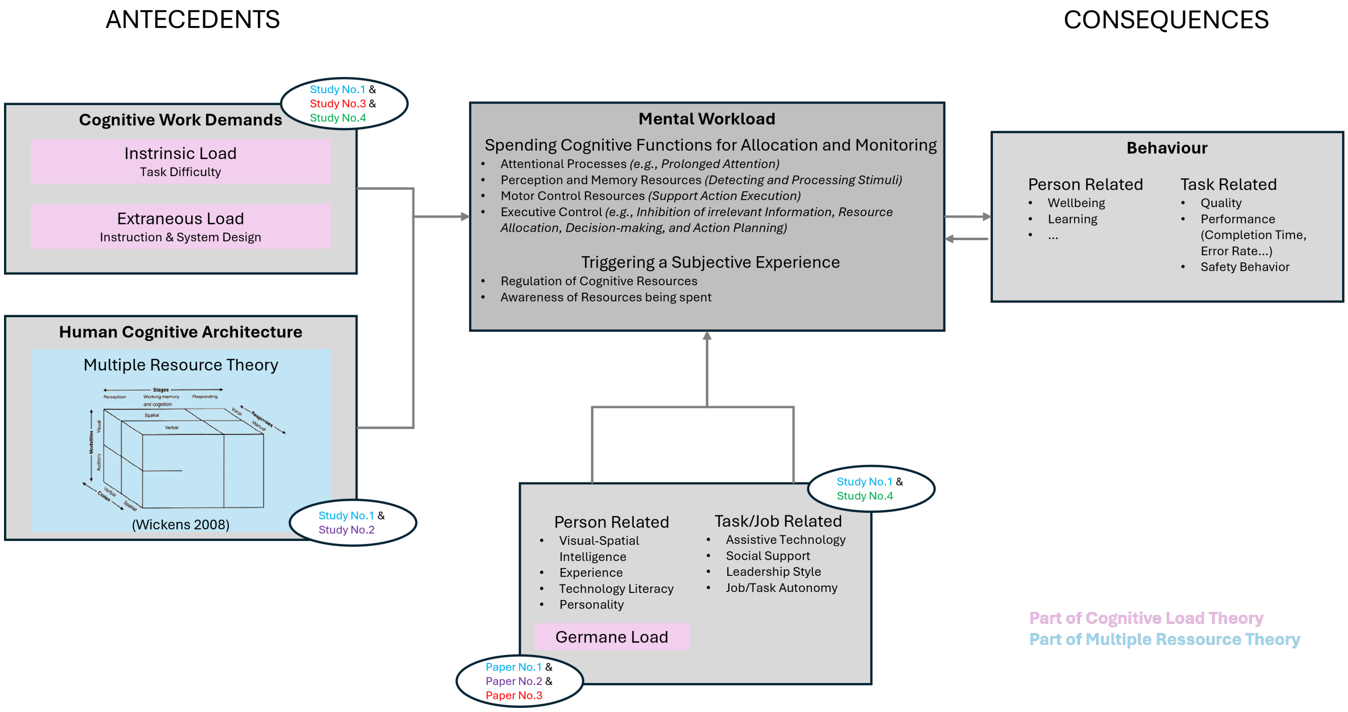

Figure 1: Adapted framework model based on [15].

involving cognitive resources, cognitive experience, and task demands [15]. Mental workload can manifest in various forms. When it becomes excessive, known as mental overload, the operator may experience delayed information processing, reduced performance, and increased likelihood of errors [19]. Conversely, when mental workload is too low, the operator might misperceive task demands, leading to boredom and more mistakes [6].

In this work, I follow the proposed framework by [15], aiming to disentangle mental workload into its antecedents, defining attributes, and consequences, leading to a clear conceptual definition and a generic explanatory framework incorporating insights from cognitive load theory [14]. Based on a concept analysis, predictors such as cognitive work demands and human cognitive architecture, defining attributes (working memory functions and subjective experience), consequences of mental workload, and moderator variables (person-related and task-related) were established. At its core, mental workload is understood as a subjectively experienced physiological processing state that involves the interplay between one's limited and multidimensional cognitive resources and the cognitive work demands being faced [15]. It is important to note that mental workload does not directly equate with performance (consequences) or with the demands of the task (task load), but depends on other factors, such as practice, experience, and the condition of the operator (person- and task/job-related factors) [13, 15]. For example, two people can achieve the same performance score on the same task, with one having enough attention resources to attend to another task simultaneously [10].

This dissertation adds two new aspects from cognitive load theory to the framework model: the difficulty of the task itself (intrinsic load) and the presentation and design of the information (extraneous load). Research results demonstrate that human-centered design solutions significantly minimize users' cognitive load. These solutions effectively free up mental resources, enabling users to perform better and stay more attuned to their surroundings [9]. In addition, the cognitive capacities used also affect mental workload. In engineering psychology, Wickens' Multiple Resource Theory dominates the explanation of cognitive capacity, which posits that humans have several limited but differentiated pools of cognitive resources that can be used simultaneously. These resources are distributed across mental processes and tasks involving different sensory modalities, memory codes, and processing stages. When similar resources are used concurrently, performance on tasks is impaired, whereas simultaneous use of different resources can enhance performance [16].

Figure 1 presents an overview of the adapted framework model, which forms the basis for the individual studies of this dissertation. These studies examine various predictors and moderators of mental workload, identifying novel relations, particularly in the maritime context and robotics in industrial sectors such as the maritime industry. Based on the adapted framework and further research from the maritime industry and human-robot collaboration, this ongoing dissertation addresses the following research questions:

1. How does automation in safety-critical industries, especially in the maritime context and in robotic applications, influence mental workload?

2. How do individual personality traits and cognitive functions impact mental workload during interaction with automated technologies?

3. What are the specific design and interface features in safety-critical industries that can contribute to an optimized mental workload?

3 Studies & preliminary results

Overall, the thesis consists of two systematic reviews and two experimental studies, related either to the maritime context or human-robot collaboration, focusing on the following topics:

3.1 Systematic review: Mental workload in the maritime industry (No. 1)

This systematic review uses the PRISMA methodology to examine factors influencing mental workload that are specific to the maritime sector. By analyzing 57 studies, it categorizes methods for measuring mental workload, focusing on the unique challenges of the maritime environment. Maritime contexts are characterized by factors such as extreme weather conditions, constant navigational and safety risks, and limited access to external support. The isolated nature of work on board, with its inherent unpredictability and operational demands, increases the relevance of mental workload. The review identifies key factors including physiological, subjective, and performance-based measures, and distinguishes between task-related and individual factors affecting mental workload in maritime settings. It also highlights the importance of user-friendly interfaces and automation, especially for teleoperated vessels and integrated systems, which are critical to reducing mental workload and preventing errors. Overall, the study highlights the complex interplay between unique working conditions that affect mental workload, fatigue, situational awareness and task performance, and underscores the need for effective automation and support systems to enhance maritime safety and efficiency.

3.2 Individual factors influencing mental workload in ship surveillance (No. 2)

This experimental study examines the impact of automation on mental workload in safety-critical areas such as the maritime industry, where human error often leads to critical accidents. With increasing automation, humans monitor these systems remotely and intervene only in critical situations. This can lead to periods of low mental workload (vigilance decrement), resulting in delayed reactions and reduced situational awareness [3, 11]. The study recruited 70 participants to complete a simulated autonomous ship monitoring scenario. Mental workload was measured using eye-tracking and subjectively rated using the NASA-TLX. Additionally, the influence of boredom proneness and the need for cognition on performance in a standardized vigilance task and mental workload during monitoring was examined.

3.3 Systematic review: Mental workload associated with different levels of robotic system automation (No. 3)

The present systematic review employs the PRISMA methodology to investigate the effects of different levels of automation (LOA) on mental workload in human-robot collaboration. The aim is to gain insights into how the design of robots and collaborative processes can help prevent mental overload and underload.

3.4 Development and validation of a collaborative robotic system to reduce mental and physical workload in a maritime context (No. 4)

In this experimental study examines the perceived usability, physical and mental relief, and acceptance of a collaborative robotic system that assists in loading ships with liquid cargo. The goal is to evaluate the human-machine interface of the robot, developed based on focus groups using the approach of [12], and to identify factors that influence the perceived usefulness, ease of use, and acceptance of the system. The study uses the think aloud method during interaction for usability evaluation, as well as interviews and questionnaires to investigate mental and physical workload, usability and acceptance. In addition, the study extends a theoretical model of technology acceptance to include aspects of mental workload and usability to understand the adoption of such technologies better.

4 Next steps, open questions, and challenges

The next steps for this dissertation are to thoroughly analyze data from experimental studies and pre-register and analyze studies from the systematic review on human-robot collaboration. Evaluating mental workload in both human-robot collaboration and the maritime sector requires careful examination and comparison of data collected through various methods such as eye-tracking and subjective ratings. In addition, a foundational model for this dissertation will be established by synthesizing the results of individual studies within this dissertation into a comprehensive framework.

A significant challenge is recruiting participants in the maritime context and deploying measurement equipment in the field, given its specialized nature and operational constraints. To address this, a mixed-methods design was employed to facilitate robust, generalizable conclusions and effective design guidelines for mitigating mental workload in automated environments. Ensuring the transferability of results to real-world settings and generalizability across diverse contexts remains a central concern. Another challenge is the interdisciplinary nature of this work, as the studies in this thesis rely extensively on preliminary work from the fields of computer science and engineering.

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