OPTIMIZING SPECIALIZED CABIN ENVIRONMENTS THROUGHA COGNITIVE INTERACTION-BASED MULTI-CHANNEL DESIGN MODEL

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UNIVERSITI PENDIDIKAN SULTAN IDRIS

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OPTIMIZING SPECIALIZED CABIN ENVIRONMENTS THROUGH A COGNITIVE INTERACTION-BASED MULTI-CHANNEL DESIGN MODEL

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ABSTRAK

Mereka bentuk persekitaran kabin khas berasaskan interaksi kognitif adalah penting. Ia secara langsung memberi kesan kepada kesihatan fizikal dan mental operator, keselamatan misi, kecekapan kerja dan keselesaan keseluruhan. Namun begitu, kajian terkini memberi perhatian yang tidak mencukupi kepada reka bentuk ruang kabin khas dan faktor-faktor sistem utama di dalam interaksi kognitif. Justeru, kajian ini membangunkan pendekatan reka bentuk multi saluran berasaskan interaksi kognitif dengan mengintegrasikan pembelajaran mendalam, penapisan kolaboratif neural, algoritma genetik, dan kaedah Delphi bagi mengoptimumkan persekitaran kabin khas. Kajian ini menggunakan reka bentuk kaedah campuran, menyepadukan teknik kualitatif (temu bual berstruktur dan pemerhatian sistematik) dengan penilaian kuantitatif (penjejakan mata, elektromiografi, dan aktiviti elektrodermal). Kaedah ini secara kolektif menilai bagaimana susun atur ruang, pencahayaan dan skema warna mempengaruhi prestasi dan keselesaan subjektif operator. Di bawah kondisi eksperimen(n=25), keputusan menunjukkan bahawa persekitaran ruang yang dioptimumkan dengan penjajaran paksi-Y, jarak 1000 mm, orientasi bertentangan, pencahayaan pada 340 lx, dan suhu warna 4500K secara signifikan dapat meningkatkan kecekapan operasi dan keselesaan pengguna. Dapatan kajian menunjukkan bahawa reka bentuk yang dioptimumkan, berasaskan model reka bentuk berbilang saluran dan disahkan melalui penilaian oleh lima orang pakar, meningkatkan kecekapan operator serta persepsi keselesaan. Walaupun kajian ini terhad kepada parameter persekitaran tertentu dan tetapan eksperimen terkawal, ia menawarkan pandangan berharga terhadap reka bentuk kabin berpusatkan manusia. Secara keseluruhannya, kajian ini memajukan bidang interaksi kognitif dengan memperkenalkan metodologi dipacu data yang mengintegrasikan algoritma lanjutan bagi meningkatkan keupayaan penyesuaian, membuat keputusan, dan prestasi agregat di dalam persekitaran kabin yang kompleks.

OPTIMIZING SPECIALIZED CABIN ENVIRONMENTS THROUGH A COGNITIVE INTERACTION-BASED MULTI-CHANNEL DESIGN MODEL

ABSTRACT

Designing specialized cabin environments based on cognitive interaction is essential. It directly affects operators' physical and mental health, mission safety, work efficiency, and overall comfort. However, recent research has paid insufficient attention to specialized cabin space design and key system factors in human cognitive interaction. Thus, this study develops a cognitive-interaction-based multi-channel design approach that integrates deep learning, neural collaborative filtering, genetic algorithms, and the Delphi method to optimize specialized cabin environments. The research adopts a mixed-method design, integrating qualitative techniques (structured interviews and systematic observations) with quantitative assessments (eye tracking, electromyography, and electrodermal activity). These methods collectively evaluate how spatial layout, lighting, and color schemes affect operator efficiency and subjective comfort. Under experimental conditions(n=25), results demonstrate that an optimized spatial environment featuring a Y-axis alignment, a 1000 mm distance, opposite orientations, lighting at 340 lx, and a 4500K color temperature significantly enhanced both operational efficiency and user comfort. Findings indicate that the optimized design based on a multi-channel design model and validated through evaluations by five expert reviewers, improves operator efficiency and perceived comfort. Although this research is constrained by specific environmental parameters and controlled experimental settings, it offers valuable insights into human-centered cabin design. Overall, this research advances the field of cognitive interaction by introducing a data-driven methodology that integrates advanced algorithms to enhance operator adaptability, decision-making, and aggregate performance in complex cabin environments.
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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANN	Artificial Neural Network
ANOVA	Statistical Analysis of Variance
AOI	Areas of Interest
CMYK	Cyan, Magenta, Yellow, Key
CNN	Convolutional Neural Network
CPS	Cyber-physical Fusion System
CSP	Constraint Satisfaction Programming
DBN	Deep Belief Networks
DEA	Data Envelopment Analysis
DES	Discrete Event Simulation
ECG	Electrocardiogram
EEG	Electroencephalogram
EMG	Electromyography
EOG	Electrooculogram
ER-SCR	Event-related SCR
FDM	Fuzzy Delphi Method
FFT	Fast Fourier Transform
GA	Genetic Algorithm
GEM-AHP	Group Eigenvalue Method-Analytic Hierarchy Process

HMI	Human-machine Interaction
HRA	Human Reality Analysis
HRV	Heart Rate Variability
HSB	Hue, Saturation, Value
iEMG	The Integrated Value of the Electromyographic Signal
KMO	Kaiser-Meyer-Olkin
KNN	K Nearest Neighbor Algorithm
LDA	Linear Discriminant Analysis
LED	Light Emitting Diode
LSD	Least Significant Difference
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-criterion Decision-making Problem
MLP	Multi-layer Neural Network
MMC	Maximum Margin Criterion Algorithm
MSE	Mean Square Error
MVC	Maximum Voluntary Contraction
NCF	Neural Collaborative Filtering
NS-SCR	Non-response SCR
OSTP	Office of Science and Technology Policy
PCA	Principal Component Analysis
PD	Phasic Data
PLS	Partial Least Squares
PROMETHEE	Preference Ranking Organization Method for Enriched Evaluation
RBM	Restricted Boltzmann Machine
RGB	Red, Green, Blue

RNN	Recurrent Neural Network
SCL	Galvanic Skin Level
SCR	Galvanic Skin Response
SOM	Self-organizing Map
SPSS	Statistical Package for the Social Sciences
SVM	Support Vector Machine
TD	Tonic Data
TOPSIS	Technology for Order Preference by Similarity to an Ideal Solution
VIF	Variance Inflation Factor

CHAPTER 1

INTRODUCTION

1.1 Introduction

The special cabin is a small working space similar to the vehicle shelter, tank cockpit, operated submersible working cabin, and aircraft cockpit (Weng et al., 2025; Campese et al., 2016; Deng, 2016). As the carrier of electronic equipment and operators, its primary function is to provide an excellent internal space environment in special operating environments such as command operations, engineering rescue, living reserves, medical recovery, and power supply. In these special operational environments, people's working posture will also be restricted due to the limited working space. In addition, due to the nature of work, people cannot stop working at will and need to maintain a working posture for a long time (Micović et al., 2021).

Furthermore, due to the small space in the cabin and the special working environment, the cabin may also be accompanied by complex environmental factors such as vibration and noise that are harmful to the human body (Gong et al., 2021). Therefore, the man-machine complex operating environment in special cabins is particularly critical. To improve operators' comfort, physical and mental health, the space environment of special cabins needs to comprehensively consider factors such as the cabin functions, performance, safety, and comfort. For the human-machine interaction (HMI) system in special cabins, the core is to adapt to the size of the human body, the mechanical properties of the human body, the physiological performance of labour and the psychological performance of labour as the goal to reach the state of "machine-friendly" and "human-suitable machine" (Grobelna et al., 2025).

Designing the HMI system in the special cabin should be human-centered, adopting a multi-channel approach, and take HMI as the ultimate goal to quickly obtain information and make accurate judgments based on this information. This can significantly improve operational efficiency, enhance cabin reliability, enhance operator awareness, reduce decision and reaction times, and reduce the risk of operating errors (Yang et al., 2020). This is of great significance for the development of special cabin design.

Practically, the HMI design of the special cabin is centered on the operator, planning and optimizing the functions of the man-machine system, display and control resources, display and control interface, and crew control process to complete the operation task objectives efficiently (Kettwich et al., 2021). The research on special cabins is mainly aimed at improving the utilization rate of space and materials from the perspective of engineering practice. Still, only some people use the cognitive characteristics of HMI as constraints to study human factor reliability.

Consequently, human factors design are always ignored due to engineering quality constraints, resulting in many ergonomic problems in the design, which reduces the quality and effect of cabin ergonomics design. Supposedly, the interaction design of human-machine fusion should reduce the difficulty of human operation tasks as much as possible and improve their cognitive efficiency and task execution quality to improve the operational efficiency of special vehicles. Therefore, designing an effective and reliable man-machine space environment that can be applied to complex environments based on interactive cognitive characteristics is a critical problem that needs to be solved urgently in the design of special cabins.

1.2 Research Background

The special cabin is the area for performing mission observation and manipulation control, and it concentrates on terminal interfaces such as display instruments, manipulators, seats, lockers, signals, and alarms (Chen et al., 2018). As the only space for the operator to communicate with the machine equipment, the special cabin is the direct space for the interaction between man and machine in the operating system and plays an essential role in the system efficiency of the system operation. Thus, the space environment design is critical to improve and optimize the cabin's system efficiency (National Research Council et al., 2002).

However, special cabins are different from some conventional spaces, and a reasonable space organization and method design is required for their different functions and uses. For example, it is necessary to consider whether the various areas or workstations in the special compartment need to be isolated from each other or whether an open and relatively accessible layout is adopted (Gosende et al., 2021).

Fundamentally, the space environment design of special cabins needs to consider how to enable operators to effectively perceive and recognize the space environment, including emphasize the key space through layout, usage of special color, lighting environment, and so forth (Gabbatore & Germak, 2023; Tamer et al., 2020; Tolis et al., 2021), how to improve the salience and recognition of the space, and study the cognitive process of the operator in the special cabin environment, including perception, attention, memory, thinking, language and so forth.

The operator needs to rely on the visual and auditory multi-channel mode to obtain the outside world and system operation information through the equipment and display in the space, and then make a quick decision through the brain and transmit the control signal to the control system through the movement organ system to run the system (Ricci et al., 2022). Therefore, it is essential to have an excellent interactive adaptability relationship between sensory organs and space environment, motor organs and manipulator equipment (Li et al., 2022).

In the current special cabin, the cabin equipment includes a head-up display, down-view display, radio navigation system, various communication links and other airborne equipment to provide information to the operator continuously. Tens of thousands of sensors can sense different (Abedi et al., 2023). The organ provides the ability to collect mission information for the cabin. With the increment in the number of sensors, operators face the problem of a severe "overload" of information. The presentation of massive information and data is like a "double-edged sword" (Ninnemann et al., 2022).

Therefore, the functional operation and interaction method is critical in the design of the special cabin space environment (Fuchs et al., 2022). It is necessary to effectively classify, combine, perceive, and memorize the functions and operations required by the operator, simplify the operation process, reduce the mis-operation rate, and improve the user's operating efficiency through a design that meets the requirements of ergonomics and cognitive characteristics (Gou et al., 2023). In addition, the environmental elements, including lighting, color, air quality and other factors, are also essential due to analyze their impact on human cognition and behaviour and providing guidance for special cabin design.

Furthermore, in perceptual simulation and interaction design, software modelling and rendering simulate the function of the virtual environment in special cabins, so that users can realize perceptual simulation in virtual space (Lou et al., 2022). This step requires designing various perception methods, such as vision and hearing, to provide operators with a more realistic and vivid spatial experience (Crescenzio et al., 2021). It is required to put forward corresponding design principles from three aspects of spatial layout, color and light environment according to cognitive interaction characteristics, functional operations, environmental elements, and virtual interaction characteristics, and optimize the environmental design of special cabins.

For the exploration of the above research directions, starting from the cognitive layer, emotional experience layer, and image perception layer, the interactive cognitive characteristics are introduced into the optimization design of the man-machine space environment of special cabins, and the focus is on the fusion of man-machine under the multi-channel interactive cognition of special cabins. Man-machine space facility layout design method, light environment design method, color environment design method are based on engineering, cognitive psychology, behaviour, information science, human factors and other related theories, and through cabin HMI effect simulation analysis and synthesis evaluation and verification.

The research results are beneficial in improving the cognitive reliability and user experience of the special cabin space environment, the physical and mental health of operators, reduce the occurrence of human error in the cabin and ensure the safety of the system. It will help further to improve the design of the special cabin space environment. The research on the theory and method system of industrial design provides theoretical and method guidance for designers in the engineering field, reduces the design complexity related to special cabins, and reduces the time and resources required to design special cabins, thereby shortening the turnaround time and reducing costs.

1.3 Research Problem Statements

The space environment design of special cabins is a complex process, including human factors analysis, comfort analysis, product design, reliability analysis and evaluation and other stages (Chen et al., 2023). In the past, many of the underlying demand analysis methods, fundamental theories of human factors, design principles and evaluation methods of traditional automobiles could not be directly applied to the design practice of special cabins (Li et al., 2025).

This is because, the research on the cabin's human-machine interface layout only focuses on the two-dimensional system interface in a single channel, ignoring the human comfort, physiological and psycho-emotional effects (Lu et al., 2023). Also, ergonomics design is often ignored due to the measurement standards and constraints of engineering quality, and ergonomics is through the study of the structural and functional characteristics of the human body, which can provide information including the size of various parts of the human body, the range of limb movement, and the range of force exerted (Trstenjak et al., 2025).

Additionally, for the cabin space environment system design, the human cognitive behavior process is very complex, and some cognitive activities are difficult to express in formal methods. As the cognitive interaction characteristics interact with the cabin space environment, as well as from reliability and visual comfort, there are few studies on the effectiveness of cognitive and behavioural factors such as degree on the design of complex spatial environment of special cabins (Auer et al., 2023).

In the design and development process of special cabins, due to engineering quality measurement standards and constraints, ergonomic design, human factor reliability process, are based on the psychological feelings during the visual and tactile multi-channel process. Physiological behavior is used as feedback, and the comfort and work efficiency in the layout environment, light environment, and color environment of the special cabin human-machine space environment system are analyzed, and the operation process, information reading, and control input in the working situation of the special cabin space environment system are analyzed in other aspects, the operation efficiency and user experience comfort of special cabin human-machine space environment can be improved (Herbig et al., 2023).

Furthermore, in the design of the human-machine space environment system in special cabins, HMI designers often make special cabins in the early stage of design based on ergonomics and human factor requirements such as HMI, environment, visibility, and comfort (Tufano et al., 2023). By contrasts, the interior environment of special vehicles is complex, including spatial layout, color, lighting, noise, vibration, thermal environment, and many other factors (Qiang & Huang, 2021). There are many quantitative and qualitative attributes objectively, and it is difficult to make a comprehensive assessment.

At this stage, in the context of the rapid development of information technology and the cabin mentioned above research directions, as a bridge for information communication between humans, computers, and machines, and as a methodology for guiding system development based on human-centeredness, HMI has not developed as it should, its bottleneck effect is becoming increasingly evident.

There is less research on the interaction between human and environmental factors (Kim et al., 2022). Direct environmental interference will affect the formation of correct decisions and cause mistakes. There are many experimental studies on engineering quality and intelligent algorithm innovation.

Moreover, changes in application scenarios in the era of intelligence lead to new requirements and pose a considerable challenge to HMI (Rong et al., 2021). In the era of intelligence, the application of Artificial Intelligence (AI) technology in special cabins needs to be improved, and the development of HMI technology in special cabins is in the future (Rawat et al., 2024). In addition to researching various factors of HMI from various research perspectives, humans are the core of it and will also be integrated with interactive devices with the development of technology. Therefore, improving the operational efficiency of special cabins and ensuring the safety and health of personnel has become an urgent problem to be solved. It is necessary to explore the application of HMI technology in designing special cabins to improve operational efficiency and comfort.

Despite existing advancements in cabin design, several issues remain unresolved. First, the increasing integration of displays and controls often leads to cognitive overload and decreased operational efficiency. Second, ergonomic considerations are frequently under-prioritized, resulting in insufficient comfort and usability for operators during long-duration tasks. Third, previous evaluation methods mainly rely on single-channel subjective measures, which do not fully capture the complexity of human cognitive and physiological responses. These issues highlight a clear research gap: the lack of a systematic approach that combines multi-channel cognitive evidence with advanced optimization models for specialized cabin design. Addressing this gap has formed the basis for the next step of this investigation.

1.4 Research Objectives

Premised on the issues and problems stated earlier, three(3) research objectives were identified to guide the research as follows:

To analyze operator comfortness and efficiency in specialized cabin environments by examining spatial layout, lighting design, and color environment using cognitive interaction and multi-channel approaches.

To evaluate the design model validate design and evaluation methodologies that enhance operator comfort and efficiency in specialized cabin environments.

To establish an integrated design model for specialized cabin environment design based on human-centered and cognitive interaction principles.

1.5 Research Questions

Currently, due to the increasing complexity of work tasks in special cabins, more attention is paid to the nature of work and workplaces in the digital industry in the field of small spaces. Due to the integration of complex environments, complex equipment, complex manipulators, and so forth, operators are under extra pressure on their work. This research aims to answer the following questions:

How can the spatial layout, lighting design, and color environment of specialized cabin spaces be analyzed through cognitive interaction and multi-channel approaches to improve operator comfortness and efficiency?

What methodologies can be developed to evaluate the effectiveness of spatial layout, lighting, and color environment designs in specialized cabins?

How can an integrated design model for specialized cabin space environments be developed?

1.6 Research Scope

This research conducts in-depth and systematic research on designing a special cabin space environment with cognitive interaction characteristics. The research involves many disciplines, content and knowledge, but corresponding limitations exist. The empirical research direction and its limitations can be specifically divided into three systems. First, building the cognitive interaction model of special cabins and human cognition is complicated, and some activities take more work to express formally. Therefore, in this research, the feature quantification construction model is carried out when building the cognitive model, only aiming at the description of the operator's perceptual intention. However, in future research, cognitive behaviour and mechanism can be studied and improved through mathematical models.

Second, in the exploratory research system, the special cabin only focuses on land-based military cabins and does not take special cabins such as spacecraft and submersibles as the research content. In the follow-up research, the above-mentioned comprehensive research should be dealt with to improve the universality and integrity of the method.

Third, in the research of empirical systems, the methods, theories, and principles proposed in this research are only in the trial and development stage. In order to prove the feasibility of the method, the follow-up method demonstration stage is required to prove the method's effectiveness in the direction of practical production.

1.7 Research Significance

The special cabin is the carrier for the operator to interact with the environment and is the primary workplace for the operator to complete the entire task.

1.7.1 Operators

For operators of specialized cabins, this research holds significant importance. By thoroughly investigating multi-channel sensory information and cognitive interactions within specialized cabins, it provides optimized design solutions for cabin environments. The enhanced environment configuration, including a seat spacing of 1000mm, illumination of 340 lux, a color temperature of 4500K, and a mixed Hue, Saturation, Value (HSB) color database, significantly improves operational efficiency and comfort. These improvements not only enhance operators' visual and tactile perception capabilities but also refine their work experience in high-demand and complex task environments. Furthermore, the development of a deep learning-based multi-channel interaction visual and tactile cognition efficacy algorithm has provided an intelligent evaluation system for specialized cabin design, ensuring that design solutions are more scientific and reliable. These advancements not only elevate the overall performance of specialized cabin environments but also offer operators a more efficient and safer working space, thereby substantially enhancing their operational efficiency and comfort.

1.7.2 Cabin space manufacturers

For manufacturers, the construction and optimization of high-performance specialized cabins hold significant importance. Firstly, by adopting advanced design principles and technologies, manufacturers can enhance their market competitiveness and demonstrate their expertise in high-precision and high-performance environment construction. Manufacturers, can expand their product lines and increase market share by offering specialized cabin products that meet the latest technological standards. This efficiency in design and optimization not only improves the quality and reliability of the products but also meets increasingly stringent industry standards and customer requirements, thereby increasing customer satisfaction and loyalty.

Secondly, manufacturers can reduce resource waste and cost expenditures during the construction and production processes by implementing scientific design and engineering practices. This leads to improved economic efficiency of the overall project. Accurate design and efficient production processes also help shorten project delivery timelines and accelerate market responsiveness, thereby enhancing operational efficiency and flexibility. Finally, by participating in the construction and manufacturing of high-standard specialized cabins, builders and manufacturers contribute to technological advancement and innovation within the industry. Integrating the latest technological achievements and optimizing design methodologies allows them to set new technical standards and lead industry development trends. This innovation not only boosts their technical capabilities but also advances the entire industry, carrying long-term strategic significance.

1.8 Operational Definitions

Important bywords have been used continuously throughout the research to guide the overall processes involved.

1.8.1 HMI

Hewett et al. (2022) pointed out in the report that the Human-Computer Interaction Professional Organization of the American Computer Society defines HMI as an interdisciplinary subject, mainly studying the principles and technologies of natural and efficient information exchange between humans and computer systems and conducting basic research. In this research, HMI adopts the multi-disciplinary method of the cognitive, perception, visual, and psychological systems. It is necessary to consider the experience, reliability, and safety of the operator to achieve the concept of HMI and to consider the limitations of the cabin environment.

1.8.2 Special cabin space

Special cabins refer to semi-enclosed or fully enclosed special workplaces with special performance requirements and certain limitations in specific complex environments (Su et al., 2018). The site contains a complex man-machine-environment system, usually composed of people, machines and workspaces. The special cabin defined in this research belongs to the vehicle-mounted command cabin, which is composed of different spaces, such as physical space and digital space. It comprises operators, cabin facilities, cabin environment and cabin automation system to form a complex man-machine space environment system.

1.8.3 Cognitive interaction

Cognitive interaction emphasizes the cooperation of multiple disciplines, such as cognitive psychology, AI, HMI, linguistics, neuroscience and philosophy (Chen et al, 2021). It pays more attention to human cognitive activities, including perception, attention, memory, reasoning, problem-solving, cognitive development, and so forth.

As for this research, cognitive interaction refers to the interaction efficiency and effect between the operator and the cabin. It is necessary to start with environmental and space perception, optimize the design and function of the cognitive interaction system, and make it more in line with human cognitive characteristics and interaction needs, thereby, improving the effect of cognitive interaction and user experience.

1.8.4 Multi-channel

Multi-channel interaction uses multi-model information such as voice, image, text, eye movement and touch to exchange information between humans and machines (Lu et al., 2014). It has broad application prospects in physiological and psychological assessments, office education, military simulation and medical rehabilitation. The multi-channel defined in this research is based on multiple sensory channels, such as vision and tactile, trying to describe the human perception process comprehensively. The model divides the perception process into three (3) stages: perception input, processing, and behaviour output, and proposes various cognitive strategies and modules to explain human perception and decision-making processes.

1.9 Organization of Theses

The organization of theses starts with chapter 1, slowly go in depth into Chapter 2, Chapter 3 and Chapter 4. Chapter 5 concludes the theses.

Chapter 1 discusses on introduction. Chapter 2 explores on characteristics of cognitive interaction. Chapter 3 defines phase by phase methodology. Chapter 4 presents research process and analysis. Chapter 5 revisits the objectives and gives appropriate suggestions or recommendations for future studies. Conclusion ends up the theses.

1.10 Summary

This chapter briefly introduces the issues surrounding the design of the special cabin space environment under multi-channel and cognitive interaction, thereby formulating the problem statements, research objectives and research questions that help guide the overall research. In addition, this chapter also highlights the research scope and research significance. Furthermore, this chapter focuses on layout, light environment, and color environment issues under multi-channel and cognitive interaction and suggested models to overcome this problem. Chapter 2 will explore thoroughly on the previous literatures related to this research.