Analysis of Research Hotspots of Cognitive Load from the Perspective of Product Design Based on Measurement System, Cause Analysis, and Regulation Strategy

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Abstract. In order to sort out and analyze the research hotspots of cognitive load in product design, this paper analyzed the domestic and international research progress of cognitive load research from the perspective of product design by means of literature research method and other tools such as CiteSpace, with a focus on the analysis of three hotspots of the cognitive load measurement system, cause analysis, and regulation strategy in product design and exploring the development of cognitive load research hotspots in product design. To this end, the trend of research hotspots on the cognitive load of product design in the context of the digital age was proposed. In view of the three hotspots of cognitive load research from the perspective of product design, the research framework for the innovative application of cognitive load theory in product design is clarified; with the development of neuropsychology and Internet technology, the measurement of cognitive load in product design will be refined and objectified, and the measurement methods will be more diversified; the focus on the analysis of the causes of product design will be gradually changed from product factors to the product, users' cognitive processing, and users' psychology; the preconditioning, naturalization, and refinement of cognitive load regulation strategy in product design can fundamentally adjust cognitive load and clearly guide the innovative design of products.

Keywords: product design · cognitive load · measurement system · cause analysis · regulation strategy

1 Introduction

With the advent of the digital age, the "human-physical" system in product design has evolved into a "human-information-physical" system. Information becomes an important part of product design (both material and immaterial). With the gradual diversification of product functions, the amount of product information continues to increase, the information logic becomes increasingly complex, the difficulty of information processing gradually rises, and the product's requirements for user cognition continue to

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raise. Due to the limited cognitive processing resources and capabilities of users, the cognitive load of users will continue to increase and the user experience will decrease, which has become an important part of product design research. It is necessary to sort out the status quo and progress of cognitive load research in product design, especially the clear development trend.

2 Clustering of Research Hotspots of Cognitive Load in Product Design

Cognitive Load is derived from the term Mental Load (which is often translated as mental load or brain load). American psychologists Miller (1956) [1], Kahneman (1973) [2] and American artificial intelligence expert, Rumelhart (1980) [3] conducted research on brain load, cognitive resource theory, and schema theory respectively, which lays a theoretical foundation on the research of cognitive load. Australian cognitive psychologist, Sweller (1988) [4] proposed a widely accepted definition based on the previous theoretical basis, that is, cognitive load refers to the total amount of mental activity imposed on an individual's cognitive system during a given operational time. Subsequently, the research results of many scholars, such as Sweller (1998) [5] and Xie's (1998) [6] cognitive load category research, Paas, Van (1994) [7], and Neerincx's (2003) [8] cognitive load Model research, etc., jointly constructed the theoretical framework of cognitive load.

Cognitive load theory is a relatively complete theoretical research system, which provides a theoretical basis and research framework for cognitive load research in product design. This research used SU = 'product design' * 'cognitive load' as the retrieval formula, retrieved academic journals and academic papers from 2010 to 2021, and selected 126 valid documents. The keyword clustering analysis was conducted by CiteSpace visual literature analysis software, and three research hotspots of cognitive load metrics, cause analysis, and regulation strategies in the study of cognitive load theory in product design were summarized and inferred by combining literature study.

3 Current Status of Research Hotspots of Cognitive Load in Product Design

3.1 Research on Cognitive Load Measurement System in Product Design

The research on cognitive load measurement system in product design mainly includes three aspects: measurement mode, setting of indicators and weights, and measurement method.

3.1.1 Measurement Mode

Khawaja of the University of New South Wales in Australia (2014) [9] proposed a measurement model of cognitive load from the input of environment, user, and other modal data, combined with the attributes of users and tasks. Park of Korea University (2018) [10] quantitatively evaluated the user cognitive load of complex system interface design based on each sub- indicator of the NASA-TLX subjective evaluation scale and the impact of time pressure on information processing speed. Xue Yaofeng et al. (2019) [11] constructed a cognitive load quantification model based on the metrics of eye-tracking technology. Chen Haolong and He Renke (2020) [12] obtained the cognitive load measurement model of robot voice interaction based on the measurement indicators of the NASA-TLX scale through the Analytic Hierarchy Process (AHP).

3.1.2 Setting of Indicators and Weights

There are two ways to construct cognitive load measurement indicators, as shown in Fig. 1. One is to extract indicators related to cognitive load by analyzing existing cognitive load measurement methods. This way of constructing metrics is simple and there are more studies using this type of method [12–14], but it is vulnerable to the limitations of measurement methods, as shown in Fig. 1-A. The other is to analyze the generation mechanism of cognitive load and product characteristics [15, 16], so as to summarize and propose measurement indicators and determine the measurement method according to the constructed indicators. In this way, the construction of indicators is more comprehensive and accurate, as shown in Fig. 1-B.

3.1.3 Measurement Method

There are two main types of cognitive load measurement methods in product design: subjective measurement method and objective measurement method [17–19], as shown in Table 1. Subjective measurement method has a long application time, is easy to use, and is not limited by experimental instruments, but the data objectivity is weak; objective measurement method is objective and can more accurately measure changes in cognitive load, but it is limited by experimental conditions and subjects, with a small scope of application.

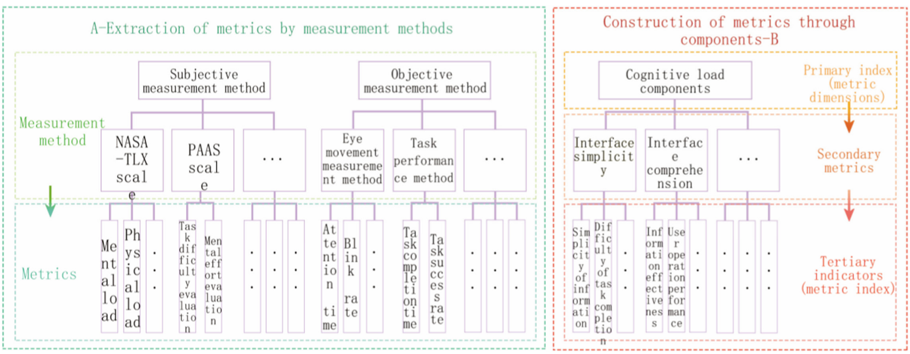

Fig. 1. Two ways of constructing cognitive load measurement indicators in product design (Drawn by the author)

Table 1. Cognitive load measurement method (Drawn by the author)

Category	Measurement method	
Subjective measurement method	Scale method	NASA-TLX scale
		WP scale
		PAAS scale, etc.
	Observation	Non-participatory observation
		Participatory observation
Objective measurement method	Peripheral nervous system Electrophysiological Signal measurement	Electrocardiogram (ECG), Eye movement experiment (EOG) Galvanic skin test (GSR), etc.
	Central nervous system Electrophysiological signal metrics	Electroencephalography (EEG), Event-related potential experiment (ERP)
	Behavioral experimentation	Handwriting behavior experiment, etc.
	Task performance measurement method	Single task performance test
		Multi-task performance test

3.2 Research on Cognitive Load Measurement System in Product Design

Cognitive load cause analysis in product design explores the causes of users' cognitive load fluctuations in product design, mostly from the cognitive load category dimension and cognitive load factor dimension.

3.2.1 Cause Analysis of Category Dimension

Sweller (1998) [5] proposed that cognitive load is divided into three categories: external cognitive load, internal cognitive load, and related cognitive load, and conducted cause analysis on the cognitive load of the three categories based on cognitive psychology. Among them, the external cognitive load is caused by the way of information presentation, the internal cognitive load is caused by the inherent characteristics of the information, and the relevant cognitive load is involved in the working memory resources invoked in the cognitive processing process.

Based on this research, scholars such as Luo Xiaoyun (2015) [20], He Xiaomei (2020) [21], and other scholars have carried out research on the causes of cognitive load category dimension in product design and made the following conclusions: the causes of external cognitive load in product design include the organization and presentation of product information; the causes of internal cognitive load include the inherent complexity and interactivity of product information and the relevant schemas mastered by users; the causes of relevant cognitive load include the process of schema construction and factors such as emotion and motivation.

3.2.2 Cause Analysis of Element Dimension

Pass (1994) [7] proposed a structural model of cognitive load and three causal factors that affect cognitive load: task characteristics, learner characteristics, and the interaction between tasks and learners. On the basis of this research, many scholars took the three factors of cause and effect as the starting point, combined with the schema theory and the theory of limited cognitive resources, to explore the causes of cognitive load in the factor dimension in the cognitive process.

On this basis, scholars such as Li Jing (2015) [22], Wu Xiaofeng (2017) [23], Yuan Yifan (2020) [16], and other scholars have analyzed the components of cognitive load, namely, limited working memory capacity, uneven distribution of attention resources, and construction and extraction of graphs. Based on the three elements of cognitive load, the analysis and research on the causes of cognitive load in product design were carried out. Among them, Li Jing built the element model of the cognitive load of human-machine interface based on the product interface, the user, and the interaction of the two in the process of generating user cognitive load, and believed that task difficulty, users' cognitive ability and ways, and the relevance of interface and user schema can cause cognitive load fluctuations; Wu Xiaofeng thought that too many options in the product operation process, too much user thinking, and insufficient interface clarity will cause cognitive load; Yuan Yifan divided the causes of cognitive load into implicit causes, explicit causes, and interactive causes.

3.3 Research on Cognitive Load Regulation Strategies in Product Design

The research objects of cognitive load are users and information, including the cognitive level of users, the performance of information, and the interaction between users and information. The main application directions of its regulation strategies are product interaction design and product interface design.

3.3.1 Regulation Strategies in Product Interaction Design

The basis of product interaction design is the interaction behavior and interaction process between users and products [24], which are closely related to user cognition. The regulation strategy of cognitive load theory in product interaction design mainly focuses on the regulation of cognitive load in terms of product interaction logic, interaction mode, and interactive information point setting by means of simplification, naturalization, and clarification. For example, from the perspective of cognitive load, Kuo (2013) [25] proposed a regulation strategy to simplify the operation of the monitor and reduce the operation error rate; Wu Xiaofeng (2017) [24] proposed that interaction design should avoid unnecessary elements, use basic design principles and control elements, reduce redundant operations, reasonably display the available options, ensure the readability of the design, and carefully use icons and other cognitive load regulation strategies; Wang Haibo (2018) [26] proposed optimized interaction logic and interactive information points, simplifying the interaction process and other regulation strategies. Gao Han (2019) [27] studied the information interaction logic of automobile human-machine interface based on cognitive load and proposed a regulation strategy for information layout optimization. Luo Chenchen (2019) [28] proposed regulation strategies such as easy-to-read, easy-for-decision, easy-to-input, and easy-to-return in the design of Internet products for the elderly. He Xiaomei (2020) [21] put forward regulation strategies such as optimizing element presentation and interaction logic, reducing interaction complexity and interactivity, and clarifying feedback mechanisms for cognitive load in human-computer interaction. In the research of product interaction mode, with the gradual increase in the amount of product information interaction, the information interaction logic and interaction scenarios are increasingly complex, and a single interaction mode gradually cannot meet the existing interactive information volume. In order to reduce the cognitive overload caused by a single interaction method, multiple interaction methods are integrated to form a multi-modal interaction [29].

3.3.2 Regulation Strategies in Product Interface Design

As the interface between the product and the user, the product interface guides the user to operate, and its design should conform to the user's cognitive characteristics as much as possible. Therefore, it is of great significance to apply regulation strategies to reduce the cognitive load of interface design and optimize product interface design. Taking the product interface as the design carrier, the interface layout and elements are optimized through strategies such as simplification, ordering, integration, and visualization, and prompt and feedback are optimized through strategies such as emphasis, timeliness, and metaphor, so as to regulate the user's cognitive load. For example, Li Jing (2015) [22] suggested balancing the cognitive load of the human-machine interface through regulation strategies such as information filtering, information highlighting, and information performance optimization. Yuan Yifan (2020) [16] presented regulation strategies such as simplification, ranking, and migration to regulate the cognitive load of the interface of the course selection system in colleges and universities. Cheng Jiaoyan (2019) [30] proposed regulation strategies such as the proximity principle and the concise principle to achieve the purpose of rationally organizing and presenting interface elements and reducing the cognitive load of the interface. Martina (2020) [31] and Air (2020) [32] conducted research on cognitive load regulation strategies for health record interfaces in terms of interface feedback and information visualization. Based on this research, scholars such as Luo Xiaoyun (2015) [20], He Xiaomei (2020) [21], and other scholars have carried out research on the causes of cognitive load category dimension in product design and made the following conclusions: the causes of external cognitive load in product design include the organization and presentation of product information; the causes of internal cognitive load include the inherent complexity and interactivity of product information and the relevant schemas mastered by users; the causes of relevant cognitive load include the process of schema construction and factors such as emotion and motivation.

4 Research Hotspots of Cognitive Load in Product Design

4.1 Research Trend of Cognitive Load Measurement in Product Design

With the development of neuropsychology and the deepening of cognitive load research, the research on cognitive load measurement in product design presents the following three trends:

4.1.1 Focusing on Measures of Cognitive Load Contacts

In the construction of the measurement index system, increasing attention is paid to building a measurement system from the perspective of the user and product information contacts, so as to more accurately screen and measure user cognitive load contacts, and its research granularity is becoming more and more refined.

4.1.2 Emphasizing the Application of Objective Measurement Methods

In the selection of measurement methods, emphasis is increasingly put on the application of objective measurement methods, so as to obtain more accurate and real-time cognitive load data, showing a research trend of focusing on objective experiments, supplemented by subjective scales, and emphasizing quantitative research.

4.1.3 Advocating the Validation of Multiple Measurement Methods

In view of the large individual differences of users' cognitive load and the characteristics of being easily affected by the environment, in the experimental design, multiple measurement methods tend to be used at the same time to mutually verify the experimental results, avoid the deviation caused by a single measurement method, and improve the measurement reliability.

4.2 Research Trend of Cognitive Load Cause Analysis in Product Design

The research on the causes of cognitive load in product design mainly presents the following four trends:

4.2.1 Focusing on the Cause Analysis at the Component Level

The cause analysis of cognitive load components starts from the theoretical basis of cognitive load, focuses on the difference analysis of different users' cognitive load components, and reduces users' cognitive load by optimizing the inclusiveness of product cognitive load.

4.2.2 Emphasizing the Cause Analysis at the User Perception Level

The user's feeling and perception of product information determine the quantity and quality of product information obtained by the user, which is not only the premise of the user's information processing but also directly produces the user's instinctive perception experience. The analysis of the causes of cognitive load at the user perception level emphasizes guiding the regulation of user cognitive load in the information acquisition stage.

4.2.3 Strengthening the Cause Analysis at the Information Processing Level

The process of processing product information by users is based on the information obtained by perception, and the problems are solved through thinking, invoking, and combining habits in long-term memory, experience, knowledge, etc. The cause analysis at the information processing level mainly focuses on the analysis of cognitive load contact structure, cognitive logic, interaction mode, prompt and feedback, etc., with an emphasis on guiding the cognitive load regulation of complex product information.

4.2.4 Paying Attention to the Analysis of the Causes at the User's Psychological Level

The research is mainly carried out from the perspective of the user's internal psychological driving force, focusing on the influence of changes in psychological factors such as needs, motivation, mood, emotion, and other psychological factors in the user's consumption and use process on the user's internal driving force to overcome the cognitive load. Then by strengthening the emotional value of products, users' intrinsic drive and subjective initiative are boosted, and users' cognitive load experience is regulated.

4.3 Research Trends of Cognitive Load Regulation Strategies in Product Design

The research on the causes of cognitive load in product design mainly presents the following three trends:

4.3.1 Paying Attention to the Research on Preconditioning Regulation Strategy

With the advent of the digital age and the rapid development of technological applications such as artificial intelligence, big data, and the Internet of Things, the transformation of cognitive subjects and the transfer of cognitive processing have become possible. The prepositional characteristics of cognitive load regulation in product design are becoming more and more obvious. In product design, the cognitive process that originally requires users to acquire, process, and output information is transferred or partially transferred to products and product systems, thereby fundamentally regulating user cognitive load.

4.3.2 Emphasizing the Research on Naturalized Regulation Strategies

Attention is given to the matching of product usage intentions, usage steps, usage methods, usage results, usage feedback, etc. with the user's existing habits, experience, knowledge, etc. Thus, a natural interaction that conforms to the user's cognition is generated, thereby achieving cognitive load regulation in the process of product interaction.

4.3.3 Attaching Importance to the Research on Refined Adjustment Strategies

With the deepening of the research on regulation strategies, the research objects show a trend of continuous refinement from cognitive tasks to cognitive processes and continuously refining cognitive load contacts, and the research dimensions are also refined into target population, product value, functional structure, information logic, interaction, system representation, and other dimensions. Its research objects and dimensions are becoming more and more refined on the basis of the original systematization, the direction of refined adjustment strategies is clearer, and the guidance for product design innovation is also more specific.

5 Conclusion

With the continuous strengthening of the "information carrier" characteristics of products in the context of the digital age, the importance of cognitive load research in product design has become increasingly prominent. From the analysis of the current situation of research hotspots, it can be concluded that the cognitive load research framework in product design supported by the three research hotspots of the measurement system, cause analysis, and regulation strategy is gradually taking shape. Among them, the research of measurement system focuses on expanding and optimizing qualitative and quantitative methods and tools, which are mainly used for the acquisition of design problems in the early stage of design when used in pre-design and design evaluation in the later stage of design when used in post-test; the analysis of cognitive load problem is applied to user research, design positioning and other links in the product design process by virtue of the analysis of the acquired cognitive load problem; the regulation strategy acts on the solution of design problems and the generation of innovative design schemes by clarifying the innovative ideas and paths for solving design problems. In the research hotspot prospect, three development trends of three research hotspots are put forward, and it can be concluded that with the continuous optimization of research methods and technical means, the breadth and depth of cognitive load research in product design continue to expand, which has important academic and theoretical value on the research on application to cognitive load and product design innovation; at the same time, it has important application value for enterprises to innovate design ideas, optimize design methods, and improve design quality and user experience in the practice of product design innovation.

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