Study on Human-machine Interface Design of Rotary Drilling Rigs

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Abstract. In response to the irrational design of various module elements in the digital display interface of rotary drilling rigs, ergonomic design principles such as consistency principle, information visual feature organization principle, information encoding principle, and color perception principle were considered, and the human-machine interface of rotary drilling rigs was improved by combining the actual requirements of information presentation and functional module design. A two-factor [display interface (before and after the improvement) × task type (five functional modules)] intragroup experiment was designed. The usability and cognitive load of the improved interface were validated and evaluated by measuring the physical parameters of eye movement, the operating time, and the subjective questionnaire score. As revealed by the study results, the improved human-machine interface of rotary drilling rigs exhibits higher usability and lower cognitive load. This study provides a reference for the reasonable layout and design of the human-machine interface of complex construction machinery.

Keywords: Construction machinery; human-machine interaction; eye movement test; usability

1 Introduction

Construction machinery, which is an essential part of the machinery industry, is closely related to the development of transportation construction, energy industry construction, agriculture, forestry, and water conservancy construction, industrial and civil building construction, and national defense engineering construction, being especially associated with the modernization of such fields. With the continuous expansion of the global infrastructure and the strengthening of the environmental protection-centered construction concept, pile foundation, especially bored cast-in-place concrete pile foundation, has been widely applied in place of nearly all other foundations [1]. As representative boring construction machinery in building foundation engineering, rotary drilling rigs have been widely used in various foundation construction, such as cast-in-place piles and foundation reinforcement [2]. Large-scale construction machinery, such as rotary drilling rigs, operates in harsh open-air environments, and the operator works for a long time under substantial pressure, making them susceptible to fatigue-induced operational errors. Therefore, how to reduce the working pressure of operators through an efficient design mode has become the primary purpose of the interactive design of rotary drilling rigs.

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With the development of digital technology, the interactive digital display screen is adopted as the display interface for large-scale construction machinery. With rotary drilling rigs as an example, the operations that the operator needs to complete are complicated, involving many functional modules and display labels. In complex and even dangerous environments, the display interaction design with strong usability and low cognitive load can effectively help the operator complete all operations. However, the existing display interaction design has obvious ergonomic problems, such as unreasonable interface layout and color design. Specifically, the layout and color are the core pain points in the current display interface design. The layout design is an essential part of the domain of human-machine interface design, and the layout of the human-machine interface should adapt to people's understanding and operation process [3]. The design idea of the human-machine interface layout is to make the interface layout conform to the operator's cognitive ability for interface information using principles of information organization rule and visual search mode based on the characteristics of human thought. For instance, the layout of panel modules and components can be optimized by means of module importance analysis [4]. For another example, the user interface layout can be optimized based on principles of visual field accessibility, visual search, and information organization rules [5]. The contrast principle and encoding principle of colors, which constitute an important influencing factor in ergonomics, can provide valuable insights for interaction design [6].

Given the particularity of the field of construction machinery, the display interface of large-scale construction machinery has been rarely investigated in China, lacking theoretical guidance of human factors engineering in display interaction design, and aesthetic design principles have not been combined comprehensively enough [7]. The display interface design under the guidance of human-machine interface design can enhance the usability and ease of use of the interface and significantly improve the driver's operation comfort, operating accuracy, and working efficiency. In this study, the display interface layout of a rotary drilling rig was explored. The layout and color design of this drilling rig proceed, drawing upon key principles of human factors engineering design. These include the functional zoning principle, encoding principle, and color design principle. Such deliberate application aims to optimize the user experience and elevate interaction comfort for the operator.

2 Design Principles

The principle of cognitive psychology related to information organization serves as an important reference for interface design, and the interface designed with relevant layout principles is more in line with people's cognitive process and can reduce the load during the use of the interface [3]. Many ergonomics principles can also be referenced for the use of colors. The improvement scheme can refer to such common ergonomic design principles as consistency principle, information visual feature organization principle, information encoding principle, and color perception principle.

Consistency principle: The user's learning time and memory time can be reduced, and mistakes can be avoided by using a human-machine interface conforming to user experience and knowledge with objectivity-subjectivity consistency and a handling method in line with the current situation. For example, the handles with similar functions should be arranged in the same region and represented by icons similar to the material objects. In addition, the consistency of design elements in the design interface is beneficial for the identifiability of the display interface [8]. According to the principle of consistency, in the information display of construction machinery, it is usually necessary to indicate warning in red, danger in yellow, and safety in green.

Information visual feature organization principles: Visual feature organization principles include the neighborhood principle, similarity principle, proximity principle, and symmetry principle, which play a guiding role in interface design. For instance, when a large amount of information needs to be displayed on the interface, related information should be organized together by the neighborhood principle, or similar information should be represented in the same color by the similarity principle, which enables the user to quickly and accurately identify grouped information. The Gestalt theory has pointed out many visual feature organization principles related to interactive design [9]. For example, the similarity principle points out that people are used to grouping elements with similar shapes, colors, and sizes, making it effective to distinguish functional modules of the same type by different colors or shapes, which can effectively highlight their differences in functional type. According to the proximity principle, people tend to group the elements close to each other, and functional zoning can be implemented based on the proximity principle in the design process. As indicated by the symmetry principle, when perceiving objects, people are used to treating symmetrical shapes as a whole. The law of subject/background reveals that people always automatically divide the visual area into subject and background when perceiving objects and can distinguish the relationship between element modules by highlighting some elements in the design, and so on. These visual organization principles can play a guiding role in the interface layout design. The dashboard layout designed according to the Gestalt principle can effectively improve the work performance of operators and enable them to quickly identify changes in information [10]. As shown in **Figure 1**, The three elements above are closer, while the three elements below are closer, with a dividing line added in the middle, indicating that they belong to two modules.

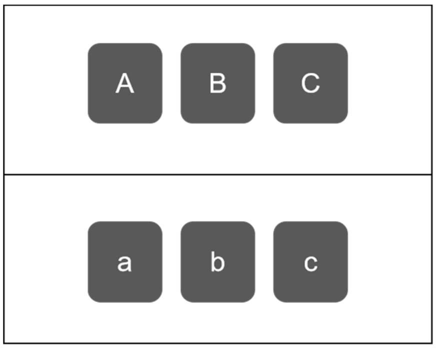

Figure 1. Example of Information Visual Feature Organization Principle

Information encoding principle: Encoding in the digital display interface is an essential principle in design. Encoding technology can reduce visual information disorder and improve visual cognitive performance. Color encoding, an important encoding mode in digital display, can strengthen visual display separation through color difference and improve visual search performance [11]. The degree of visual attention capture is related to visual perception, and the cognitive speed is affected by the color difference [12]. In the study on color encoding of aircraft display interfaces, it has been pointed out that under a black background, red and yellow can serve as the suitable codes needing to accurately identify information, and light green and yellow as the suitable codes needing to rapidly identify information, while blue may not serve as any code [13]. Color encoding has also found extensive applications in the design of warning information. When red, yellow, and green colors that people are familiar with are used to express the meanings of alarming, warning, and safety, the visual search performance can be significantly improved [14], and the ability to judge potential dangers can also be bolstered [15]. In addition, setting the display content of different functional zones into different color or shape display formats can make it difficult to confuse visual modules and effectively reduce the visual load in visual search [16]. Different colors (black and gray) and shapes (square and circular) can clearly divide the six elements into two modules, see Figure 2.

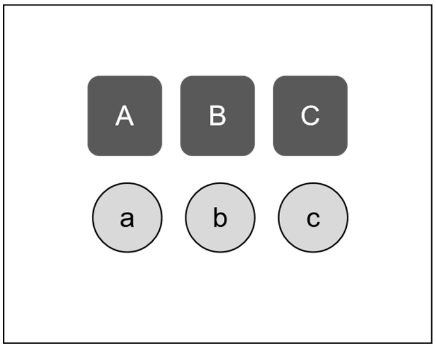

Figure 2. Example of Information Encoding Principle

Color perception principle: The color perception principle in ergonomics can also be used to guide interface improvement. Under the dark background, for example, white and yellow fonts are easy to read, and the bottom color and background color with a contrast of not less than 8:1 are easy to read [12]. A higher contrast can lead to better readability, and brighter text colors can have a better impact on readability and visual comfort [17]. For the automobile dashboard, white characters and pointers under the black background are more readable [18]. As shown in Figure 3, due to the increase in color contrast, B on the right is easier to see than A on the left.

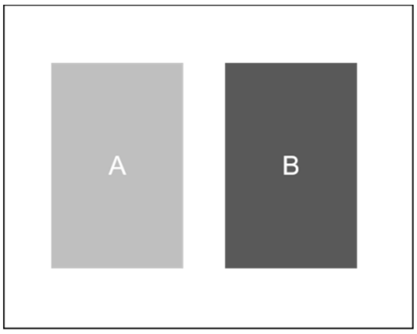

Figure 3. Example of Color Perception Principle

3 Design Example

Through field investigation and interview, five functional modules are clearly presented on the display interface of the rotary drilling rig: engine, mast, drilling, hydraulics, and fault. The engine module refers to the display of engine-related operating parameters, including engine speed, engine oil quantity, hydraulic oil temperature, hydraulic oil level, oil pressure, cooling water temperature, working time, battery voltage, etc.; the mast module is used to check and adjust mast parameters, including mast adjustment mode, deflection and rotation angle, mast position, rotation resetting, etc.; the drilling module is used to detect the drill in real time, including drill bit and boring parameters, depth resetting, winding parameters, and power head parameters; the hydraulic module displays the reading of hydraulic pressure everywhere and the reading changes; the fault module prompts fault information and relevant inquiries can be made.

In the human-machine interface design of the rotary drilling rig, the principles of consistency, information visual feature organization, information encoding, and color perception should be considered comprehensively at first. For example, the information layout is disordered in the original interface, and in the improved interface, the information of different modules is displayed in the same region as a whole, conforming to the neighborhood principle in the principles of information visual feature organization. In the original interface, visual elements are excessively complicated, accompanied by a high identification difficulty and high cognitive load. In the improved interface, different modules are designed in a uniform circular or strip shape or with pure characters, which conforms to the similarity principle and the information encoding principle. Simultaneously, it is essential to integrate functional requirements with interface logic. This involves considering the visual impact of various visual elements, their combinations, and their display styles. The initial interface of the rotary drilling rig is shown as Figure 4 (a), and the finally designed interface is as Figure 4 (b).


The safety handle is not opened

The safety handle is not opened !

Figure 4. Interface of the Rotary Drilling Rig: (a) Before Improvement; (b) After Improvement.

4 Evaluation Experiment

4.1 Experimental design

In this study, a two-factor [display interface (before and after the improvement) × task type] intragroup design experiment was designed. The five functional modules are denoted as A, B, C, D, and E, respectively, and the corresponding experimental tasks are shown as Table 1.

Table 1. Experimental Tasks

Module	Specific interaction tasks
Engine (A)	Check the relevant information of the engine, including engine speed, engine oil quantity, hydraulic oil temperature, hydraulic oil level, oil pressure, cooling water temperature, working time, and battery voltage successively.
Drilling (B)	Check relevant drilling information, including the animation, position, winding parameters, and power head parameters.
Mast (C)	Check the relevant information of the mast, including the mast coordinate, XY reading, rotation angle, and resetting after rotation once.
Fault (D)	Check the relevant information about the fault, including the alarm hint and sound, and enter the fault inquiry and engine fault pages.
Hydraulics (E)	Check the relevant information on hydraulic pressure, including the reading of hydraulic pressure and the change in the hydraulic column.

The experimental subjects were 12 experienced rotary drilling rig operators at the age of (30.27±8.93) with driving experience of (10.36±6.27) years, height of (173.16±2.38) cm, and weight of (65.32±16.37) kg. All subjects were males, free from visual impairment with uncorrected visual acuity of 1.0 or above.

The rotary drilling rig works under complex conditions, involving various environmental parameters and making the simulation difficult. In this study, two versions of the display interface were successively updated on a rotary drilling rig, and a real vehicle experiment was carried out. Tobii Pro glasses 3 eyeglasses-type eye tracker was adopted, with an acquisition frequency of 100 Hz and a resolution of 1920 ×1080 px.

The eye movement physiological indexes collected in this experiment were the mean time of fixation points, the pupil diameter, and its change rate, and the completion time of each task was recorded as the behavioral index. The mean time of fixation points is the mean duration of each fixation point (unit: s). The pupil diameter change rate is the pupil diameter ratio at one fixation point to the mean pupil diameter. The completion time of the operation denotes the time spent in completing the task since the task instruction is received (unit: s).

4.2 Experimental process

Before the experiment, the subjects were informed of the experimental process and asked to read and fill in the informed consent and personal basic information. Then, the physiological measurement equipment was put on the subjects and calibrated. Subsequently, the subjects entered the cockpit, started the engine, sat in the usual driving posture, and freely viewed and operated the interface for 2 minutes according to their habits. Next, the formal experiment began, and the subjects interacted with the display interface on the real vehicle according to the requirements of the main test and completed the experimental tasks of five modules: engine, mast, drilling, hydraulics, and fault. The experiment was performed once in a positive sequence from Module A to Module E and in reverse sequence from Module E to Module A once. The measurement results (twice) of each module were averaged to avoid the influence of the learning effect. The eye movement signals were acquired and recorded throughout the experiment.

After the experiment, the subjects were required to fill in the System Usability Scale (SUS) for each interface. As shown in the following Table 2, this scale has been widely used and verified in evaluating the usability of human-machine interfaces. A total of 10 items were included in this scale and scored 1-5 from "disagree very much" to "agree very much", and the scores were added to acquire the total usability score.

Table 2. Usability Evaluation Questionnaire

	Description
1	I find that all functions in the system can be integrated well.
2	I can use this system only with the support of technicians.
3	I need to learn a lot of things before using this system.
4	I find that the system is unnecessarily complicated.
5	I think that this system is easy to use.
6	I think that most people will learn how to use this system very fast.
7	I find this system very cumbersome to use.
8	I want to use this system regularly.
9	I think that there are too many consistencies in this system.
10	I am very confident in using this system.

5 Analysis of Results

5.1 Operating time

Table 3. Statistical Operating Time of Interfaces and Modules (mean± standard deviation)

	A	B	C	D	E	Grand mean
Original	9.88±1.95	7.57±2.33	8.76±2.73	5.30±0.96	7.47±1.97	7.80±2.52
New	7.40±0.75	6.24±1.22	5.38±1.20	5.10±0.64	5.88±1.40	6.00±1.32

Table 4. Two-way ANOVA Results of Operating Time

Source of variance	Quadratic sum	df	Mean square	F	p
Intercept	5709.622	1	5709.622	1941.674	0.000**
Interface	96.674	1	96.674	32.876	0.000**
Module	143.605	4	35.901	12.209	0.000**
Residual	335.225	114	2.941		

Operating time directly reflects the usability of the human-machine interface. Indeed, the quicker the completion time for a given task within an interface, the more aligned the design is with users' needs. This often translates to higher satisfaction and increased ease of use. Two-way ANOVA was performed to analyze the influence of the two interfaces and different modules before and after the improvement of the operating time. From Table 4, it is observable that the two interfaces before and after improvement would generate significantly different influences on the operating time (F=32.876, p=0.000<0.05). Meanwhile, the influence of different modules on the operating time was also significant (F=12.209, p=0.000<0.05). Combined with the comparison of means as shown in Table 3 and Figure 5, after the improvement, the operating time of each module was shortened, and Modules A, C, and E were improved very evidently. These three modules were rightly the modules for information rearrangement based on the principles of information visual feature organization, and their behavioral performance was significantly improved, which proved the effectiveness of the improvement.

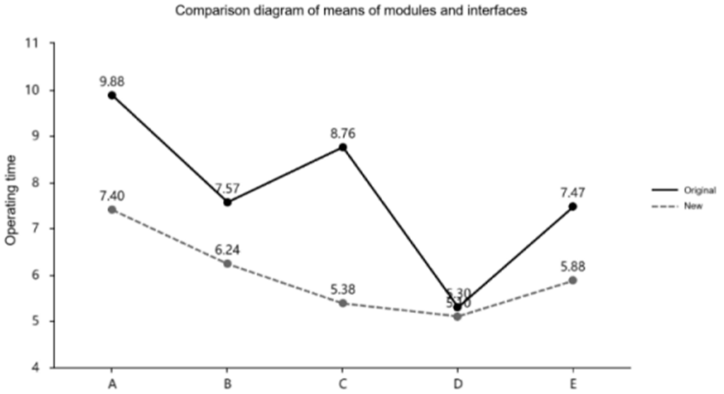

Figure 5. Comparison Diagram of Mean Operating Time

5.2 5.2 Mean time of fixation points

Table 5. Statistical Mean Time of Fixation Points of Interfaces and Modules (Mean ± Standard Deviation)

	A	B	C	D	E	Total
Original	516.05 ±373.23	489.33 ±334.89	593.77 ±588.76	824.48 ±746.43	495.06 ±380.05	565.52 ±496.32
New	471.29 ±282.01	462.79 ±314.20	520.94 ±340.65	622.87 ±400.06	435.16 ±287.23	497.76 ±325.51

Table 6. Two-way ANOVA Results of Mean Time of Fixation Points

Source of variance	Quadratic sum	df	Mean square	F	p
Intercept	5328976829.008	1	5328976829.008	31910.978	0.000**
Interface	25347087.318	1	25347087.318	151.783	0.000**
Module	136470089.607	4	34117522.402	204.303	0.000**
Residual	3470325054.751	20781	166995.094		

The mean time of fixation points can effectively reflect the cognitive load. When processing visual information, the longer the fixation point lasts, the greater the cognitive load [19]. Descriptive statistics were made on the mean time of fixation points of two interfaces and different modules before and after improvement. As shown in Table 5, the mean time of fixation points of different modules in the original interface was higher than that in the new interface, and the difference in Module C was larger. Furthermore, two-way ANOVA was implemented to explore the influence of interfaces and modules on the mean time of fixation points. From Table 6, it could be seen that the two interfaces before and after improvement would exert significantly different influences on the mean time of fixation points (F=151.783, $p=0.000<0.05$). Meanwhile, the influence of different modules on the mean time of fixation points was also significant (F=204.303, $p=0.000<0.05$). Combining the comparison of means in Figure 6, it could be known that after improvement, the mean fixation time of each module was shortened, indicating that the attention required to be input was significantly reduced, the cognitive difficulty was relieved, and the usability of the interface was significantly improved.

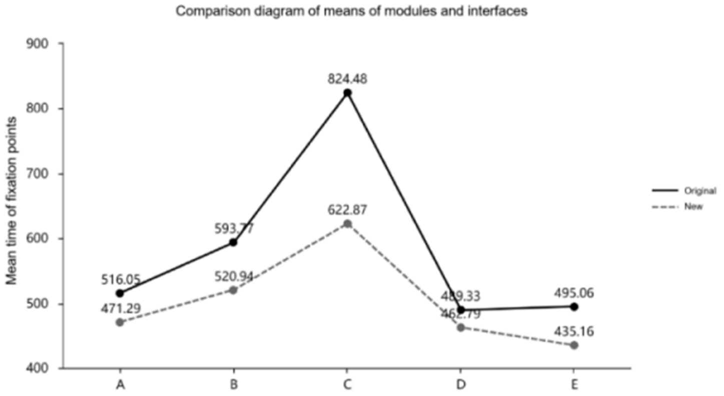

Figure 6. Comparison Diagram of Mean Time of Fixation Points

5.3 Change rate of pupil diameter

Table 7. Statistical Change Rate of Pupil Diameter of Interfaces and Modules (Mean ± Standard Deviation)

	A	B	C	D	E	Total
Original	0.06±0.04	0.06±0.04	0.08±0.02	0.04±0.03	0.07±0.04	0.06±0.04
New	0.05±0.04	0.05±0.03	0.07±0.04	0.04±0.03	0.06±0.04	0.05±0.04

Table 8. Two-way ANOVA Results of Change Rate of Pupil Diameter

Source of variance	Quadratic sum	df	Mean square	F	p
Intercept	61.551	1	61.551	50057.584	0.000**
Interface	0.386	1	0.386	314.216	0.000**
Module	2.199	4	0.550	447.121	0.000**
Residual	25.552	20781	0.001		

The change in pupil size is a commonly used physiological index to reflect cognitive load, which is more reliable because it is not controlled by subjective consciousness. The pupil change is positively correlated with cognitive load: the greater the pupil change, the higher the cognitive load level [20]. Considering the individual difference in pupil size, the pupil change can be more effectively reflected by the change in pupil diameter. First, the change rates of the pupil size of the two interfaces and different modules before and after improvement were subjected to descriptive statistical analysis, as seen in Table 7. It could be seen that the mean pupil diameter change rates of different modules in the original interface were higher than those in the new interface. Furthermore, two-way ANOVA was performed to investigate the influence of interfaces and modules on the mean time of fixation points. It could be observed from Table 8 that the two interfaces before and after improvement generated significantly different influences on the difference in the change rate of pupil diameter (F=314.216, $p=0.000<0.05$). The influence between different modules in the change rate of pupil diameter was also significant (F=447.121, $p=0.000<0.05$). By further comparing the means shown in Figure 7, it could be found that the change rate in the pupil diameter of the improved interface decreased significantly, indicating that the visual processing difficulty of the brain was reduced, the cognitive load was lowered, and the improvement was effective.

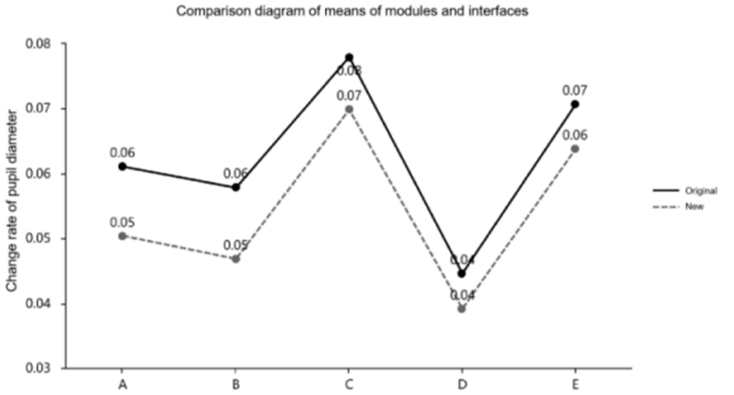

Figure 7. Comparison Diagram of Mean Change Rate of Pupil Diameter

5.4 Subjective questionnaire results

Table 9. T-test Results of Usability Score of Interfaces

	Interface (Mean ± Standard deviation)		t	p
	Original	New		
A	29.58±3.34	42.92±0.67	-13.549	0.000**
B	34.58±3.96	45.92±1.08	-9.552	0.000**
C	32.92±3.34	46.92±0.67	-14.226	0.000**
D	29.17±6.34	46.08±1.08	-9.116	0.000**
E	35.00±4.26	46.33±1.44	-8.726	0.000**
Total	29.75±3.14	43.67±1.15	-14.422	0.000**

The two interfaces before and after improvement and each of their internal modules were subjectively evaluated using the SUS scale, followed by the t-test of evaluation results. The results manifested that the total usability score of the interface before and after improvement and the usability score of each module all exhibited significant differences ($p<0.05$), being higher after improvement, see Table 9. This revealed that the improved interface was of better usability, which coincided with the objective results.

6 Conclusions

The rotary drilling rig is a typical piece of complex construction machinery and equipment, and its highly usable human-machine interface can facilitate efficient and safe operations. In this study, a pertinent improvement scheme was designed through definite functional indication, reasonable module design, and clear visual encoding and zoning based on the principles of consistency, information visual feature organization, information encoding, and color perception and then verified through comparative experiments. The results revealed that significant differences were observed in operating time, mean time of fixation points, and change rate of pupil diameter before and after improvement, and the improved interface showed stronger usability and lower cognitive load.

In this study, the improvement design of the construction machinery interface was guided by the ergonomics theory, and the effectiveness of the improvement scheme was co-verified by the subjective SUS evaluation and objective eye movement physiological measurement. This idea of design and verification provided a feasible reference for the subsequent construction machinery design. In addition, real vehicle experiments were implemented, and portable physiological measuring equipment was fully utilized, effectively overcoming the limitations of data measured in laboratory environments in the existing studies and ensuring the authenticity and reliability of experimental results. The study results can serve as an important reference for the experimental method in the follow-up construction machinery design.

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