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RESEARCH ARTICLE

Interface Layout Optimization for Electrical Devices Using Heuristic Algorithms and Eye Movement

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ABSTRACT The safe operation of electrical devices is related to the national economy and people's safe and well-being. It is crucial for operators to correctly and quickly identify interface information. To achieve this goal, optimizing the facility layout to reduce operator cognitive load and improve layout usability are vital prerequisites. Studies have developed methods for arranging interface elements, but their evaluations have rarely focused on the usability verification of optimized schemes; hence, the optimal effect has been uncertain in real situations. Given these considerations, this study proposed a new method that combines heuristic algorithms (genetic algorithm [GA] and ant colony algorithm [ACA]) and eye movements to obtain optimal interfaces. The optimized mathematical model was constructed using the Delphi method and analytic hierarchy process. A comparative study found that the GA-based interface (GABI) achieved superior results to the ACA-based interface (ACABI). Furthermore, the eye movement results indicated that compared with the original interface (OI) of the armored exhaust AC metal-enclosed switchgear, both algorithm-based interfaces significantly reduced the cognitive load and improved the overall usability. The results demonstrated that the GABI was superior to the ACABI overall. Therefore, the method proposed in this study can obtain better applicable schemes that account for both ergonomic requirements and user experience, thereby facilitating the convenient production of more effective layout schemes and providing a reference for electrical device designers and practitioners.

INDEX TERMS Ant colony algorithm, analytic hierarchy process, cognitive load, Delphi method, eye movement, genetic algorithm, heuristic algorithm, layout interface, usability.

I. INTRODUCTION

Power systems feature interfaces that function as interactive information systems; the interface is how operators manage power, and a poor interface is a burden on the operator and increases the information processing time and error rate [1], [2]. The typical layout can help operators complete the basic tasks of switch control but cannot facilitate the quick and correct identification of switch status and line information changes. Therefore, developing an effective facility interface and increasing human reliability are crucial for optimizing operational performance.

Interface layouts belong to the domain of facility layout planning (FLP), which aims to determine the optimal arrangement of the elements in a facility that shape industrial production systems [3], [4], [5]. FLP problems have been widely addressed, with major focus on types of problems, the approach and planning phase, characteristics of

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production facilities, material-handling system configurations, and methods for generating and assessing layout schemes [6], [7]. However, establishing the optimal layout is a complex problem that involves a set of design requirements; as a combinatorial optimization and NP-hard problem, this problem is considered one of the most vital design decision methods.

Over the years, heuristic and metaheuristic algorithms have been extensively employed in FLP layout scheme generation [8], [9], [10], [11], [12]. Notably, genetic algorithm (GA) and ant colony algorithm (ACA) have been successfully applied across various domains, such as construction sites [13], [14], ship multi-deck compartment [15], military operations center [16]. Pourvaziri et al. [17] presented a practical approach for mitigating the effects of changing environments and avoiding the need to rearrange the layout. In their study, changes in product demand and mix were addressed by altering product routes rather than by rearranging the layout. Through the use of a hybridized genetic-tabu search algorithm, the layout for the critical period was determined. In another study, Ma et al. [18] developed a nature-inspired ACA to improve the path planning of Autonomous Underwater Vehicles in terms of both the path planning model and the optimization algorithm. Previous studies suggest that both GA and ACA algorithms are effective for optimizing interface layouts; however, their applicability to the optimization of electrical device interfaces remains unconfirmed.

In addition, interface optimization is a complex problem that necessitates consideration of multiple design factors. In particular, human factors have a substantial influence on interface optimization [19]. At present, the design stages of almost all devices consider ergonomics. Ergonomic principles can help ensure that human factors considerations are addressed [20]. It would involve designing facilities that are easily accessible and safe for operators. Therefore, recent studies that have addressed the FLP problem have applied algorithms that consider ergonomics [21], [22]. Şenol [23] developed a relative layout design model to optimize cockpit interfaces; this model simultaneously considers engineering requirements, human factors, ergonomics, and pilots' preferences, and thus the subjectivity of traditional usability evaluation is diminished. Qiu et al. [24] proposed a modified multiobjective particle swarm algorithm that features objective functions for four ergonomic principles in the design of a display and control console. Deng et al. [25] introduced cognitive ergonomics and a combination of a GA and an ACA for cabin layout optimization. To improve human reliability, the layout of a manned submersible cabin was optimized by combining aesthetics theory and human factors, and the feasibility and effectiveness of this method were verified through a multiobjective GA [26].

The aforementioned studies have explored interface optimization by employing heuristic and metaheuristic algorithms. They have developed methods to meet multiple human–machine interaction objectives. However, layout assessment has yet to be comprehensively discussed [6]. Some methods for collecting data can affect user behavior during measurement. For instance, a traditional ergonomics evaluation consists of a questionnaire that operators are asked to complete while operating a prototype [27]. Another measurement is posture assessment, which employs a simulation mode such as RULA [28], REBA [29], OWAS [30], PATH [31], or even a driving simulator [32]. These methods are all helpful for solving FLP problems; however, they are not applicable for determining whether optimal interfaces decrease cognitive load, improve usability and yield superior task performance. Besides, they are difficult to apply in real situations. Therefore, a new and effective method for collecting data and optimizing the process of obtaining new layouts is required; this method must be able to leverage the advantages of algorithm-based productivity.

In the graphical user interface domain, one of the commonly used evaluation methods employs eye movements to assess cognitive load [33], [34]. This technique has relatively low subjectivity and has increasingly become a crucial measure for evaluating layout interfaces [2]. Well-designed interfaces can optimize the allocation of cognitive load and thus reduce human error, improve system safety, and enhance the user experience (UX) [35], [36], [37]. Roth et al. [38] examined the relationship between location and speed in finding web objects on web pages and found that typical placement leads to relatively few fixations and relatively rapid searching. In addition, placing web objects at expected locations facilitates user orientation and is beneficial for overall UX. To better understand user workload and how it relates to interface optimization, we focused on fixation time, time to first fixation, fixation count, and pupil diameter as specific indices of participant behavior. These features indicate fluctuations in cognitive load [39], [40], [41].

A limited number of studies have assessed interfaces generated by GAs using eye-tracking or mouse-tracking data. They have demonstrated that GA-based interfaces increase the efficacy, efficiency, and satisfaction of users when they interact with the developed interfaces [42]. However, These studies mainly focused on layout of software-based interfaces such as control panels or applications with customizable menus and toolbars. How to evaluate electrical device interface optimization using GA or ACA from the cognitive perspective remains unclear.

In summary, while numerous studies have been conducted on the process of interface generation and the assessment of layout schemes proposed by experienced designers, the evaluation of algorithm-optimized layout schemes from a cognitive aspect remains largely unexplored. Accordingly, this research aims to establish a new procedure for the generation and evaluation of electrical device layouts that takes into consideration ergonomic principles and ensures an appropriate operator workload. To our knowledge, this study is the first to apply such an approach for assessing ergonomic factors based on integrating the analytic hierarchy process (AHP) method and cognitive load by using objective physiological measures.

The main contributions of the present study can be summarized as follows:

- We present a method for quantifying ergonomic principles to reduce subjective interference, utilizing Delphi and AHP techniques.
- We expound on a novel method for evaluating GA-based interface (GABI) and the ACA-based interface (ACABI) from cognitive aspect, using quantifiable eye-movement data.
- We examine the applicability of both GA and ACA in optimizing layout interface of electrical devices.
- We demonstrate that GABI exhibits favorable usability and outperforms both the ACABI and the original interface (OI) of electrical devices.

The remainder of this paper is structured as follows. Section II gives an overview of the methods. An electrical device interface assignment problem incorporating four ergonomic principles using Delphi is modeled in Section III. Section IV proposes the optimal model based on the GA and ACA layout plus AHP. Section V presents the optimal layout design and evaluation experiments. The final section summarizes this study and proposes future work.

II. METHODS

In this study, we utilized a multifaceted approach that combined mathematical modeling and eye movement methods to conduct our research. This involved reviewing the relevant literature, conducting interviews, and making field visits, in addition to implementing the Delphi method to gather qualitative data on ergonomic indices. To obtain quantitative index weights, we employed AHP, which enabled us to construct mathematical models. We further conducted a differential test on the physiological data acquired during the eye movement experiment to assess better optimal layouts. Fig. 1 provides an overview of the comprehensive research process used in this study.

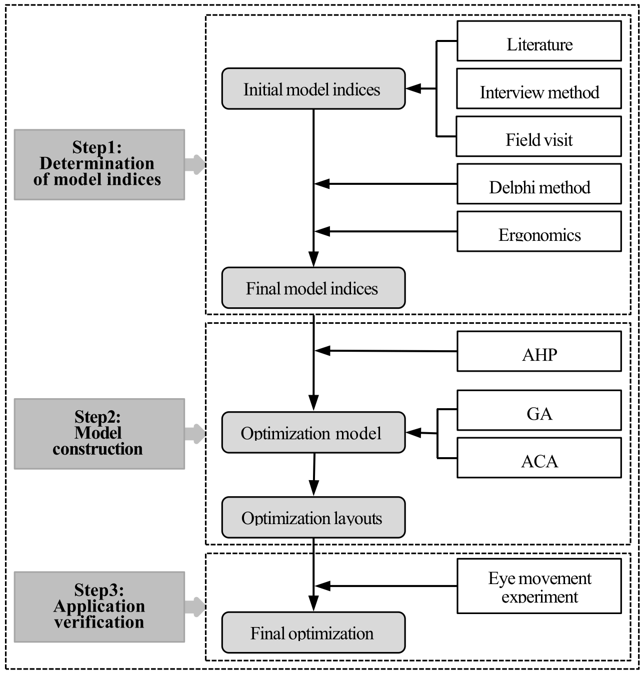

FIGURE 1. Overall research process. This research was conducted in three steps: Step 1 summarized initial model indices and determined final model indices; step 2 constructed an optimization model and identified optimization layouts; step 3 assessed optimal layouts using eye movement.

A. LITERATURE REVIEW: INTERVIEW METHOD AND FIELD VISIT

The methodological approach of this study comprised three aspects: First, a literature search was conducted to understand how others have researched the FLP problem. Second, three experts with relevant work experience were recruited to complete a questionnaire survey. The questionnaire consisted of expert self-assessment queries and scoring based on relevant indicators (e.g., pairwise comparison of the importance of each partition of the switchgear). Third, a field investigation that entailed direct observation of actual operating behavior was conducted to understand the operating process and determine existing problems; on this basis, we prepared to optimize the electrical device operational interface.

B. DELPHI METHOD

The Delphi method involves a consensus-based iterative process in which varied opinions are eventually converged into a consensus; an anonymous response form facilitates the collection of independent and authentic opinions, which is conducive to evaluating the selected indices [43].

TABLE 1. Scale definition.

Scale	Definition
1	Element i and element j are equally important
3	Element i is slightly more important than element j
5	Element i is significantly more important than element j
7	Element i is very much more important than element j
9	Element i is absolutely more important than clement j
2、4、6、8	Intermediate values are used when a judgement falls between two of the aforementioned levels of importance
1/2，1/3，1/4	Reciprocals are used for an inverse comparison when element j is considered more important than element i

In this study, three experts were recruited. The questionnaire was completed one-on-one offline. After listening to a description of the experimental study, the experts completed the questionnaire and then conducted posttest interviews. The questionnaire was designed to quantify the optimization index through the relative judgment matrix. The scale of the judgment matrix is presented in Table 1.

C. ANALYTIC HIERARCHY PROCESS

The AHP involves weighting decisions in a hierarchical manner proposed by American operational research expert Saaty [44]. It integrates qualitative and quantitative multicriteria decision-making and renders the human thinking process hierarchical and quantitative. By employing mathematical methods, we can effectively solve complex decision-making problems, including those that involve multiple objectives, multiple criteria, and non-structured elements. The AHP method is suitable for the analysis of decision-making with qualitative and quantitative aspects, especially when qualitative judgments and decision-making results cannot be directly and accurately yielded [45].

The specific calculation process of the AHP is described as follows.

The original matrix is established according to the hierarchical system of the target interface:

$$A_{m\times n}=\begin{bmatrix}1 & a_{12} & a_{13} & \dots & a_{1n}\\ a_{21} & 1 & & & a_{2n}\\ a_{31} & & 1 & & a_{3n}\\ \dots & & & 1 & \dots\\ a_{m1} & & & & a_{mn}\end{bmatrix},\quad \times(i=1,2,\dots,m;j=1,2,\dots,n) \tag{1}$$

a_{ji} is the degree of importance of index i compared with index j $(i,j=1,2,\dots\dots,m)$

Calculate the product of each column element in the original matrix A, namely

$$M_j=\prod_{i=1}^{m}a_{ij},\quad (j=1,2,\dots,n) \tag{2}$$

Calculate the nth root of M_j as $\overline{W}_j$:

$$\overline{W}_j=\sqrt[n]{M_j},\quad (j=1,2,\dots,n) \tag{3}$$

Normalized processing $\overline{W}=(\overline{W_1},\overline{W_2},\dots,\overline{W_n})$,

$$W_j=\frac{\overline{W_j}}{\sum_{j=1}^{n}\overline{W_j}},\quad (j=1,2,\dots n) \tag{4}$$

$W=(W_1,W_2,\dots W_n)$ is the AHP weight vector after expert weighting.

A consistency test is conducted on the obtained weight values, with the consistency index CR calculated to judge the consistency of matrix logical thinking:

$$CR=\frac{CI}{RI}, \tag{5}$$

$CI=\frac{\lambda_{\max}-n}{n-1}$, $\lambda_{\max}$ is the maximum eigenvalue of the judgment matrix, and the average random consistency index RI can be obtained by referring to Table 2. When $CR<0.10$, the consistency of the judgment matrix is reliable.

TABLE 2. Random consistency index.

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52

III. MATHEMATICAL CONSTRUCTION

A. CONSTRUCTION OF OBJECTIVE FUNCTION

The process of establishing an objective function is shown in Fig. 2.

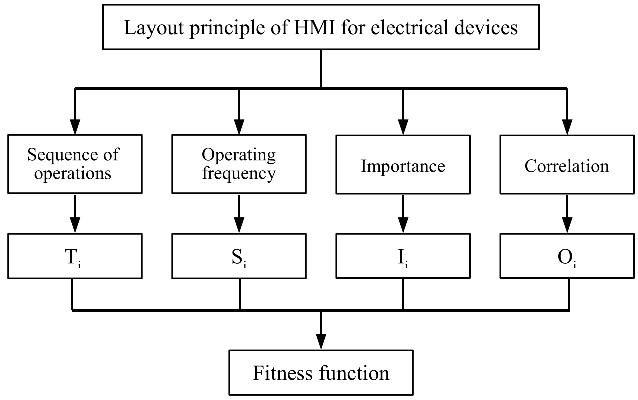

FIGURE 2. The process of establishing an objective function. According to the four ergonomic principles, we determined the optimization objective.

The final objective function is expressed as follows:

$$f(i)_{best}=\max\left[\sum_{i=1}^{n}(\delta_{1\iota}\cdot(T_i+S_i+I_i)+O_{ij})\right] \tag{6}$$

where

$$\delta_{1i}=1-i/n \tag{7}$$

where T_i represents the weight of the sequence of operations, S_i represents the weight of the operating frequency, I_i represents the weight of importance, O_{ij} represents the weight of correlation of operating element i and j, and represents the control coefficient.

B. SOLUTION UTILIZING HEURISTIC ALGORTHMS

1) GA

The specific process is described as follows [46]:

- Coding: Generate initial population

The sequence encoding is expressed as follows:

$$C_m=\left[C_1^m,C_2^m,C_3^m\dots,C_n^m\right] \tag{8}$$

where m is the population size and n the number of layout objects.

- Construct the fitness function

By calculating the fitness value of each randomly generated permutation and combination, which will be treated as an individual, the optimal solution to the scheme can be found. The fitness function is expressed as follows:

$$f(i)_{best}=\max\left[\sum_{i=1}^{n}(\delta_{1\iota}\cdot(T_i+S_i+I_i)+O_{ij})\right] \tag{9}$$

- Selection

The Roulette Wheel selection method is used, with selection probability directly proportional to individual fitness value, as represented in the following formula:

$$P(C_i) = \frac{fitness(C_i)}{\sum_{i=1}^{n} fitness(C_i)} \tag{10}$$

- Crossover

This study utilized an ordered crossover method, where new individuals were generated by exchanging sections of genes between parent individuals.

- Mutation

Employing swap mutation to perform variation operations on individuals ensures population diversity and prevents premature convergence. The mutation rate is typically set within the range of 0.001 to 0.1.

- Termination conditions

The algorithm terminates when the fitness value of the best individual reaches a predetermined value, when the fitness value of the best individual tends towards stability, or when the iteration has completed a preset number of times.

2) ACA

The specific process is described as follows [47]:

- Initialization

At the beginning of the computation, relevant parameters are initialized, such as the number of ants m, the pheromone factor α, the heuristic function factor β, the pheromone evaporation factor ρ, the pheromone constant Q, and the maximum number of iterations t. Then, m ants are placed on n nodes.

- Constructing the solution space

The state transition rule for the ant transferred from operating element i to operating element j at time t is expressed as follows:

$$p_{ij}^{k}(t) = \begin{cases} \dfrac{[\tau_{ij}(t)]^{\alpha}[\eta_{ij}]^{\beta}}{\sum_{l\in U}[\tau_{il}(t)]^{\alpha}[\eta_{il}]^{\beta}}, & j \in U \\ 0, j \notin U \end{cases} \tag{11}$$

$$\eta_{ij} = \frac{1}{D_{ij}} \tag{12}$$

$$D_{ij} = \left|T_i - T_j\right| + \left|S_i - S_j\right| + \left|O_i - O_j\right| + \left|I_i - I_j\right| \tag{13}$$

where $\tau_{ij}(t)$ represents the pheromone between operating element i and operating element j at moment t, $\eta_{ij}(t)$ represents the heuristic information between operating element i and operating element j at moment t, D_{ij} represents the difference between the comprehensive weights of operating element i and operating element j, α represents the pheromone factor, β represents the heuristic function factor, and U represents the set of feasible points.

- Update pheromone

Each ant's traversed path length L is calculated, and the optimal solution (shortest path) within the current iteration is recorded. Simultaneously, the pheromone concentration on each city's connecting path is updated.

- Termination conditions

If the iteration times is less than the maximum iteration limit, then the iteration times is incremented, the record of the ants' traversed paths is cleared, and the process returns to the second step. Otherwise, computation stops and the optimal solution is outputted.

IV. LAYOUT DESIGN OF ELECTRICAL DEVICE INTERFACE

Electrical devices connect materials, devices, appliances, fixtures, instruments, and similar mechanical or mechanical parts with electricity. The HMI of electrical devices is one of the key channels for operators to directly manage power, and it is an indispensable part of ensuring the safe operation of power equipment. Irrational layout designs of the operating components of the interaction interfaces of electrical devices reduce a user's search efficiency and work performance and increase cognitive load. Thus, designing an interface layout that conforms to the user's cognitive process, reduces the user's cognitive load, and improves the efficiency of information interaction is a key issue in interface design research.

The switchgear is one of the most important electrical devices in the power distribution network. Its operating status has a significant impact on the reliability of the power system. Electrical switchgears are also known as AC metal-enclosed switchgears, which are complete power distribution devices that assemble related electrical components in a closed metal shell, arranged according to a certain circuit plan. The main components inside include circuit breakers, disconnectors, load switches, operating mechanisms, transformers, and various protective devices. Their function is to switch, control, and protect electrical equipment in the process of power generation, transmission, distribution, and energy conversion. As an example, this study adopted the interface of an armored extraction AC metal-enclosed switchgear to confirm the effectiveness of the design methodology. The arrangement of the 16 operational elements on the operational interface are shown in Fig. 3.

A. PARAMETERS AND PERFORMANCE METRICS

First, we coded the 16 operating elements and arranged the elements with similar functions in the same area to reduce the operator's search time. As shown in Table 3, the 16 operating elements were divided into four groups of codes, namely {h1, h2}{1, 2}, {h3, h4, h5, h6}{3, 4, 5, 6}, {h7, h8, h9, h10, h11}{7, 8, 9, 10, 11}, and {h12, h13, h14, h15, h16}{12, 13, 14, 15, 16}.

Second, we simplified the layout area and the objects to be distributed and developed a mathematical model for the mathematical description of the design variables. Fig. 4 shows all operating elements are arranged. There are two types of operating elements, including displays (square edge length 500 mm) and operating elements, of which there are three types of operating elements, including buttons (Φ 30 mm), knobs (Φ 50 mm) and wrenches (Φ 40 mm). The intervals

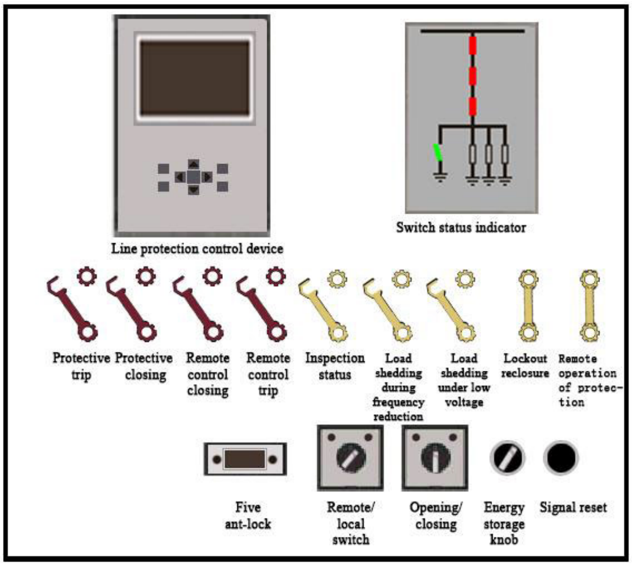

FIGURE 3. Original layout of operational interface for armored exhaust AC metal-enclosed switchgear.

TABLE 3. Electrical Switching equipment Operating Components.

Group numbers		Operating elements	Code
G1	**Display Element**	Line Protection Control Device	1
		Switch Status Indicator	2
G2	**Switch Element**	Protective Trip	3
		Protective Closing	4
		Remote Control Closing	5
		Remote Control Trip	6
G3	**Load Element**	Inspection Status	7
		Load Shedding During Frequency Reduction	8
		Load Shedding Under Low Voltage	9
		Lockout Reclosure	10
		Remote Operation of Protection	11
G4	**Conversion Element**	Five Anti-Lock	12
		Remote/Local Switch	13
		Opening/Closing Switch	14
		Energy Storage Knob	15
		Signal Reset	16

between operating elements are 100 mm. After simplification, the layout of the operating elements could be treated as an ordering problem. We used GA and ACA to determine the optimal ordering and then decided on the actual layout plan according to the corresponding findings.

In the process of operating the electrical switchgear, the following four working conditions typically need to be considered: hot standby to cold standby, hot standby to line maintenance, line maintenance to hot standby, and cold standby to hot standby. "Hot standby" means that the switchgear is in an enabled state and can immediately switch loads or route current to respond to any sudden changes or variations in the power system. "Cold standby" means that the switchgear is powered off and not in operation, but can be started and connected to the power grid when needed. The T_i of each operating element under various working conditions was determined according to the "Switching Operation Ticket". The S_i and I_i were determined through questionnaires, on-site interviews, and AHP. The T_i, S_i and I_i were shown in Table 4. The O_{ij} is shown in Table 5.

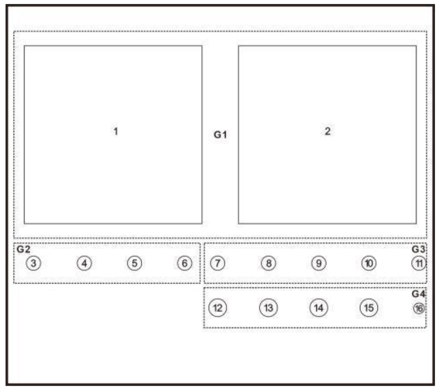

FIGURE 4. Simplified layout of switchgear. G1 are displays, G2-G4 are operating elements.

B. COMPUTATIONAL EXPERIMENTS

1) PERFORMANCE RESULTS

GA begins by randomly initializing an initial population and continuously iterates through processes of selection, crossover, and mutation. Fig. 5 illustrates the process of ordered crossover and swap mutation. The parameters for GA were set as follows: population size $N = 100$, crossover rate $P_C = 0.9$, mutation rate $P_m = 0.075$, generation gap $G_{GAP} = 0.95$, and when the number of iterations reaches $Gen_{max} = 300$, the GA terminates.

For ACA, the parameters were set as follows: number of ants $m = 100$, influence of pheromone on direction $\alpha = 0.3$, influence of heuristic information $\beta = 1$, pheromone persistence $\rho = 0.9$, and pheromone added by each ant $Q = 100$, and when the number of iterations reaches $\mathrm{Nc}_{max} = 100$, the ACA terminates.

Over 30 simulations were run on each algorithm. Given that FLP is a NP-hard problem, we selected the one with the smallest objective function value out of 30 runs as the layout scheme, and obtained two optimization schemes based on the ordering of the operating elements given by the test results (see Fig. 7). The objective function value given by the GA was 4.368, whereas the objective function value of the ACA was 4.438 (see Fig. 6). Although the ACA's solution speed exceeded that of the GA, the GA was superior to the ACA. In addition, we verified that the GA's initial optimization speed was slower but that its global search ability was stronger; by contrast, the ACA's initial optimization speed was faster, but it too readily slipped into the regional optimum.

2) DISCUSSION

The layout design principles for electrical devices were summarized, quantized, and used in the analysis of the information-processing process of operators.

TABLE 4. Operation sequence, frequency, and importance weights of *TI*, S_i, and I_i.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
T_i	0.1817	0.0649	0.0378	0.0189	0.0378	0	0.0413	0.0162	0.0142	0.0284	0	0.4542	0.0790	0	0	0
S_i	0.2546	0.1032	0.0364	0.0124	0.0096	0.0055	0.0236	0.0113	0.0111	0.0092	0.0036	0.1956	0.1725	0.0192	0.0192	0.0180
I_i	0.4374	0.0552	0.0382	0.0119	0.0065	0.0250	0.0076	0.0028	0.0030	0.0212	0.0108	0.1756	0.1047	0.0495	0.0495	0.0129
									9	10	11	12	13	14	15	16

TABLE 5. Correlation weight O_{ij}.

O_{ij}	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	1	0.672	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0.672	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	1	0.318	0.192	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0.318	1	0.018	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0.192	0.018	1	0.036	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0.036	1	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	0.446	0.428	0.5	0.09	0	0	0	0	0
8	0	0	0	0	0	0	0.446	1	0.82	0.234	0	0	0	0	0	0
9	0	0	0	0	0	0	0.428	0.82	1	0.784	0	0	0	0	0	0
10	0	0	0	0	0	0	0.5	0.234	0.784	1	0	0	0	0	0	0
11	0	0	0	0	0	0	0.09	0	0	0	1	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	1	0.964	0.036	0.8	0.018
13	0	0	0	0	0	0	0	0	0	0	0	0.964	1	0.036	0.674	0.018
14	0	0	0	0	0	0	0	0	0	0	0	0.036	0.036	1	0.018	0
15	0	0	0	0	0	0	0	0	0	0	0	0.8	0.674	0.018	1	0
16	0	0	0	0	0	0	0	0	0	0	0	0.018	0.018	0	0	1

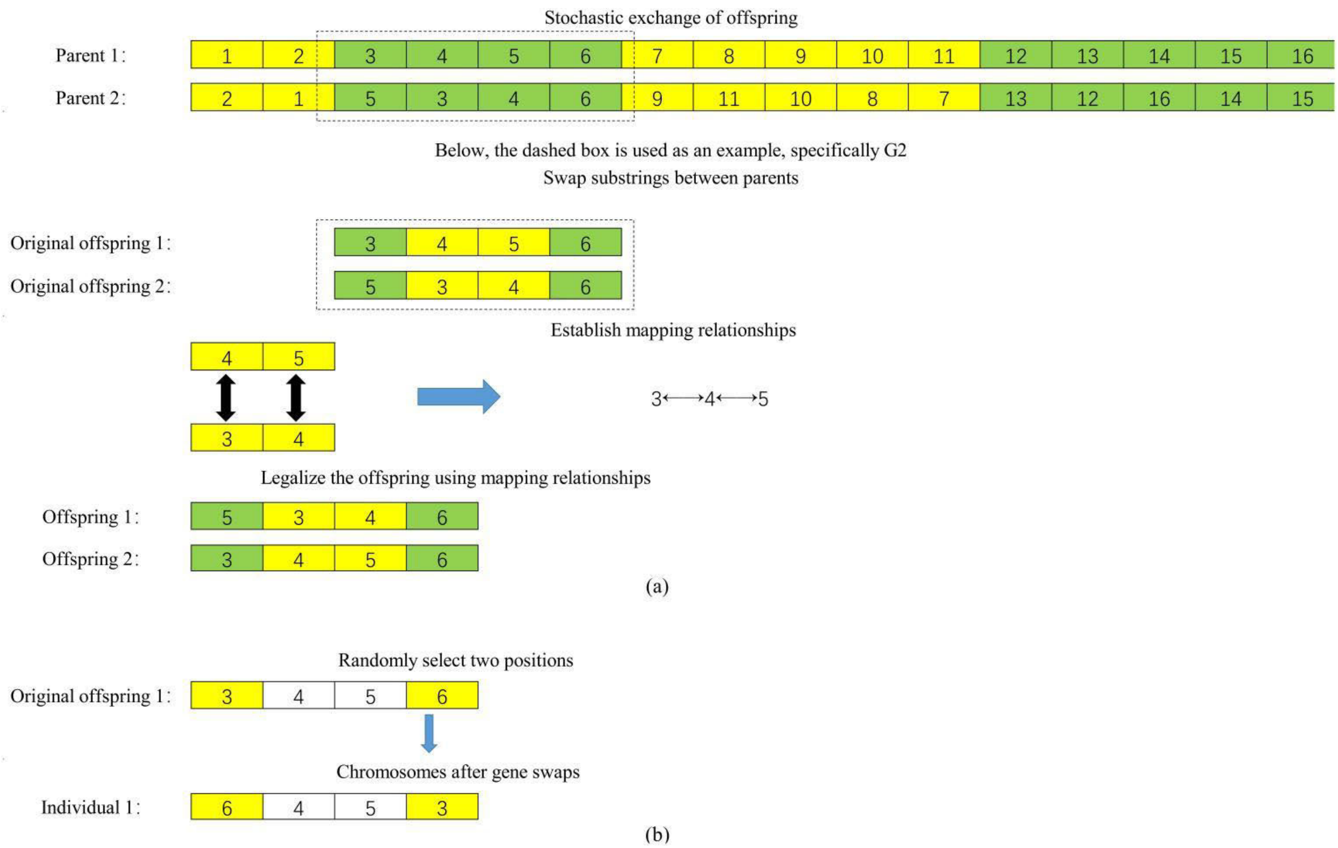

FIGURE 5. Crossover and mutation. (a) Ordered crossover. New offspring are generated through partial gene exchange between parents. Parent chromosomes are partitioned into four groups(See Fig. 4). The crossover operation is restricted to intra-group gene swapping, ensuring that elements from different groups do not interchange. All groups undergo simultaneous, independent operations. (b) Swap Mutation: It induces mutations via inter-group gene swapping, performed simultaneously and independently across all four groups.

Heuristic algorithms were employed to handle the optimization schemes. The acquisition of the layout principles combined objective rules and subjective evaluation data. The layout principles must be further refined because some cognitive activities are difficult to quantify owing to the complexity of the human cognitive behavior process.

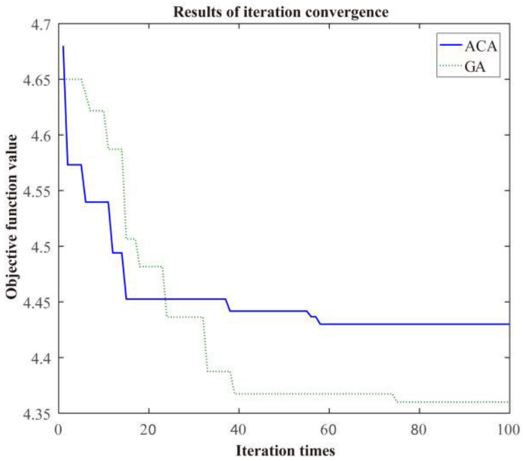

FIGURE 6. Results of iteration convergence of the GA and ACA.

TABLE 6. Comparison of GA and ACA.

algorithm	Operating element layout scheme	Objective function value
GA	1, 2, 4, 3, 5, 6, 7, 10, 9, 8, 11, 16, 14, 13, 12, 15	4.368
ACA	1, 2, 6, 3, 4, 5, 10, 8, 7, 9, 11, 16, 15, 14, 13, 12	4.438

V. VALIDATION USING EYE TRACKING

A. EYE MOVEMENT INDICES

To verify the effectiveness of various interface schemes, we analyzed and verified such schemes on the basis of experiments in which eye movement was measured physiologically. Holsanova et al. [48] demonstrated that layout has a substantial impact on eye movement behavior and verified that eye movement indicators have a significant correlation with user cognitive load. The longer the average fixation time of the user, the higher is the fixation count, the more complex is the layout of the interface elements, the more difficult it is to search information, and the greater is the cognitive load. King et al. [35] determined that time to first fixation represents the difficulty a user has in searching for relevant information, reflects the attention of users in initial processing, and has a positive correlation with cognitive load. Pupil diameter is a sensitive index of attentional allocation and psychological load in cognitive processing activities. Its change is closely related to emotion, which can reflect the psychological or emotional changes of users and reveal changes in the cognitive load of users under different stimuli. Zekveld et al. [49] found that a user's cognitive load increases when the pupil dilates—pupil diameter difference is positively correlated with cognitive load.

B. DESCRIPTION OF THE EXPERIMENT

1) EXPERIMENT DESIGN

In this experiment, a Swedish Tobii pro X3-120 Eye Tracker (sampling rate: 120 Hz) was used to record the eye movement data of the participants in real time during the simulation tasks. Tobii Pro Lab software was also used.

OI (see Fig. 3), GABI, and ACABI (see Fig. 7) were selected as experimental conditions. Three experimental groups were created, namely the OI experimental group, the GABI experimental group, and the ACABI experimental group. To avoid the learning effect, 10 participants were randomly assigned to each group to complete the experiment, and each participant completed the operation according to the experimental process. First, they read the task request prompt, and then they searched and clicked the components in the specified area to complete the electrical interface operation task. Each group of experiments required the completion of the following seven operation tasks using the interface: 1) find and observe that the switch control power supply has been closed; 2) find and observe that the switch energy storage knob has been closed; 3) find and observe that the grounding switch has been pulled open; 4) find and observe that the protection tripping switch has been put into position; 5) find and observe that the background electromechanical current display is definitely zero; 6) find and observe that the switch mechanical position has been disconnected; and 7) find and observe that the remote local switch has been put in the "remote" position.

2) PARTICIPANTS

A total of 30 volunteered students (17 males and 13 females) participated in this experiment. The participants were aged 18–25 years, with an average age of 19.6 years. All participants reported normal or corrected-to-normal vision. All participants signed informed consent and received course credit for their participation. The participants were all novices who had not previously operated the switch cabinet. Before the formal experiment began, the participants needed to be trained to acquire relevant knowledge of the electrical switch cabinet and the types of operating components in order to pass the knowledge assessment. This study was approved by the Internal Review Board of Ergonomics Laboratory, Shanghai Dianji University, People's Republic of China.

3) TASKS

Switchgear has four operating states; the switching tasks between states are described as follows:

Cold standby to hot standby: ① Observe that the background electromechanical current display has reached zero; ② observe that the mechanical position of the switch is definitely in the disconnected position; ③ observe that the remote control closing is definitely in the input position; ④ observe that the locking reclosing pressure plate is definitely in the input position; ⑤ observe that the protection closing is definitely in the input position; ⑥ observe that the maintenance status is in the exit position; ⑦ observe that the remote local-switching switch is definitely in the "remote" position; and ⑧ end the task.

4) PROCEDURE

Participants sat in front of a computer screen comfortably in the lab, and they were asked to focus on the center

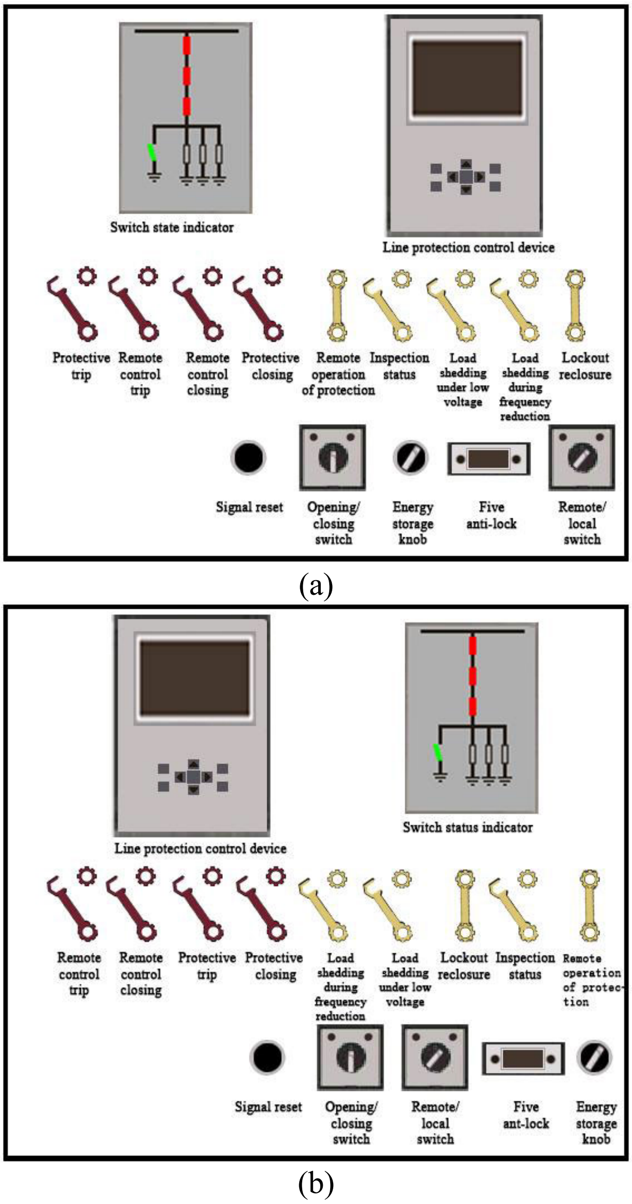

FIGURE 7. Optimized interfaces for armored exhaust AC metal-enclosed switchgear. (a) ACABI, (b) GABI.

of the screen. The task was programmed and presented using Tobii pro studio software. After a brief introduction of the experiment process and tasks, facility layout interfaces were displayed. Before the start of the experiment, The eye movement experimental process is illustrated in Fig. 8.

C. DATA COLLECTION AND ANALYSIS

All data were imported into IBM SPSS 19.0 to test the homogeneity of variance of the eye movement data among the three groups. The average fixation time ($P = 0.441 > 0.05$), time to first fixation ($P = 0.432 > 0.05$), fixation count ($P = 0.111 > 0.05$), and pupil diameter difference ($P = 0.052 > 0.05$) were all less than 0.05. For the homogeneity of variance test, the next step was to perform a one-way analysis of variance (ANOVA) on the data.

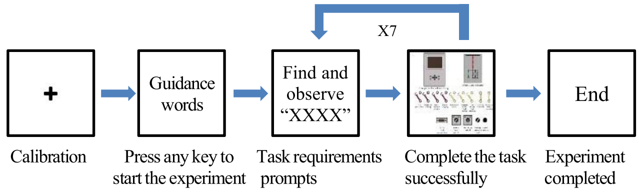

FIGURE 8. Flow chart. After the calibration process is complete, participants should review the instructional text. Once they feel prepared, they can initiate the session by pressing any key. Each participant is required to complete seven tasks.

The one-way ANOVA was performed on the eye movement data in the three interface groups, and the results are shown in Table 7. The average fixation time ($F = 10.58$, $P = 0.00$), time to first fixation ($F = 8.74$, $P = 0.001$), fixation count ($F = 5.37$, $P = 0.011$), and pupil diameter difference ($F = 5.58$, $P = 0.009$) were all less than 0.05. The data showed that the optimization schemes had a significant effect on the average fixation time, time to first fixation, fixation count, and pupil diameter difference.

TABLE 7. One-way analysis of variance.

Index		Sum of Squares	df	Mean Square	F	P
average fixation time	Between Groups	541.33	2	270.67	10.58	0.00
	Within Groups	691.00	27	25.59		
	Total	1232.33	29			
time to first fixation	Between Groups	9.45	2	4.73	8.74	0.001
	Within Groups	14.60	27	0.54		
	Total	24.05	29			
fixation count	Between Groups	529.07	2	264.53	5.37	0.011
	Within Groups	1330.24	27	49.27		
	Total	1859.31	29			
pupil diameter difference	Between Groups	.502	2	.251	5.576	.009
	Within Groups	1.216	27	.045		
	Total	1.718	29			

The average fixation time (26.50 ± 5.86 s) and time to first fixation (2.91 ± 0.47 s) of the ACABI were shorter than the OI, with significant differences ($P = 0.023 < 0.05$, $P = 0.009 < 0.05$) (Table 8). The average fixation time (21.57 ± 5.58 s) and time to first fixation (2.49 ± 0.49 s) of the GABI were shorter than the OI, with significant differences ($P = 0.000 < 0.05$, $P = 0.000 < 0.05$). The fixation count of the ACABI (20.95 ± 3.76) and the GABI (20.01 ± 6.72) were less than the OI (29.35 ± 9.41), with significant differences ($P = 0.013 < 0.05$, $P = 0.006 < 0.05$).

The pupil diameter difference of the GABI (0.22 ± 0.11 mm) was less than that of the OI (0.34 ± 0.12 mm).

TABLE 8. Average fixation time, time to first fixation, fixation count, and pupil diameter difference of interface layouts.

	average fixation time/s	time to first fixation/s	fixation count/number	pupil diameter difference/ mm
OI	31.97±3.35	3.83±1.07	29.35±9.41	.34±.12
ACABI	26.50±5.86	2.91±0.47	20.95±3.76	.53±.33
GABI	21.57±5.58	2.49±0.49	20.01±6.72	.22±.11

D. RESULTS AND DISCUSSION

In this study, the cognitive load of the participants was reflected in the eye movement indices. The experimental results revealed that the various interface layouts had a significant effect on eye movement, as judged by the participant data. The collected eye movement data were the average fixation time, time to first fixation, fixation count, and pupil diameter difference, which were all positively correlated with cognitive load.

Because the operating elements were arranged in order of operation, the attention required by the participants to find the target element was reduced when the interface was optimized, indicating that the processing difficulty of this interface was low, resulting in the average fixation time required by the participants to be shorter and the number of fixation points to be reduced, which in turn reduced the cognitive load of the participants.

Multiple studies [50], [51] have found that first fixation time indicates how long it takes a user to find a target and that a shorter first fixation time means less visual searching. Therefore, in this experiment, because the operating elements were arranged in order according to the cognitive process of human beings, the proposed interface was relatively effective in searching for a target object, resulting in the participants expending relatively little cognitive effort to find specific object and leading to reduced cognitive load.

One study [52] found that an increase in cognitive load increases the pupil diameter of the human eye and thus concluded that pupil size change is a key indicator for measuring cognitive load. In the present experiment, because the arrangement of the operating elements met the psychological expectations of the participants, the overall pupil diameters of the participants decreased, signifying reduced cognitive load.

VI. CONCLUSION

Although the layout design of HMIs has become a key research topic in recent years, studies have largely neglected electrical devices. To reduce user cognitive load and improve user search efficiency, this study fully considered the objective interface layout principle and operators' subjective operating requirements and developed an objective optimization function for the electrical interface layout. On the basis of the ACA and GA, two electrical interface layout schemes were designed, and the usability of the electrical interface layout was evaluated through eye movement experiments. The results demonstrated that the ACABI and the GABI were superior to the OI, with the GABI being slightly favorable to the ACABI. In electrical interface layout design, GA could be prioritized to provide a reference for designers, thus minimizing the subjectivity in interface layout design. Although this instance is small, the approach developed can be useful for larger instances. In future research, the optimization of interface layouts of electrical devices could be performed with a focus on the color and shape of the operating components. Depending on the characteristics of the HMI of other equipment, designers could adjust the layout principles accordingly.

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