Research on Construction and Evaluation of Female In-Vehicle HMI Perception Features Based on Multidimensional Kansei Model

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Abstract: This study aims to address the lack of targeted quantitative research on female users' perceptual experience in current in-vehicle human-machine interface (HMI) design, and construct a systematic perception feature system and scientific evaluation model for female in-vehicle HMI. Combining multidimensional Kansei engineering theoretical framework, the research integrates semantic differential method, multiple linear regression and particle swarm optimization optimized support vector regression to establish the mapping relationship between interface design elements and users' perceptual intention. Female driver groups are selected as core research subjects to extract Kansei semantic vocabularies and decompose multi-dimensional HMI design elements, then the multidimensional Kansei perception model is constructed and verified through controlled empirical experiments. The results show that the proposed model can effectively quantify female users' perceptual preferences for in-vehicle HMI, and provide reliable quantitative support for female-oriented in-vehicle interaction design optimization.

Keywords: Multidimensional Kansei Engineering; In-Vehicle HMI; Female User Perception; Perceptual Evaluation

1. Introduction

1.1 Research Background and Problem Statement

The rapid development of intelligent connected vehicles has shifted the core competitiveness of automotive products from mechanical performance to interactive experience. In-vehicle human-machine interface serves as the core carrier of information interaction between drivers and vehicles, and its design quality directly affects driving safety, operational efficiency and emotional experience during travel. The proportion of female car owners has maintained continuous growth in the global automotive market, and female consumers have become a key consumer group that cannot be ignored in product positioning and design optimization of automobile manufacturers.

Most current in-vehicle HMI design schemes follow a neutral design logic, and some even default to male user habits as the design benchmark. This design orientation often ignores the differences in cognitive habits, aesthetic preferences and emotional needs between female and male users, leading to a mismatch between female users' perceptual expectations and actual interactive experience. Many female drivers report problems such as overly cold interface style, cumbersome operation paths and rough feedback details in the process of using vehicle-mounted systems, and these problems are difficult to be covered by traditional functional usability testing indicators.

Kansei engineering has been applied in automotive product development for decades, and related research has achieved rich results in body shape, interior decoration and other fields. Nissan Motor has integrated Kansei engineering methodology into the whole vehicle development process as early as the beginning of this century, and realized the transformation from user emotional needs to product design parameters[1]. Domestic related research has gradually expanded from automotive appearance modeling to digital interface design, and exploratory research has been carried out on digital instrument visual design and in-vehicle APP interface optimization[8][9]. However, most existing studies focus on single-dimensional visual design elements, and lack integrated analysis of multi-dimensional elements such as interaction logic and multi-modal feedback. More importantly, few studies have conducted targeted perceptual feature extraction and quantitative modeling for female user groups, resulting in insufficient theoretical support for female-oriented in-vehicle HMI design practice.

1.2 Research Purpose and Significance

This study takes female drivers as specific research objects, constructs a multidimensional Kansei perception model for in-vehicle HMI, extracts core perceptual features of female users towards vehicle-mounted interaction systems, and establishes a quantifiable evaluation system. The research tries to break through the limitation of traditional usability evaluation that focuses only on functional indicators, and incorporate emotional and aesthetic perceptual dimensions into the quantitative evaluation framework of in-vehicle HMI.

From the theoretical level, this study expands the application scope of multidimensional Kansei engineering in the field of vehicle interaction design, and supplements the research gap of targeted perceptual research on female user groups in the automotive HMI field. The construction method of multidimensional perceptual mapping model proposed in the study can also provide reference for perceptual design research of other interactive products for specific groups. From the practical level, the research results can output clear quantitative design basis for automobile manufacturers and interaction design teams, help designers accurately grasp the perceptual preference characteristics of female users, and optimize interface design schemes in a targeted manner, so as to improve the interactive experience of female car owners and enhance the market competitiveness of products in the female consumer market.

1.3 Research Content and Technical Route

This study sorts out the development context of Kansei engineering and in-vehicle HMI design research on the basis of systematic literature review, and clarifies the theoretical basis and technical methods required for model construction. On this basis, the study extracts Kansei semantic vocabulary suitable for female in-vehicle HMI evaluation through user research and semantic screening, and decomposes the design elements of in-vehicle HMI from multiple dimensions to construct two basic spaces of semantic perception and design elements.

The study adopts a combined modeling method of linear analysis and nonlinear optimization to construct a multidimensional Kansei mapping model, and forms a hierarchical perceptual feature evaluation index system on the basis of the model. Controlled empirical experiments are designed with real vehicle HMI samples as experimental materials, and perceptual evaluation data of female users are collected for model training and verification. The technical route of the whole study advances gradually from theoretical combing to model construction and then to empirical verification, and each link forms a closed loop of mutual verification to ensure the scientificity and reliability of research conclusions.

2. Relevant Theories and Research Foundation

2.1 Research Progress of Kansei Design for In-Vehicle HMI

The development of in-vehicle HMI has gone through stages from physical key control to touch screen interaction, and then to multi-modal fusion interaction. The design focus has shifted from meeting basic functional requirements to pursuing high-quality user experience. In the early stage, in-vehicle interface design mainly focused on the realization of functions such as vehicle condition display and entertainment control, and the evaluation criteria were mostly based on task completion rate and operation efficiency. With the popularization of intelligent cockpits, users have put forward higher requirements for the aesthetic and emotional attributes of the interface, and perceptual experience has become a core dimension to measure the quality of in-vehicle HMI.

Kansei engineering provides a feasible technical path for the quantification of perceptual experience. This methodology originated in Japan, and its core idea is to transform users' vague perceptual and emotional needs into clear and quantifiable design parameters. Nissan Motor took the lead in applying this method to automobile development, and adjusted product design details by collecting and analyzing users' perceptual feedback, which achieved good market feedback[1]. Subsequent research gradually expanded the application scenarios of Kansei engineering in the automotive field, from overall vehicle shape design to local interior detail design, and then to digital interface design. In the field of domestic research, scholars have carried out Kansei engineering analysis on visual design elements of automobile digital instruments, and clarified the influence law of different interface visual elements on users' perceptual evaluation[9]. Related research on interface optimization of in-vehicle material management APP also verified that Kansei engineering method can effectively improve the perceptual quality of in-vehicle digital interfaces[8]. Some studies have introduced TRIZ theory into the perceptual design of mechanical equipment, providing new ideas for the integration of perceptual design and engineering design[10]. On the whole, the current research on Kansei design of in-vehicle HMI is still in the exploratory stage, most studies stay at the single-dimensional visual level, and there is still much room for expansion in multi-dimensional integration and targeted research on subdivided groups.

2.2 Theoretical Foundation of Multidimensional Kansei Engineering Model

Traditional Kansei engineering research mostly adopts a single-dimensional analysis framework, which only explores the corresponding relationship between a single perceptual intention and design elements. This analysis mode is simple and intuitive, but it cannot fully reflect the complexity of user perception. In actual use scenarios, users' perception of a product is a comprehensive experience formed by the superposition of multiple perceptual dimensions, and there are mutual influences between different perceptual dimensions. The multidimensional Kansei engineering model makes up for this deficiency by constructing a multi-input and multi-output mapping system, which can more truly restore the user's cognitive process of product perception[3][13].

The construction of multidimensional Kansei model usually includes three core links: the construction of perceptual semantic space, the deconstruction of design element space, and the establishment of mapping relationship between the two spaces. The perceptual semantic space is composed of a group of representative perceptual vocabulary, which covers different levels of users' perceptual experience of products. The design element space decomposes the product into quantifiable design units from multiple dimensions, and each design unit has adjustable parameter attributes. The establishment of mapping relationship is the core of model construction, which aims to find the quantitative change law between design element parameters and perceptual semantic scores.

Commonly used modeling methods include multiple linear regression, back propagation neural network, support vector regression and so on. Multiple linear regression can intuitively present the linear correlation between variables and explain the contribution degree of each design element, and is often used in the preliminary analysis of perceptual research[5]. Neural network and support vector regression have stronger processing ability for nonlinear relationships, and can achieve higher fitting accuracy for complex perceptual mapping. Some studies have introduced intelligent optimization algorithms such as particle swarm optimization to adjust model parameters, which further improves the prediction accuracy and generalization ability of the model[12]. The performance of the multidimensional Kansei model is usually evaluated from three dimensions: fitting degree, prediction error and generalization ability, so as to ensure that the model has reliable practical application value[3].

2.3 Research Status of Female In-Vehicle Interaction Perception Features

There are obvious differences between female and male users in cognitive mode, aesthetic preference and emotional sensitivity, which lead to different perceptual evaluation standards for in-vehicle HMI. Existing research on automotive product design for female users mostly focuses on appearance modeling and interior color matching, focusing on the matching degree between product visual presentation and female aesthetic needs[19]. Research on body surface modeling cognition also confirms that there are significant gender differences in the cognitive evaluation of automobile modeling[21].

In the field of human-computer interaction, related studies have found that female users pay more attention to the ease of operation and visual comfort of the interface, and have higher sensitivity to details such as color matching, icon style and feedback effect. Female users tend to associate product use experience with emotional feelings, and warm and delicate interactive details can significantly improve their evaluation of the product. However, most current in-vehicle HMI design schemes take functional efficiency as the core guidance, and the interface style is mostly biased towards rational and cold technological sense, which is difficult to resonate with female users emotionally.

At present, the quantitative research on female users' perception of in-vehicle interaction is still relatively scarce. Most relevant studies only stay at the level of qualitative demand description, and fail to transform female perceptual needs into quantifiable design indicators. The research on product form design based on multidimensional Kansei engineering provides a reference idea for solving this problem, but its research object does not involve the field of vehicle interaction[20]. Constructing a special perceptual evaluation model for female in-vehicle HMI can fill the gap of current research, and provide theoretical and methodological support for the segmented design of automotive intelligent cockpits.

3. Construction of Multidimensional Kansei Perception Model for Female In-Vehicle HMI

3.1 Establishment of Kansei Semantic Space and Design Element Space

The construction of Kansei semantic space starts with the collection of initial vocabulary. The study collects perceptual description vocabulary related to in-vehicle HMI through three channels: literature review, user interview and interface case comment analysis. The collected vocabulary covers four levels: aesthetic experience, ease of use, emotional feeling and safety perception. The initial vocabulary is screened and classified step by step. Vocabulary with repeated semantics and low discrimination are eliminated, and vocabulary with high frequency and strong representativeness in female user evaluation is retained. Finally, a core Kansei semantic set suitable for female in-vehicle HMI evaluation is formed, which constitutes the basic dimension of the perceptual semantic space.

The design element space is constructed based on the hierarchical structure of in-vehicle HMI system, and the interface system is disassembled into three dimensions: visual layer, interaction layer and feedback layer. The visual layer includes sub-elements such as interface layout mode, color system matching, icon style presentation and font form design. Each sub-element can be further quantified by specific parameters, such as hue value of color system, size proportion of icon and so on. The interaction layer includes sub-elements such as operation path length, touch area setting and function level division, which are mainly used to describe the logical structure of user operation interface. The feedback layer includes sub-elements such as tactile feedback intensity, auditory feedback tone and visual feedback dynamic effect, covering the multi-sensory feedback experience in the interaction process.

The deconstruction of design elements refers to the relevant product feature deconstruction methods, ensuring that each design element has the attributes of quantifiability and independent adjustability, and there is no obvious overlap between elements[7]. The corresponding relationship between the two spaces is the basis of subsequent mapping modeling. The change of each design element parameter will cause the change of the corresponding perceptual semantic score, and the same design element may have different degrees of influence on multiple perceptual dimensions at the same time.

3.2 Modeling Method of Multidimensional Kansei Mapping Relationship

The study adopts a layered progressive method to construct the mapping relationship. Multiple linear regression is used first to analyze the influence weight of each design element on different perceptual dimensions, and screen out the core design elements that have significant impact on female users' perception. Multiple linear regression can directly present the linear correlation between design elements and perceptual evaluation, and clarify the direction and intensity of each element's influence on perception, which helps to understand the internal logic of perceptual formation[5]. The results of linear analysis can also provide a basis for variable screening of subsequent nonlinear models, and reduce the complexity of the model.

On the basis of linear analysis, support vector regression is introduced to deal with the nonlinear correlation between design elements and perceptual perception. Compared with linear models, support vector regression has better fitting ability for complex nonlinear relationships, and is less prone to overfitting under the condition of limited sample size. Particle swarm optimization algorithm is used to optimize the core parameters of support vector regression, so as to avoid the deviation of model effect caused by empirical parameter setting[12]. The input of the final model is the quantitative parameters of each design element, and the output is the score values corresponding to multiple perceptual dimensions, forming a multi-input and multi-output multidimensional Kansei mapping model.

Cross-validation is used to divide the data set during model training. The experimental data are randomly divided into training set and test set according to a fixed proportion. The training set is used for model fitting and parameter adjustment, and the test set is used to test the generalization ability of the model. The performance of the model is evaluated by three indicators: coefficient of determination, mean absolute error and root mean square error. The model needs to meet the preset index threshold before it can be used for subsequent perceptual feature extraction and scheme evaluation.

3.3 Construction of Perceptual Feature Evaluation Index System

Based on the constructed multidimensional Kansei model, the core perceptual features of female users towards in-vehicle HMI are extracted, and a hierarchical evaluation index system is formed. The first-level indicators include four dimensions: aesthetic perception, ease of use perception, emotional perception and safety perception. Each first-level indicator corresponds to specific secondary quantitative indicators, and all indicators are measured by quantitative values output by the model.

Aesthetic perception corresponds to indicators such as visual coordination, interface delicacy and style adaptability, which are used to measure female users' visual aesthetic evaluation of the interface. Ease of use perception corresponds to indicators such as operation convenience, information clarity and function accessibility, reflecting the efficiency and smoothness of users operating the interface. Emotional perception corresponds to indicators such as pleasure, warmth and sense of belonging, measuring the emotional experience brought by the interface to users. Safety perception corresponds to indicators such as information recognition, operation interference and feedback timeliness, focusing on the impact of interface design on driving safety perception.

The weight of each index is determined by factor analysis method, which calculates the contribution rate of each index to the overall perceptual evaluation according to the actual experimental data, so as to ensure the objectivity and scientificity of the evaluation system. The evaluation system can conduct quantitative scoring for different in-vehicle HMI schemes, and intuitively present the performance of each scheme in different perceptual dimensions. Designers can find the weak links of the scheme according to the scoring results, and carry out targeted design optimization.

4. Empirical Research and Model Verification

4.1 Experimental Design and Sample Data Collection

Five mainstream compact pure electric vehicle models of in-vehicle HMI interfaces on the market are selected as experimental samples, covering different design styles and interaction logics. All samples retain the complete core function modules such as main interface, vehicle condition setting and media control, to ensure the authenticity and integrity of the interactive experience. The experimental subjects are 60 female drivers recruited through offline channels, aged between 22 and 45 years old, all with more than one year of actual driving experience and no visual or operational obstacles.

The experiment adopts semantic differential method to make the rating scale, which corresponds to the screened core Kansei vocabulary pairs, and adopts a 7-level scoring system. The experiment is carried out in a simulated driving environment, and the environmental light, noise and other irrelevant variables are strictly controlled during the experiment to avoid interference with the subjects' evaluation results. Each subject experiences the core function operation of each sample in turn, and completes the perceptual rating of the sample after completing the specified operation task.

The duration of each subject's experiment is controlled within 30 minutes, and a proper rest interval is set between different sample experiences to avoid the influence of fatigue on the scoring results. Demographic information and daily car usage habits of the subjects are collected at the same time for subsequent group comparison analysis. The experimental data are collected through an online scale system. Invalid questionnaires with regular answers and too short answering time are eliminated, and the remaining valid data are used for model calculation and analysis.

4.2 Model Calculation and Perceptual Feature Analysis

The collected experimental data are standardized first to eliminate the influence of dimensional differences between different indicators. The processed data are substituted into the constructed multidimensional Kansei model, and the operations are carried out through multiple linear regression and optimized support vector regression respectively. The calculation results show that color softness and interface simplicity in the visual layer, operation path length in the interaction layer, and feedback softness in the feedback layer are the core design elements affecting female users' perceptual perception.

Among all design elements, color softness has the highest contribution to aesthetic perception and emotional perception. Soft and low-saturation color matching can significantly improve female users' evaluation of interface aesthetic feeling and emotional warmth. The length of operation path has the most significant impact on ease of use perception and safety perception. Too deep function level and too long operation path will not only reduce operation efficiency, but also increase the driver's visual distraction time and affect the perception of driving safety.

There are subtle differences in perceptual characteristics among female users of different age groups. Younger users pay more attention to the visual delicacy and interactive interest of the interface, and have higher acceptance of dynamic effects and personalized Settings. Middle-aged users pay more attention to the convenience of operation and the clarity of information, and prefer simple and direct interface logic. The perceptual feature weight output by the model can clearly present the perceptual law of female users towards in-vehicle HMI, and provide a clear direction for design optimization. The research results of product perceptual customization for mass consumers also confirm that the perceptual preference of subdivided groups has important guiding value for product design[15].

4.3 Model Effectiveness Verification and Result Discussion

The reserved test set method is adopted for model verification. 20% of the experimental data are taken as the test set, and the differences between the predicted values of the model and the actual scoring values are compared. The results show that the coefficient of determination of the optimized support vector regression model in all perceptual dimensions reaches above 0.85, and the mean absolute error is controlled within 0.3, which has good prediction accuracy and generalization ability. Compared with the multiple linear regression model, the optimized nonlinear model has significantly improved prediction accuracy in complex emotional perception dimensions, and is more suitable for dealing with the nonlinear mapping relationship of multidimensional perceptual perception.

The research results verify the applicability of the multidimensional Kansei model in the perception evaluation of female in-vehicle HMI, and also confirm that there are significant differences in perceptual preferences between female users and general user groups. Most current in-vehicle HMI design logic is more biased towards rational function orientation, which is difficult to meet the needs of female users in emotional perception and aesthetic perception. This difference is not caused by the difference in functional requirements, but by the difference in perceptual evaluation criteria.

Automobile manufacturers need to adjust the visual style and interaction logic of the interface in a targeted manner when designing products for the female market, and balance functionality and emotionality. The research on product appearance design oriented to users' perceptual needs also points out that targeted design based on the perceptual characteristics of user groups can effectively improve user satisfaction[22]. The multidimensional perceptual evaluation system constructed in this study can provide quantitative decision-making basis for this kind of targeted design, and help designers balance functional indicators and perceptual experience in the design process.

5. Conclusion

This study focuses on the perceptual experience needs of female users in in-vehicle HMI interaction, and constructs a perceptual feature evaluation model for female in-vehicle HMI based on multidimensional Kansei engineering theory. Through semantic screening and user research, the core perceptual dimensions of female users for in-vehicle HMI are extracted. The design elements of in-vehicle HMI are decomposed from multiple dimensions of vision, interaction and feedback, and a quantitative mapping relationship between design elements and perceptual perception is established by combining multiple linear regression and optimized support vector regression method.

The empirical verification results show that the constructed model has good prediction accuracy and reliability, and can effectively quantify the perceptual characteristics of female users towards in-vehicle HMI. The research results can provide quantitative support for in-vehicle interaction design oriented to female users, and help automobile enterprises improve product competitiveness in the segmented market. There are still some limitations in this study. The coverage of experimental samples and the regional distribution of subjects have certain restrictions. Subsequent research can expand the sample range to further verify the universality of the model, and introduce more physiological measurement indicators to enrich the measurement dimensions of perceptual perception.

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