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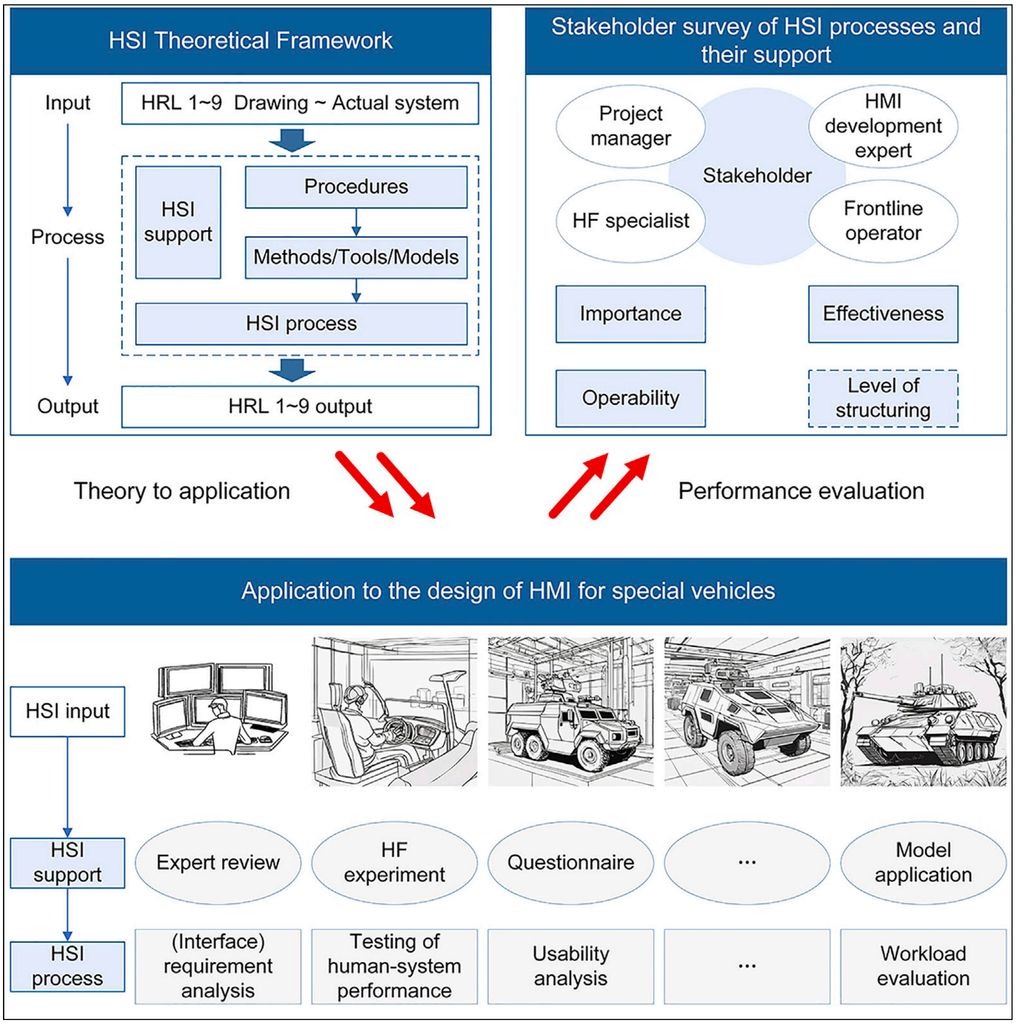

Chuanyan Feng, Shuang Liu, Xiaoru Wanyan, Zhenjia Sun, Fang Xie

wanyanxiaoru@buaa.edu.cn

Highlights

We propose an HSI framework that includes the HSI process and its support

The framework is implemented for special vehicle HMI within HRLs 4–6

The HSI framework and its application are validated through a stakeholder survey

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A human-system integration framework and its application for special vehicle interface design under typical human readiness levels

Chuanyan Feng,[1] Shuang Liu,[1] Xiaoru Wanyan,[1,3,*] Zhenjia Sun,[1] and Fang Xie[2]

SUMMARY

Life cycle Human System Integration (HSI) practices are crucial for optimizing human system performance, reducing costs, and ensuring safety. To address the limited HSI practices under typical Human Readiness Levels (HRLs), our study proposes an HSI theoretical framework and applies it to the design of human-machine interfaces (HMIs) for special vehicles. A stakeholder survey evaluates effectiveness of the framework and its application. Conclusions: (1) The framework, based on the input-process-output model, covers HSI processes and their support across HRLs. (2) The case study of HMI design in HRLs 4–6 identifies key processes and their specific support, contributing to the refinement of the framework. (3) The stakeholder survey underscores the importance and effectiveness of HSI processes and their support in the case study for life cycle human factor practices, suggesting areas for improvement in structuring and operability. The study offers insights into HSI practices under typical HRLs, merging theoretical and case study perspectives.

INTRODUCTION

In the practical considerations of safety-critical systems susceptible to severe consequences in case of failure, integrating Human Factors (HFs) across all life cycle phases (concept, development, production, utilization, support, and so on) proves instrumental in mitigating technical risks, minimizing costs, and optimizing system performance and safety.[1–6] Human-System Integration (HSI) encompasses HF considerations across the entire life cycle, striving for an integration with system engineering.[7,8] Researchers highlight the potential criticality of studying HSI processes to achieve this objective. Additionally, in facilitating the implementation of HF practices across the life cycle, the HFES/ANSI 400 standard introduces the concept of Human Readiness Level (HRL).[9,10] This concept serves as an assessment mechanism to effectively integrate HSI across different stages of technological or system maturity.

In addition, the practice of HF in complex industrial systems is often "too little, too late",[11,12] and is not effectively and consistently applied in critical life cycle phases such as development. Typically, in systems engineering, the input-process-output (IPO) model is frequently employed to summarize processes. However, safety-critical domains continue to rely on the ongoing development of standards/specifications to guide the practice of HF throughout the life cycle.[13–17] Most research on HSI processes remains theoretical or involves fragmented, discrete applications, facing challenges such as poor operational feasibility and a lack of effective practical applications. Therefore, there is a necessity for structured expression and systematic summarization of HSI processes. In conclusion, there is currently a gap in the availability of a structured and operational HSI theoretical framework tailored to different HRLs, along with a scarcity of effective practical cases for the associated HSI processes.

Building upon the foregoing, this study introduces an HSI theoretical framework tailored to different HRLs, followed by its practical application in the design of human-machine interfaces (HMIs) for special vehicles. Initially, we introduce a theoretical HSI model based on the IPO model, incorporating HSI processes and their support across various HRLs. Subsequently, we apply this theoretical framework to a case study on HMI design for special vehicles. This includes a structured summary and operational steps for platform status and personnel characteristics, key HSI processes and their support, and HSI inputs and outputs across the five stages within HRLs 4–6. Conclusively, a subjective stakeholder survey was employed to evaluate the importance, operability, and effectiveness of HSI processes and their support across individual stages and the overall five stages in the case study. Furthermore, it also explores the degree of structuring across the whole five stages.

RESULTS

In this section, a theoretical framework for HSI across various HRLs is presented. The framework encompasses nine HRLs during the development phase, ranging from HRL 1, Basic Human Research, to HRL 9, Operational Use and Monitoring.[9] Additionally, this framework is

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[1] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[2] China North Industries Group Corporation Limited, China North Vehicle Research Institute, Beijing 100072, China
[3] Lead contact
*Correspondence: wanyanxiaoru@buaa.edu.cn
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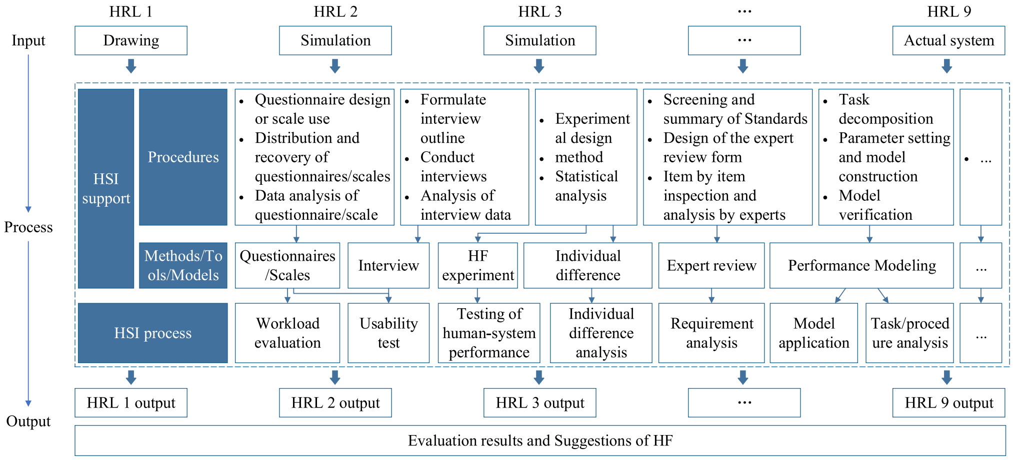

Figure 1. Theoretical Framework of HSI

architectured upon the IPO model, comprising inputs, HSI processes, and outputs across various HRLs. In this context, HSI inputs typically encompass the technical status of the evaluated object within the specified HRL, such as drawings, simulations, or physical representations. The core of the framework lies in the HSI process, where executing the process based on inputs generates relevant outputs. HSI outputs generally consist of outcomes and recommendations from the corresponding HF assessment. Focused on conventional HSI processes, this framework provides dedicated HSI support, detailing specific methods/tools/models and their operational steps. As depicted in Figure 1, these processes encompass workload evaluation, usability testing, and testing of human-system performance.[18]

HSI support encompasses practical and structured elements, exemplified by methods/tools/models like questionnaires/surveys, interviews, and HF experiments. For workload evaluation and usability testing within the HSI processes, the supporting methods/tools can be questionnaire/scale-based. As shown in Figure 2, this involves three key steps: questionnaire design (or scale adoption), distribution and collection of questionnaires/scales, and subsequent data analysis.[19] For the two HSI processes of the testing of human-system performance and individual difference analysis, the supporting methods encompass HF experiments and individual differences studies, comprising three essential steps: experimental design, methodology, and statistical analysis.[19] In support of the requirement analysis HSI process,[20] the methods for expert review encompass three key steps: filtering and organizing design standards, crafting expert review forms, and conducting detailed examination and analysis by experts. Concerning the HSI process of performance application, the supporting models facilitate performance modeling through three key steps: task decomposition, parameter configuration and model construction, and model validation.[21]

Additionally, our study specifically examined the HMI of special vehicles during the development phase, validating the HSI theoretical framework through a case study. The emphasis was on the practical application of key HSI processes and their support. Referring to Figure 2, the case study encompasses five stages under three prototypical HRLs: HRL 4 Part-Task Testing, HRL 5 Prototypes in Mission-Relevant Simulations, and HRL 6 Human Systems Design Fully Matured. The subsequent discussion systematically summarizes and elaborates on HSI process practices in three aspects: (1) platform status and personnel characteristics; (2) key HSI processes and their support; and (3) HSI inputs and outputs.

Stage 1 of HRL 4 static task testing of multiple interface schemes

Stage 1 of HRL 4 static task testing of multiple interface schemes occurs in the early stages of the development phase. During this stage, expert review and (user experience testing) questionnaires can be utilized to support the implementation of two key HSI processes: requirement analysis and usability testing. As indicated in Table 1, expert review involves the creation of a checklist and meticulous itemized examination to derive evaluation outcomes. User experience testing questionnaires, on the other hand, yield results through the formulation of user experience surveys, data collection, and subsequent analysis. The provided HSI support and implementation steps offer a practical application for executing the requirement analysis and usability testing processes, thereby providing an initial validation and detailed refinement of the HSI theoretical framework. The execution of the two HSI processes facilitated the selection of preferred interface schemes, offering insights for the subsequent optimization and design of crew interfaces.

Stage 2 of HRL 4 semi-dynamic task testing of two or more preferred interface schemes

During Stage 2 of HRL 4 Semi-dynamic task testing of two or more preferred interface schemes, HF experiments, questionnaires, and interviews can be strategically utilized to facilitate the implementation of key HSI processes, specifically the testing of human-system performance and usability testing. As indicated in Table 2, testing of human-system performance yields results through experimental design, methodologies, and statistical analysis. Usability testing results are obtained through the design of questionnaires or interview outlines, distribution or

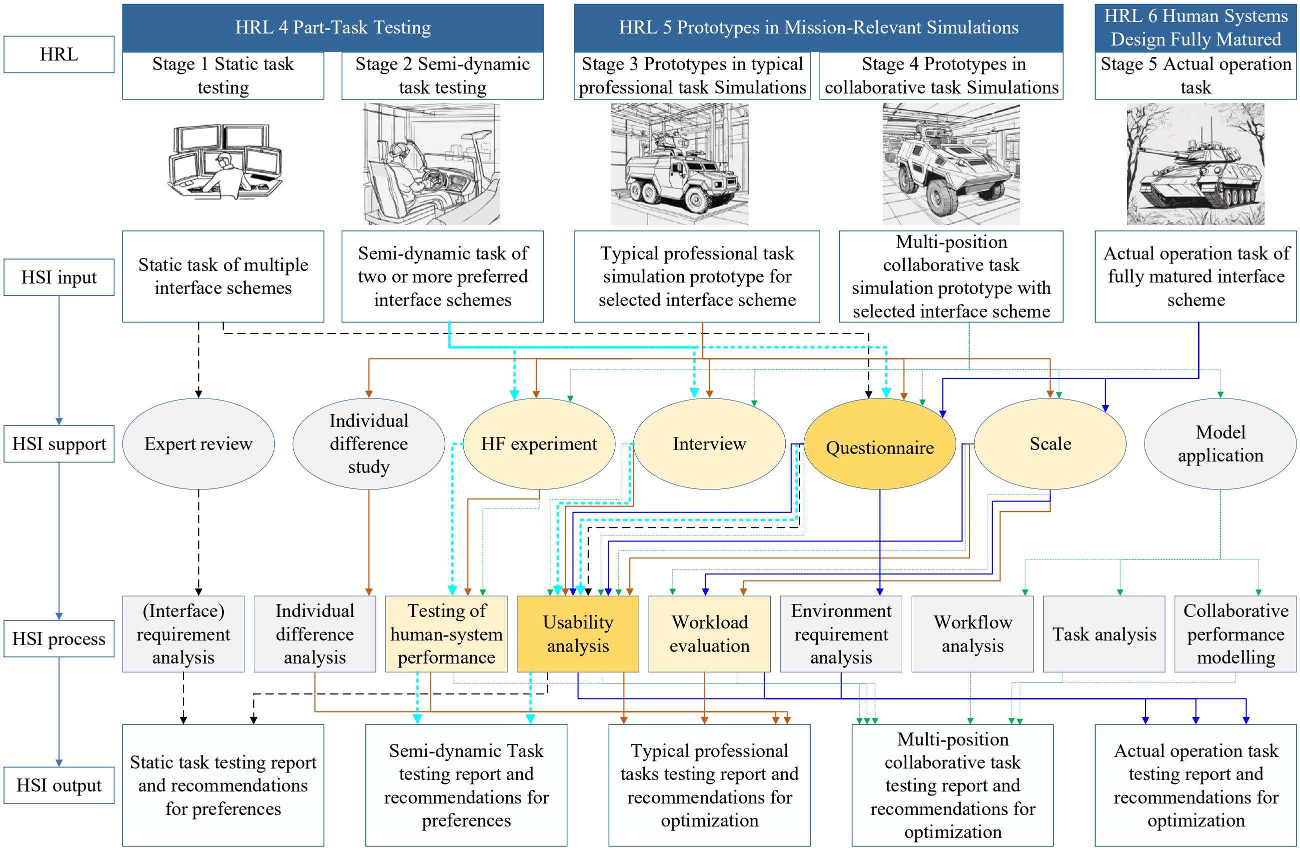

Figure 2. Examples of HSI practices for crew interfaces under typical HRLs in the development phase of special vehicles

implementation of surveys, and subsequent data analysis. In this stage, the detailed steps of HSI support operationalize the previously outlined HSI theoretical framework, specifically in the execution of testing of human-system performance and the refinement of support for usability testing. The implementation of these two HSI processes results in preferred interface schemes, serving as input for testing in the next HRL.

Stage 3 of HRL 5 prototype testing of typical professional task simulations for selected interface scheme

During stage 3 of HRL 5 Prototype testing of typical professional task simulations for the selected interface scheme, HF experiments, scales, individual difference studies, and interviews can be employed to support the implementation of the four key HSI processes: testing of human-system performance, workload evaluation, individual difference analysis, and usability testing. In the preceding stage, practical references for conducting testing of human-system performance and usability testing were provided, and these details will not be reiterated at this juncture. Furthermore, standard system usability scales (SUS)[24] were utilized in the usability testing at this stage. As depicted in Table 3, the workload evaluation process utilizes the standard National Aeronautic and Space Administration Task Load Index (NASA-TLX) scale[25] for subjective workload results. Parallel to the process of testing of human-system performance, individual difference analysis can be accomplished through HF experiments, yielding pertinent analytical outcomes. In this stage, HSI support and concrete implementation steps operationalize the previously mentioned HSI theoretical framework in the execution of workload evaluation and individual difference analysis processes. Additionally, it refines the supporting tools for usability testing. Implementation of the aforementioned HSI processes yields test results for prototype testing of typical professional task simulations for selected interface scheme.

Stage 4 of HRL 5 prototype testing of multi-position collaborative task simulations for selected interface scheme

In stage 4 of HRL 5 Prototype testing of multi-position collaborative task simulations for selected interface scheme, the implementation of HSI processes, including task analysis, workflow analysis, collaborative performance modeling, testing of human-system performance, and usability testing, is supported through the application of models, HF experiments, scales, questionnaires, and interviews. The earlier section offered practical insights into the testing of human-system performance and usability testing. This section concentrates on the practical execution of the model application process. Table 4 illustrates that the model application process involves task analysis, workflow analysis, and collaborative performance modeling. This includes collaborative task decomposition, definition of collaborative operating units and model

Table 1. Static task testing of multiple interface schemes

Category	Content detail		
(1) Platform status and personnel characteristics	a) Simulated dark cockpit operational setting; employing devices like a mouse and keyboard for human-machine interaction. b) An evaluation was conducted with the participation of several experts in HF and development.		
(2) Key HSI processes and their support	(Interface) requirement analysis → expert review	1) Creating a static interface review checklist,[22,23] encompassing elements like characters, colors, layout, etc. 2) Systematically reviewing various interface schemes.	Expert review results. For example, B > A > E > D > C.
	Usability testing → (user experience testing) questionnaires	1) Formulate a user experience questionnaire. For example, encompassing elements like color coordination, information layout, and interaction modes. 2) Execute user experience testing, involving participant experiences, observations, and subsequent questionnaire responses. 3) Collect, analyze, and diagnose user experience data for comprehensive insights.	(User experience testing) questionnaires results. For example, B > A > D > E > C.
(3) HSI inputs and outputs	Input: multiple interface schemes, e.g., scheme A∼E. Output: Static task testing report and preference recommendation for multiple interface schemes. For example, considering expert review and user experience outcomes, prioritizing schemes B and A is advised.		

construction, and validation of collaborative tasks across multiple positions. The HSI support and specific implementation steps in this stage successfully operationalize the preceding theoretical framework during the practical implementation of the model application process. By executing these HSI processes, test results for the selected interface in a multi-position collaborative task simulation prototype can be obtained, enabling the progression for tests in the next HRL.

Stage 5 of HRL 6 actual operational task testing of fully matured interface scheme

As depicted in Table 5, during stage 5 of HRL 6 actual operational task testing of fully matured interface scheme, the execution of the workload evaluation and usability testing HSI processes can be facilitated through the use of scales and questionnaires. The detailed execution steps for scales and questionnaires have been outlined in the preceding stages. It is noteworthy that they may be the most suitable methods/tools for this stage. The execution of these HSI processes yields test results for the current stage. The HSI design and optimization loop for the case study during the development phase has been initially closed, informed by the evaluation of the aforementioned five stages.

Stakeholder survey

A subjective stakeholder survey was employed to assess the effectiveness of HSI processes and their support on life cycle HF practices in the case study. This study involved ten stakeholders, including a project manager, two HMI development experts, four HF specialists, and three frontline operators. These participants brought diverse expertise from human factors engineering, vehicle engineering, computer science, and research testing. The average age was 35.8 ± 7.69 (mean ± standard deviation (SD)), ranging from 24 to 45 years, with an average work experience of 12.44 ± 7.36 years.

As illustrated in Figure 3, this study centers on evaluating the importance, operability, and effectiveness of HSI processes and their support across individual stages and the overall five stages. Survey findings highlight the high importance, operability, and effectiveness of HSI processes and their support in Stages 1–3 for life cycle HF practices, all scoring above 4. As illustrated by the items below the red line in Figure 3, the importance and operability of stages 4–5 are moderately rated, each scoring below 4. Furthermore, the effectiveness of the actual operation stage (Stage 5) is also moderate, with a score below 4. Regarding the HSI processes and their support across the whole five stages, they exhibit a moderate degree of structuring (3.7 ± 0.78) and operability (3.7 ± 0.64). Additionally, the importance and effectiveness of the overall five stages are high, scoring 4.1 ± 0.83 and 4.2 ± 0.75, respectively.

DISCUSSION

Life cycle HSI practices play a vital role in improving human-system performance, cost reduction, and ensuring safety. This paper proposes an HSI theoretical framework grounded in the IPO model across different HRLs and practically applies it to the HMI design of special vehicles. The theoretical framework incorporates HSI processes and their support across different HRLs, with the corresponding support involving specific methods/tools/models and their operational steps. The case study of HMI, conducted in five platform status and personnel characteristics within HRLs 4–6, identified key HSI processes, including workload evaluation, usability testing, and testing of human-system

Table 2. Semi-dynamic task testing of two or more preferred interface schemes

Category	Content detail		
(1) Platform status and personnel characteristics	a) Semi-dynamic interactive simulation prototype employing devices like mouse, keyboard, and joystick for human-machine interaction. b) The evaluation involved more than 10 participants with expertise in relevant fields.		
(2) Key HSI processes and their support	Testing of human-system performance → HF experiment	1) Experimental design. For example, employing N sets of optimized interface schemes in a within-subject design alongside other variables. 2) Methodology. For example, utilizing performance, subjective, and eye-tracking data collection systems; and designing simulated operational tasks based on the standard procedures for special vehicle missions. 3) Statistical analysis. For example, applying repeated measures Analysis of Variance (ANOVA) for analyzing interaction and main effects.	Results of testing of human-system performance. For example, exemplified by variations in metrics such as performance, subjective, and physiological responses among N sets of optimized interface schemes.
	Usability testing → questionnaire	1) Questionnaire design. For example, crafting surveys inclusive of diverse display control elements. 2) Questionnaire distribution and retrieval. For example, managing the dissemination and collection of surveys. 3) Questionnaire data analysis. For example, analyzing data obtained from the surveys.	Usability test results derived from questionnaires. For example, highlighting the preferences for N sets of preferred interface designs across diverse display control elements.
	Usability testing → interview	1) Interview outline development. For example, formulate an outline encompassing interface color schemes, text and table presentation, task decomposition logic, and related aspects. 2) Interview and data collection. 3) Analysis of interview data.	Usability test outcomes derived from interviews. For example, exemplified by the predisposition of N sets of optimized interface schemes concerning display control elements.
(3) HSI inputs and outputs	Input: more than two sets of preferred interface schemes. Output: Semi-dynamic task testing report of more than two preferred interface schemes and recommendation for preference. For instance, considering the results from testing of human-system performance and usability testing, it is advisable to prioritize scheme B.		

performance, along with their specific applications supported by questionnaires/scales, interviews, and HF experiments. Subsequently, the study yielded pertinent evaluation outcomes and recommendations. The obtained practical results can bolster the mentioned framework. Ultimately, a subjective stakeholder survey underscores the importance and effectiveness of the HSI processes and their support in the case study for life cycle HF practices. Nevertheless, there is a need for optimization in their structuring and operability.

The HSI theoretical framework proposed in this study features the following: (1) It articulates HSI processes, inputs, and outputs based on the IPO model across different HRLs. (2) HSI processes and their support form the nucleus of this theoretical framework. The associated support integrates pertinent methods/tools/models and their operational steps, offering practical applicability at the frontline. Presently, existing literature such as standards and manuals[26,27] either neglects HSI processes or offers only rudimentary explanations. Furthermore, there is a dearth of elaboration on HRL concepts. These limitations impede the practical application of HSI processes. The presented theoretical framework encompasses HSI processes and their support across different HRLs, substantiated through case study applications. This theoretical framework provides a solid reference for the practical application of HSI.

In this study, the theoretical framework was implemented in the crew HMI case for special vehicles within HRLs 4–6. Initially, key HSI processes were identified and implemented, followed by a meticulous refinement of the implementation details of support. This involved the application of specific methods/tools/models, and a detailed breakdown of operational steps. Practical benefits can be delineated across three aspects: (1) platform status and personnel characteristics; (2) HSI processes and their support; and (3) HSI inputs and outputs. Initially, as HRLs advance, platform dynamics evolve from "static, typical roles, simulation" to "dynamic, multi-role, real-world operations," paralleled by a shift in personnel from HF experts to frontline operators. By strategically combining different platform status and personnel characteristics, a more thorough identification of prevalent HF issues can be attained. In this case, during the initial stage (static task testing), issues were identified in different interface designs concerning character readability, color matching, and related aspects. During the mid-stage (prototype testing of a typical professional task simulation), complexities and learnability issues were noted in the interaction interface operations for the driving position. In the later stage (testing of the actual operational task), a notable subjective workload was identified,

Table 3. Prototype testing of typical professional task simulations for selected interface scheme

Category	Content detail		
(1) Platform status and personnel characteristics	a) A high-fidelity semi-physical simulation platform for a new type of special vehicle, employing actual mechanical controls and touchscreen interfaces for human-machine interaction. b) More than 20 participants, several designers, frontline operators, and researchers.		
(2) Key HSI processes and their support	Testing of human-system performance → HF experiment	1) Experimental design. For example, employing a within-subjects design incorporating factors of warning mode and noise. 2) Methodology. For example, measuring performance, subjective, and physiological responses during simulated task operations. 3) Statistical analysis. For example, using repeated-measures ANOVA for data analysis.	Results of testing of human-system performance. For example, exemplifying distinctions in performance, physiological, and subjective metrics across different warning modes and noise levels.
	Workload evaluation → scale	The standard NASA-TLX scale was used.	Workload evaluation findings. For example, instances where total scores or specific sub-dimensions surpass predefined thresholds. Notably, distinct variations in subjective workload are evident among different warning modes and noise levels.
	Individual difference analysis → individual difference studies	1) Experimental design. For example, utilizing a single-factor between-subjects design, with participants having varying levels of experience. 2) Method. For example, ensuring consistency in measurement devices and experimental tasks with HF experiments. 3) Data analysis method. For example, employing repeated measures ANOVA for data analysis.	Results of the individual difference analysis. For example, differences between groups in performance, subjective, and physiological measures.
	Usability testing → scale	A standard SUS scale was used.	Usability test results are based on the SUS scale. For example, reveal performance within the OK, GOOD, or EXCELLENT range. Room for improvement is identified within specific sub-dimensions.
	Usability testing → interview	…	…
(3) HSI inputs and outputs	Input: selected interface scheme. Output: Test reports and optimization recommendations for a prototypical professional task simulation of the selected interface scheme. For example, recommendations encompass aspects such as warning and noise design, workload optimization, informed by testing of human-system performance, workload evaluation, individual differences analysis, and usability testing results.		

accompanied by concerns in emotional response and warning handling. In this instance, the early involvement of HF experts plays a crucial role in substantiating the fulfillment of HF requirements/constraints in HMI design. The verification loop is ultimately closed through practical operations conducted by frontline personnel in later stages. Additionally, continuous human-in-the-loop testing enables dynamic assessments of HSI performance, contributing to the design and optimization of HF throughout the life cycle.

While the literature[26] provides theoretical insights into HSI processes and their support, there is a notable absence of detailed and systematically conducted operational case studies. Building upon the established theoretical framework, this case study identified and executed key HSI processes within HRLs 4–6. These processes encompassed testing of human-system performance, usability testing, workload evaluation, interface design requirement analysis, individual difference analysis, environmental requirement analysis, operational workflow analysis, task analysis, and collaborative performance modeling. On the operational level, the applied HSI support encompasses specific methods/tools/models such as questionnaires, scales, HF experiments, interviews, expert evaluations, modeling applications, individual difference studies, and their detailed operational steps. Furthermore, the supportive methods/tools/models for HSI processes in this case exhibit stage-specific relevance across diverse HRLs.[19] Specifically, (1) expert reviews are suitable for early stages, such as static task testing at HRL 3; (2) HF experiments and interviews are apt for mid-stages, such as the semi-dynamic task testing and typical task simulation prototype testing of HRLs 3–4; and (3) questionnaires, scales, and interviews apply across all five stages; notably, they could be the most favored testing

Table 4. Prototype testing of multi-position collaborative task simulations for selected interface scheme

Category	Content detail		
(1) Platform status and personnel characteristics	a) Simulation platform for multi-position collaboration; Incorporating actual mechanical controls and touchscreens for human-machine interaction. b) Multiple frontline operators.		
(2) Key HSI processes and their support	task analysis, workflow analysis, and collaborative performance modeling → model application	1) Collaborative task decomposition: For example, selecting representative collaborative tasks involving various roles such as drivers and commanders. 2) Definition and modeling of collaborative operating units: For example, establishing standard parameters for typical collaborative units and constructing a predictive model for collaborative performance. 3) Validation of multi-position collaborative tasks. For example, analyzing the correlation between theoretical predictions and observed values.	Results of task analysis, workflow analysis, and collaborative performance modeling. For example, the validity of models and the risk points in operational flows.
	Testing of human-system performance → HF experiment	1) Experimental design. For example, employing a within-subject design incorporating various collaborative task types and position roles. 2) Methods. For example, utilizing measurement devices for performance, subjective, and physiological data to execute typical collaborative tasks across multiple roles. 3) Statistical analysis. For example, applying repeated measures ANOVA for data analysis.	Results of testing of human-system performance. For example, differences in performance, subjective and physiological metrics related to collaborative tasks and position types.
	Usability testing → scales questionnaires and interviews	Standard SUS scale; Customized survey; Interview outline.	Results from the SUS scale, questionnaires, and interviews.
(3) HSI inputs and outputs	Input: Selected interfaces. Output: Test reports for multi-position collaborative task simulation prototype with the selected interface scheme. For instance, based on overall results from task analysis, workflow analysis, collaborative performance modeling, testing of human-system performance, and usability testing, recommendations are provided in aspects such as interaction design, task flow design, system usability, and team performance monitoring.		

methods during actual operations at HRL 5. The concrete implementation details and outcomes of HSI processes and their support, in this case, can contribute to refining the previously mentioned theoretical framework. In conclusion, an analysis of HSI inputs and outputs under typical HRLs facilitates the identification and implementation of HSI processes in subsequent stages of special vehicle development, thereby supporting the HMI case for HF design and optimization.

By conducting a stakeholder survey on the practical outcomes of the case study, a closed-loop validation from theoretical model construction to practical application can be efficiently accomplished. The study engages stakeholders representative of diverse perspectives, encompassing project managers, developers, HF experts, and frontline operators. As illustrated in Figure 3, HSI practices during Stages 4–5 receive moderate scores in both importance and operability. Notably, the evaluation results for the effectiveness of actual vehicle operations (Stage 5) also fall within the moderate range. These findings suggest a delayed implementation of HSI processes in the later stages of the life cycle, leading to constrained practical utility. In alignment with this, the elevated scores for importance, operability, and effectiveness during Stages 1~3 underscore the substantial practical value of initiating HSI practices in the early stages of the life cycle. Summarily, the holistic evaluation across all five stages emphasizes the importance and effective role of HSI processes in supporting HF practices throughout the life cycle. However, there remains an opportunity for refinement, particularly in enhancing operability and structuring. This highlights noteworthy aspects for future HSI practices, specifically emphasizing model-based HSI and its detailed operational implementation.

Conclusions

To address the issue of "a relative scarcity of HSI practices under typical HRLs", our study proposes an HSI theoretical framework under different HRLs and applies it to the design of HMI for special vehicles. Additionally, a stakeholder survey was employed to evaluate the effectiveness of the proposed framework and its application. The conclusions are as follows.

Table 5. Actual operational task testing of fully matured interface scheme

Category	Content detail		
(1) Platform status and personnel characteristics	a) Actual special vehicle; utilizing physical controls, touchscreens, and other devices for HMI; b) Several front-line operators.		
(2) Key HSI processes and their support	Workload evaluation → Scale	The standard NASA-TLX scale was used.	Workload evaluation results.
	Usability testing → Scales and questionnaires …	Standard SUS scale; a developed questionnaire …	SUS scales and questionnaires results …
(3) HSI inputs and outputs	Input: Fully mature interface. Output: Test reports and optimization recommendations for actual operational tasks with fully mature interfaces. For instance, incorporating the overall results of workload evaluation and usability testing to provide recommendations on subjective workload, emotions, and warnings.		

1) A theoretical framework for HSI based on the IPO model is proposed under different HRLs. This framework encompasses HSI processes and their support, with the respective support entailing specific methods/tools/models and their operational steps.
2) The HMI case of special vehicles was conducted in five stages of HRLs 4–6, covering the identification of key HSI processes such as workload evaluation, usability testing, and testing of human-system performance, as well as their specific applications supported by questionnaires/scales, interviews, and HF experiments. The results can be used to refine the framework described above.
3) The stakeholder survey indicates that the HSI processes and their support in the case study are deemed important and effective for life cycle HF practices. However, there is a potential for optimization in terms of the degree of structuring and operability.

Limitations of the study

The HSI framework and its application in this study can contribute to HSI practice in the development phase from the perspective of theoretical framework and case application. However, this study is not without imperfections, including the need for future improvement in operability and structuring. Additionally, the encompassed HSI processes are not exhaustive, with certain processes primarily at the methodological level, suggesting the necessity for supplementation through case-specific applications.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
    - ○ Lead contact
    - ○ Material availability
    - ○ Data and code availability
- EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS
    - ○ Participants
- METHOD DETAILS
    - ○ Stakeholder survey preparation
- QUANTIFICATION AND STATISTICAL ANALYSIS
    - ○ Statistical analysis
- ADDITIONAL RESOURCES

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AUTHOR CONTRIBUTIONS

All authors have read and agreed to the published version of the manuscript. Conceptualization, formal analysis, investigation, methodology, validation, visualization, and writing – original draft, C.F.; Conceptualization, formal analysis, data curation, investigation, methodology, resources, validation, and writing – review and editing, project administration, S.L.; Conceptualization, data curation, methodology, resources,

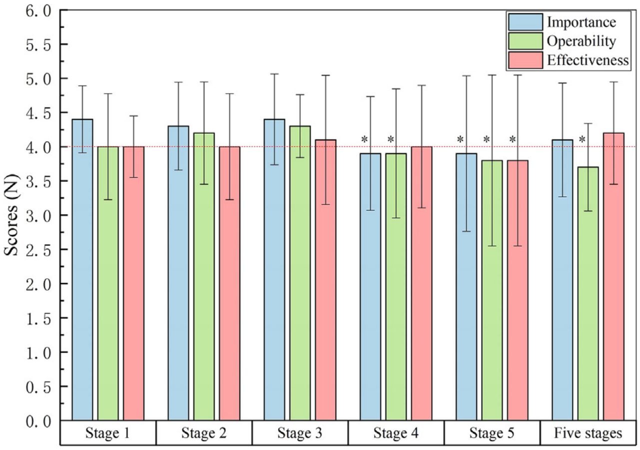

Figure 3. Results of the subjective stakeholder survey

Data are represented as mean ± SD. *denotes a score below 4 for the item.

supervision, and writing – review and editing, project administration, funding acquisition, X.W.; Visualization, validation, and writing – review and editing, Z.S.; Investigation, software, resources, validation, F.X.

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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REFERENCES

1. American Bureau of Shipping (2018). Guidance Notes on the Application of Ergonomics to Marine Systems (American Bureau of Shipping).
2. Edmonds, J. (2016). Human factors integration within design/engineering programs. In Human Factors in the Chemical and Process Industries, J. Edmonds, ed. (Elsevier), pp. 169–185.
3. Ahlstrom, V. (2016). Human Factors Design Standard (Federal Aviation Administration, U.S. Department of Transportation).
4. International Organization for Standardization (2016). ISO 6385 Ergonomics Principles in the Design of Work Systems (International Organization for Standardization).
5. International Organization for Standardization (2019). ISO 9241-210 Ergonomics of Human-System Interaction – Part 210: Human-Centred Design for Interactive Systems (International Organization for Standardization).
6. Department of Defense (2011). MIL-STD-46855A Human Engineering Requirements for Military Systems, Equipment, and Facilities (Department of Defense).
7. Silva-Martinez, J., Etchells, M., and Bradshaw, T. (2023). Implementation of Human Systems Integration technical and management process for the lunar Gateway Program. Acta Astronaut. *207*, 200–205. https://doi.org/10.1016/j.actaastro.2023.03.018.
8. Boy, G.A. (2023). An epistemological approach to human systems integration. Technol. Soc. *74*, 102298. https://doi.org/10.1016/j.techsoc.2023.102298.
9. Human Factors and Ergonomics Society (2021). ANSI/HFES 400-2021 Human Readiness Level Scale in the System Development Process (Human Factors and Ergonomics Society).
10. Phillips, E.L. (2010). The development and initial evaluation of the human readiness level framework.
11. Czaja, S.J., and Nair, S.N. (2012). human factors engineering and systems design. In Handbook of human factors and ergonomics, Gavriel Salvendy (John Wiley & Sons, Inc.), pp. 38–56.
12. Lim, K.Y., Long, J.B., and Silcock, N. (1992). Integrating human factors with the Jackson system development method: An illustrated overview. Ergonomics *35*, 1135–1161. https://doi.org/10.1080/00140139208967388.
13. American Bureau of Shipping (2014). Guidance Notes on the Implementation of Human Factors Engineering into the Design of Offshore Installations (American Bureau of Shipping).
14. Energy Institute and International Association of Oil & Gas Producers (2020). Report 454: Human Factors Engineering in Projects, 2nd edition (Energy Institute).
15. IEEE Power and Energy Society (2020). IEEE Std 1023 IEEE Recommended Practice for the Application of Human Factors Engineering to Systems, Equipment, and Facilities of Nuclear Power Generating Stations and Other Nuclear Facilities (The Institute of Electrical and Electronics Engineers, Inc.).
16. National Aeronautics and Space Administration (2006). NASA/TM-2006-214535 Design, Development, Testing, and Evaluation: Human Factors Engineering (National Aeronautics and Space Administration).
17. SAE International (2021). SAE HEB1D Human Engineering - Principles and Practices (SAE International)).
18. National Aeronautics and Space Administration (2021). NASA/SP-20210010952 NASA Human Systems Integration Handbook (National Aeronautics and Space Administration).
19. Proctor, R.W., and Van Zandt, T. (2018). Human Factors in Simple and Complex Systems, Third edition (CRC Press).
20. Stanton, N.A., Salmon, P.M., Walker, G.H., Baber, C., and Jenkins, D.P. (2018). Human Factors Methods: A Practical Guide for Engineering and Design (CRC Press).
21. Guo, S., Liu, S., Liang, C., Xie, F., and Zheng, S. (2021). An execution time prediction model for crew information processing in new special vehicles. In E3S Web of Conferences (EDP Sciences), pp. 02054. https://doi.org/10.1051/e3sconf/202125302054.

22. Department of Defense (2020). MIL-STD-1472H Human Engineering (Department of Defense).
23. O'Hara, J.M., and Fleger, S. (2020). NUREG-0700-Rev.3 Human-System Interface Design Review Guidelines (U.S. Nuclear Regulatory Commission). https://doi.org/10.2172/1644018.
24. Bangor, A., Kortum, P., and Miller, J. (2009). Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale. J. Usability Stud. *4*, 114–123.
25. Hart, S.G., and Staveland, L.E. (1988). Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. Adv. Psychol. *52*, 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9.
26. Walden, D.D., RoedLer, G.J., Forsberg, K.J., Hamelin, R.D., and Shortell, T.M. (2015). Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, 4th edition (John Wiley & Sons, Inc.).
27. International Organization for Standardization (2019). ISO 9241-220 Ergonomics of Human-System Interaction – Part 220: Processes for Enabling, Executing and Assessing Human-Centred Design within Organizations (International Organization for Standardization).

STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Experimental models: Physiological measurement		
Tobii Pro Glasses 2	Tobii Technology AB, Stockholm, Sweden	Conforms to ANSI/UL Std. 60950-1
Software and algorithms		
Performance recording software	China North Vehicle Research Institute, Beijing, China	China North Vehicle Research Institute
Tobii Pro Lab	Tobii Technology AB, Stockholm, Sweden	https://www.tobii.com/products/software/behavior-research-software/tobii-pro-lab
SPSS 23	IBM, USA	https://www.ibm.com/spss
Deposited data		
Stakeholder survey data	This paper; Mendeley Data	https://data.mendeley.com/datasets/bx5zhdb7nd/1
Other		
Static task testing platform	Beihang University, Beijing, China	China North Vehicle Research Institute
Semi-dynamic task testing platform	Beihang University, Beijing, China	China North Vehicle Research Institute
Prototype testing platform	China North Vehicle Research Institute, Beijing, China	China North Vehicle Research Institute
Prototype testing of multi-position platform	China North Vehicle Research Institute, Beijing, China	China North Vehicle Research Institute
Actual operational task special vehicle	China North Vehicle Research Institute, Beijing, China	China North Vehicle Research Institute

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed and will be fulfilled by the lead contact, Xiaoru Wanyan (wanyanxiaoru@buaa.edu.cn).

Material availability

This study did not generate new materials.

Data and code availability

- The stakeholder survey data has been deposited at Mendeley data repository (https://doi.org/10.17632/bx5zhdb7nd.1) and is publicly available as of the date of publication.
- This study did not generate original code.
- Any additional information required to reanalyse the data will be shared by the lead contact upon request.

EXPERIMENTAL MODEL AND STUDY PARTICIPANT DETAILS

Participants

This study involved ten stakeholders (2 females, mean age 35.8 ± 7.69 (standard deviation), ranging 24–45 years, East Asian ancestry, with mean work experience 12.44 ± 7.36 years), including a project manager, two human-machine interface development experts, four HF specialists, and three frontline operators. Gender has no influence on this study. In relation to educational background, two hold college degrees, one holds a bachelor's degree, four hold master's degrees, and three hold doctoral degrees. These participants brought diverse expertise from human factors engineering, vehicle engineering, computer science, and research testing. The. Informed consent was obtained from all participants involved in the study. The study has been approved by Beihang University's Biological and Medical Ethics Committee (Approval number BM20230003).

METHOD DETAILS

Stakeholder survey preparation

For example, three questions of stage 1 are:

1) What is the importance of implementing the HSI process using expert review (requirement analysis) and user experience testing questionnaires (usability testing) in the static task testing of multiple interface schemes?

Importance: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)

2) What is the operability of implementing the HSI process using expert review (requirement analysis) and user experience testing questionnaires (usability testing) in the static task testing of multiple interface schemes?

Operability: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)

3) What is the effectiveness of implementing the HSI process using expert review (requirement analysis) and user experience testing questionnaires (usability testing) in the static task testing of multiple interface schemes?

Effectiveness: ☐Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
As for the whole five stages, four questions are:

1) What is the importance of implementing the previous HSI process (using HF experiment expert review (Testing of human-system performance), and scale/user experience testing questionnaires (usability testing), and scale (workload evaluation) etc.) across the entire five stages?

Importance: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐Very low (1) ☐ low (2) ☐medium (3) ☐ high (4) ☐ Very high (5)

2) What is the operability of implementing the previous HSI process (using HF experiment expert review (Testing of human-system performance), and scale/user experience testing questionnaires (usability testing), and scale (workload evaluation) etc.) across the whole five stages?

Operability: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)

3) What is the effectiveness of implementing the previous HSI process (using HF experiment expert review (Testing of human-system performance), and scale/user experience testing questionnaires (usability testing), and scale (workload evaluation) etc.) across the whole five stages?

Effectiveness: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)

4) What is the degree of structuring of implementing the previous HSI process (using HF experiment expert review (testing of human-system performance), and scale/user experience testing questionnaires (usability testing), and scale (workload evaluation) etc.) across the whole five stages?

Degree of structuring: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)
Confidence: ☐ Very low (1) ☐ low (2) ☐ medium (3) ☐ high (4) ☐ Very high (5)

QUANTIFICATION AND STATISTICAL ANALYSIS

Statistical analysis

The Mean and standard deviation (SD) were calculated by Excel. For all data with error bars, the average between the datasets was calculated using the following equation:

$$\overline{x} = \frac{1}{n}\sum_{1}^{n} x_i$$

For the same sets of data the error bars were determined via the standard deviation using the following equation:

$$s = \sqrt{\frac{1}{n-1}\sum_{1}^{n}\left(x_i - \overline{x}\right)}$$

ADDITIONAL RESOURCES

This research was conducted in accordance with the Declaration of Helsinki, and further approved by Beihang University's Biological and Medical Ethics Committee (Approval No: BM20230003).