RETHINKING HUMAN FACTORS IN DESIGN FROM DESIGN ENTROPY PERSPECTIVE

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ABSTRACT
As humanity advances into the era of artificial intelligence, both human factors and design disciplines encounter new challenges. The capacity to collect, process, and understand information has become critical, with informatics emerging as a significant driving force in these fields. Against this backdrop, this article reexamines the role of human factors in design through the fundamental concept of entropy from information theory. Specifically, it introduces a concept framework of design entropy and, through an information-centric perspective, reconstructs the evaluation criteria for design processes and solutions while defining associated entropy metrics: design process entropy, design behavior entropy, and design structure entropy. Drawing from this framework, the paper explores how the guidelines and predictive models derived from human factors research influence design, particularly affecting the complexity of information collection and conversion during the design process, as well as the usability and adaptability of solutions. The paper further demonstrates the application of human factors in design through two case studies, involving producing guidelines for online English learning tool design and predictive models of air traffic controllers' workload, followed by a discussion of future research directions based on the proposed framework.

Keywords: Design Entropy, Human Factors, Design Informatics

1 INTRODUCTION

Entropy, a concept originating from thermodynamics, measures energy dissipation in physical systems, reflecting the tendency of systems to evolve towards disorder. To maintain system order, entropy must be managed through optimizing energy utilization and minimizing the effective energy converted into void energy [1]. Shannon later introduced entropy for his information theory [2] to describe information communication and uncertainty, which is also the basis for adopting the concept of entropy in contemporary design research. Statistically, entropy correlates with the probability distribution of events in a system, where more numerous and evenly spread events increase uncertainty and entropy [3]. When entropy is viewed as an indicator of system order [4], providing effective information becomes crucial to enhancing the degree of order.

Design scholars have acknowledged the utility of information entropy in describing and analyzing design processes and solutions, whether as an abstract framework or a quantitative tool. However, a comprehensive understanding of design processes through information entropy remains undeveloped. Existing research focuses on four main aspects: the role of designers in the design process [5], the impact of process management on design results [1], the information transformation in the design process [6], and the evaluation of productivity and creativity in the design process [7][8]. Research on design solutions divides into two categories. The first involves calculating entropy values to evaluate design solutions, choose alternatives, and assess improvements. The research objects include the aesthetic quality of urban skylines [9], the remanufacturability [10], recyclability [11], and adaptability [12] of products, the experience of user-product interfaces [13], the artistic complexity of drawings [14], the quality of product platforms for modular design and parametric design [15], etc. However, comprehensive quantitative methods are mainly applied in engineering contexts like software development and digital circuit design [16], while methods for artistic, industrial, and creative designs, characterized by high uncertainty, remain abstract or simplified. The second category uses information entropy as a quantitative measure of requirement importance [17][18][19].

Human factors is foundational in design, optimizing human-system interaction and encompassing ergonomics, cognitive engineering, user experience (UX), human-computer interaction (HCI),

biomechanics, safety engineering, etc. It aims to ensure efficiency, safety, and user-friendliness, aligning systems with human capacities and minimizing errors. Cognitive aspects are particularly central, making human factors closely tied to information and entropy concepts [20][21][22]. As an important quantitative method involved in design research, human factors leads to the generation and transmission of a large amount of information. The advancement of artificial intelligence (AI) further enhances human factors in managing vast data in complex scenarios like vessel traffic service (VTS) [23][24] and air traffic control (ATC) [25][26], but also introduces greater complexity and uncertainty, necessitating a reexamination of its role through the lens of information entropy.
This article will proceed as follows: Section 2 develops a comprehensive concept framework of design entropy based on existing studies, regarding both the design process and design solution. Section 3 analyzes the role of human factors in design within this new framework. Section 4 presents two case studies involving design of online English learning tools and air traffic controller (ATCO) workspaces to illustrate the relevant concepts and processes. Section 5 summarizes the findings and suggests future directions for integrating human factors into design research. As a preliminary study, specific quantitative methods are beyond this article's scope and will be addressed in future research.

2 CONCEPT FRAMEWORK OF DESIGN ENTROPY

While numerous studies investigate design issues from the perspective of information entropy, only a few have explicitly employed the term "design entropy" [13][16][27][28]. Among these, Cong et al. [28] proposed a comprehensive theory of design entropy, however, it is specifically tailored to an emerging business model—the smart product-service system (SPSS)—and lacks a clear distinction between design solutions and design processes. Consequently, the applicability of this theory beyond SPSS is limited. Furthermore, the information-theoretical approaches [29] also utilize concepts from information theory, particularly entropy, to describe design processes. Yet, these approaches primarily characterize design as "information increasing" or "information transformation," without delving deeper into the underlying informational essence of design processes and solutions. Despite these limitations, these studies generally converge on a shared understanding of entropy as a measure of system uncertainty. The following are three self-evident intuitive understandings: the easier a process is to execute, the easier an object is to implement, and the easier an object can fulfill its intended function, the corresponding lower uncertainty will be reflected. Therefore, they can all be described through entropy metrics, leading to the concept framework of design entropy, as illustrated in Figure 1. This framework deconstructs design processes and solutions through the perspective of design entropy, identifying relevant attributes as evaluation criteria and defining associated entropy metrics.

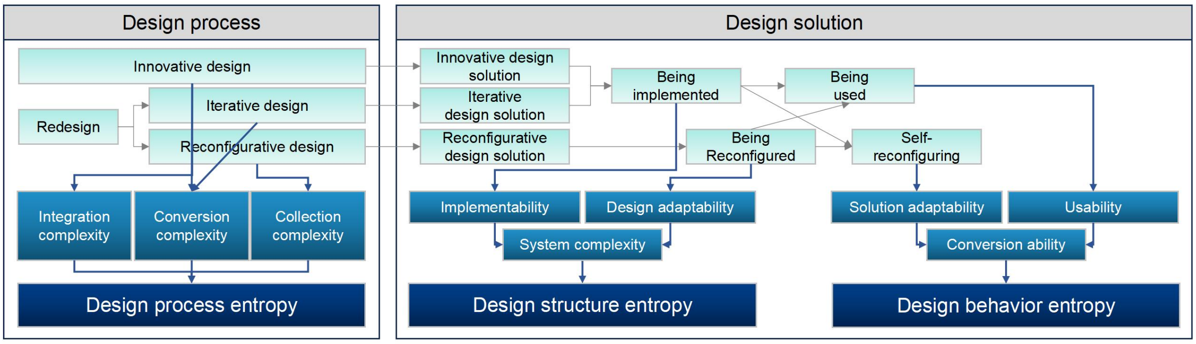

Figure 1. Concept framework of design entropy

2.1 Design entropy to describe the design process

With the rise of smart, connected products (SCPs) and SPSS featuring context-awareness, we categorize current design processes into three main types: innovative design, iterative design, and reconfigurative design, where both iterative and reconfigurative design fall under redesign.

Innovative design

This involves creating a new solution for an unresolved problem. The term "innovation" here has its limits, firstly, "unresolved" applies only to the project client. For example, designing a medical device for a pharmaceutical company to enter new markets qualifies as innovative, even if the product type is mature in the market. This highlights the first aspect of innovation: the absence of readily available, relevant information that can be reused, which directly determines the difficulty of design in the information era. Secondly, innovation refers to the design's starting point—whether the initial objective is innovative. The final solution may converge with an existing one, but the design can still be considered innovative. This reflects the second aspect of innovation, involving the integration of diverse information sources and complex synthesis, rather than simply converting requirements into solutions. The true value of innovation lies in extracting requirements from ambiguous contexts.

Iterative design
The meaning of iterative design can also be determined from an information perspective. Think about this question: If a hair dryer brand wants to transition from a common product model to an SPSS paradigm by developing a smart hair drying system, is this innovative or iterative? The answer depends on how different the new system is from conventional hair dryers. In other words, it hinges on the degree to which existing information supports designers in understanding new scenarios and the overlap between the existing and new information domains. If the difference is minimal, it is considered iterative design. Iterative design primarily focuses on converting requirements into solutions without extensive information integration.

Reconfigurative design
Previous research often uses the term "configuration/reconfiguration" interchangeably with "design" without clear definitions. Therefore, we introduce a new term "reconfigurative design", referring to a personalized design process based on adaptable products/product platforms targeting specific users or small user groups. Given that the product platform and the relationship between modules/parameters and requirements are predefined, it allows for quick customization when user expectations are unmet. Reconfigurative design requires minimal information integration or requirement conversion. The key, from an information perspective, is detecting dynamic contextual changes, enabling designers to know when intervention is necessary. Thus, the focus is on the capacity to collect information.

Understanding the design process through an information lens involves describing the complexity of information processing and providing indicators to guide the development team in selecting the optimal design path within set timelines. The main indicators include "integration complexity", "conversion complexity", and "collection complexity". Integration complexity relates to the number of information sources, the difficulty of accessing or constructing these sources, and the challenge of extracting effective information. Conversion complexity relates to the clarity, quantity, and interdependencies of requirements. Collection complexity addresses sensor types and numbers needed, data collection accuracy, and the precision of calculations from data to desired outcomes. Although three design processes are discussed separately for clarity, they often overlap in practice. For instance, innovative and iterative design may be difficult to distinguish, and iterative and reconfigurative design might be interconnected. Thus, when determining the complexity of a design process, the entropy metric should integrate these three indicators, collectively referred to as "design process entropy".

2.2 Design entropy to describe the design solution
Based on the three kinds of design processes mentioned above—innovative, iterative, and reconfigurative design—three corresponding types of design solutions can be defined: innovative design solutions, iterative design solutions, and reconfigurative design solutions. In Figure 1, four key evaluation factors are derived for assessing the design solution.

Implementability
For innovative and iterative design solutions, being implemented is a prerequisite for delivering value to users. Therefore, implementability is a crucial evaluation criterion. The term "implementation" is used instead of "manufacturing" to encompass a broader scope that includes product, service, and system design. Implementability considers the number of components within the solution, the complexity of each component, and the interdependencies between them.

Design adaptability
Design adaptability draws from the adaptability concept emphasized in adaptable design [30]. It focuses on the ability of a solution to be modified or extended into another in various ways to flexibly adapt to different application scenarios. Reconfigurative design mentioned earlier exemplifies this adaptability.

Therefore, we directly borrow the concept of design adaptability to evaluate how well a solution can be reconfigured.

Usability

No matter the design process, a solution's value is realized only when it is used by end-users. The evaluation criterion associated with this is defined as usability. Given its broad scope, usability is one of the most complex aspects of all design solutions. Moreover, it may vary significantly depending on the types of design solutions.

Solution adaptability

Solution adaptability also comes from the adaptable design concept [30]. Adapted from "product adaptability", this term is broadened to "solution adaptability" to encompass a wider range of design solutions. It highlights the ability of a design solution to respond to dynamic changes, such as the real-time reaction of SCPs to users' evolving needs through context awareness.

Among these four factors, usability and solution adaptability primarily address a solution's capacity to meet user needs. From an information perspective, this capacity can be expressed as "conversion ability" [28], which refers to the ability to transform information without a mapped solution into information with a mapped solution. The entropy metric calculated based on this ability is "design behavior entropy". Conversely, implementability and design adaptability are tied to the internal structure of the solution, described as "system complexity". The entropy metric derived from this is called "design structure entropy".

In conclusion, this article evaluates integration, conversion, and collection complexity of the design process using "design process entropy", while assessing conversion ability and system complexity of the design solution using "design behavior entropy" and "design structure entropy", respectively. These three metrics are mutually exclusive, addressing distinct aspects: the complexity faced by designers during the design process, the challenges involved in producing and delivering the target design solution, and the capacity of the design solution to achieve its intended outcomes. A holistic consideration of these factors is essential for guiding subsequent stages of development in practical design processes. Unlike prior research, which often addresses these dimensions in isolation, this study establishes a comprehensive concept framework. Due to space constraints, the article does not explore specific entropy calculation methods, leaving it as a future research focus.

3 UNDERSTANDING THE ROLE OF HUMAN FACTORS FROM DESIGN ENTROPY PERSPECTIVE

Traditional human factors experiment aims to examine how specific design elements influence human behavior, capabilities, experiences, and preferences, generating guidelines to inform design. With advancements of AI, now human states can be predicted using sensed information and produced models. Thus, human factors research primarily yields two types of information: guidelines and predictive models. In the following, we analyze the impact of these two types of information on the design process and solutions through the outlined design entropy framework, as illustrated in Figure 2.

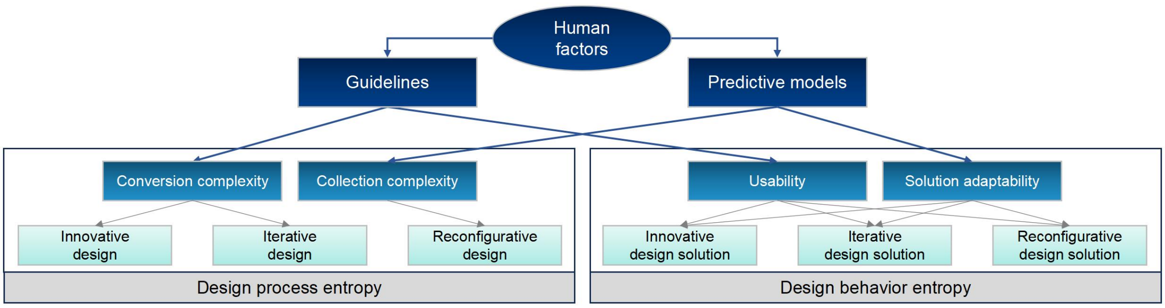

Figure 2. Influence of human factors on the design process and design solution

3.1 How human factors affects the design process

Reducing conversion complexity

The guidelines derived from human factors research provide a crucial foundation for the conversion from requirements to solutions, representing the predominant application of human factors in design practice. From the perspective of design entropy, these guidelines effectively reduce conversion complexity, thereby decreasing the design process entropy associated with innovative and iterative design processes.

Reducing collection complexity

Predictive models generated through human factors research can significantly simplify the information collection process. By employing predictive models, designers can assess contextual changes based on easily gathered data, allowing for precise interventions in the reconfigurative design process. This capability diminishes collection complexity and, consequently, reduces the design process entropy related to reconfigurative design.

Discussion on integration complexity

Currently, it remains unclear how to effectively reduce integration complexity. However, what is obvious is that when human factors studies are regarded as integral to the overall design process, their own complexity will also be incorporated. Therefore, to mitigate integration complexity through human factors, a straightforward approach would involve simplifying the challenges associated with conducting human factors research itself.

3.2 How human factors affects the design solution

Improving usability

The influence of human factors on design solutions is most directly manifested in their usability. Utilizing the guidelines established through human factors research, designers can enhance usability, leading to significant improvements in comfort, safety, accessibility, ease of learning, and overall interactive experience.

Improving solution adaptability

With the emergence of smart products, predictive models can also function as embedded modules, equipping products with robust capabilities to perceive unstable states of users and contexts. This will enable design solutions to respond in real-time to these fluctuations, thereby significantly enhancing solution adaptability.

Discussion on system complexity

Both usability and solution adaptability illustrate the conversion ability of the design solution. The current impact of human factors primarily serves to reduce design behavior entropy. In contrast, the influence of human factors on design structure entropy, determined by system complexity, is relatively limited. This is reasonable, as system complexity represents an inherent characteristic of the design solution itself, while conversion ability highlights the properties observed during the interaction between the design solution and the user—precisely the focus of human factors studies.

4 CASE STUDY

This section presents two case studies to illustrate how the guidelines and predictive models derived from human factors research can contribute to design. Specifically, it describes how human factors influences the design process to ultimately reduce both design process entropy and design behavior entropy. It is important to emphasize that the primary focus of this article is to understand the role of human factors in design through the proposed framework, rather than to discuss how to apply this framework and the associated entropy metrics.

4.1 Case 1: Guidelines for online English learning tool design

The first case examines the design of online English learning tools. Among the numerous factors influencing learning efficiency, stress is identified as a significant impediment to reading performance, particularly affecting higher-level text processing such as syntactic parsing, sentence integration, and global text comprehension. Additionally, first language (L1) and second language (L2) English readers often exhibit markedly different performances on reading tasks. To inform the development of online English learning tools through human factors research, we employed eye-tracking techniques to investigate the impact of stress on the higher-level text processing capabilities of both L1 and L2 readers. Valid data were obtained from 43 students who read GRE Verbal Reasoning Practice materials and completed corresponding multiple-choice questions. Various eye movement metrics were calculated to index the processes involved in text processing. The findings reveal that stress adversely affects syntactic parsing, sentence integration, and global text processing of L2 readers, who tend to compensate for difficulties in global text comprehension by focusing more on the topic structure of the text. In contrast, for L1 readers, only the efficiency of syntactic parsing and sentence integration was found to be impacted by stress.

From this experiment, we derive three key guidelines for the design of online English learning tools: 1) Implement customized interface layouts and guidance strategies whether the user is an L1 or L2 reader, rather than merely altering reading materials; 2) For L2 readers, design varying levels of topic structure guidance, gradually decreasing from the most explicit identification mode as readers' abilities improve; 3) In scenarios involving stage tests, employ calming strategies judiciously to accurately assess the learner's true proficiency level. These guidelines provide designers with clear objectives, facilitating innovative design that yields more targeted solutions and strategies to enhance users' English proficiency. Furthermore, these guidelines will serve as critical evaluation criteria for determining the necessity of iterative design, thereby reducing conversion complexity and, consequently, design process entropy. Correspondingly, the resulting design solutions will exhibit improved usability, with diminished design behavior entropy.

4.2 Case 2: Prediction of air traffic controllers' workload

The second case focuses on the design of workspaces for ATCOs. Maintaining a moderate cognitive workload is essential for operators engaged in complex tasks, such as those within the human-AI hybrid system described in this example. Excessive workload can lead to fatigue, while insufficient workload can diminish situational awareness, both of which pose risks of accidents and significant losses. Thus, real-time prediction and feedback on ATCO workload hold substantial value in modern human-AI hybrid environments. In this case, we developed a novel Electroencephalogram (EEG)-enabled cognitive workload recognition model based on self-supervised learning. The ATCO data used for model training were collected via EEG headsets from 24 participants trained to perform air traffic control tasks on a public online simulator, Endless ATC. The predictive model demonstrates robust performance, validated through comparisons with baseline models in environments with increased levels of masking and noise rates.

The model derived from human factors research can be integrated into the human-AI hybrid ATC system, enabling real-time predictions of ATCO workload and providing timely alerts to help operators maintain optimal working conditions. By employing predictive capabilities, we can leverage EEG data to assess ATCO workload in noisy real working environments, enhancing data collection efficiency and reducing collection complexity compared to traditional evaluation methods, thereby lowering design process entropy. When viewed as a comprehensive design solution, the intelligent ATCO workspace, enriched by this model, enhances interaction with users (ATCOs) and improves solution adaptability, ultimately reducing design behavior entropy.

5 CONCLUSIONS

Advanced sensing and AI technology have ushered in a new era for human factors research, positioning information-related topics at the forefront of the field. Simultaneously, the design discipline is experiencing a paradigm shift driven by AI technology and data science, with informatics emerging as a focal point for design researchers. In this context, this article seeks to provide a novel analysis of the role of human factors in design, with the entropy concept from information theory as a foundation.

This article begins by constructing a concept framework for design entropy and establishing a new terminology system. Within this framework, design processes are categorized into innovative, iterative, and reconfigurative design, corresponding to three types of information processing complexities: integration complexity, conversion complexity, and collection complexity. In practice, these complexities are interconnected and collectively represented in the metric of design process entropy. Each of the three design processes yields distinct design solutions—namely, innovative, iterative, and reconfigurative design solutions—associated with two evaluation metrics: conversion ability (reflected in the design behavior entropy metric), influenced by usability and solution adaptability, and system complexity (reflected in the design structure entropy metric), determined by implementability and design adaptability.

Subsequently, the article analyzes the influence of human factors on design within this framework. Guidelines produced by human factors research can directly impact conversion complexity during the design process, thereby reducing the design process entropy associated with innovative and iterative designs. Additionally, these guidelines can enhance the usability of design solutions, thereby lowering their design behavior entropy. In addition, predictive models derived from human factors research can influence collection complexity during the design process, thus reducing the design process entropy of reconfigurative design. Furthermore, these predictive models can improve the solution adaptability of design solutions, ultimately decreasing their design behavior entropy. The article concludes with two case studies illustrating the scenarios where human factors affects design.

As an exploratory work, this article acknowledges several limitations. The proposed concept framework is primarily derived from literature review and theoretical analysis, and the establishment of a sound theoretical framework requires iterative refinement through practical application. Consequently, it is necessary to establish specific quantitative methods to calculate three types of entropy outlined in this framework, which remains a significant challenge. Furthermore, implementing such quantitative methods in real-world design processes may be a challenge for designers, thus additional efforts are needed to ensure the framework's usability and accessibility in practice. As a pioneering framework study, this article underscores the current limitations of human factors in effectively reducing integration complexity in information processing and system complexity inherent in design solutions. Addressing these two challenges presents potential avenues for human factors research to achieve breakthroughs and enhance its impact on the field of design.

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