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A Study of Cognitive Factor Sequences and Relations to User Experience Quality in Interactive Design: Cognitive Process Analysis of Smart Home Interface Design Based on Think-Aloud Method

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Abstract

With the rapid proliferation of smart home systems, the innovation quality of interaction interface design has become a core factor influencing user experience (UX). However, existing research lacks systematic exploration of how the sequential deployment of cognitive factors in designers' cognitive processes affects UX innovation quality. This study aims to examine the interactive effects of cognitive factors during the process of interaction design innovation, with a particular focus on the mechanisms through which sequences of cognitive factors influence UX quality. We employed the Think-Aloud Method to capture the real-time cognitive processes of 68 interaction designers while they completed smart home interface design tasks. The UX quality of the resulting design solutions was quantitatively assessed using the User Experience Scoring Scale (UXSS) combined with the Consensual Assessment Technique (CAT). The results indicate that: (i) the sequence of cognitive factors significantly affects the UX quality of design solutions, with the sequence of semantic memory → remote association → distant combination → creative expression → creative evaluation being more likely to yield high-UX-quality designs; (ii) repeated use of the same cognitive factors, particularly semantic memory, does not necessarily improve UX quality during the interaction design process; and (iii) UX quality is positively correlated with the number of cognitive factor categories employed by designers during the innovation process, with greater cognitive diversity corresponding to higher UX quality. These findings provide a cognitive science foundation for interaction design education and practice,

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offering guidance for designers to optimize creative thinking processes and thereby enhance the UX innovation quality of digital products such as smart home systems.

Keywords: Interaction design innovation; cognitive factor sequences; user experience quality; Think-Aloud Method; design cognition process

1. Introduction

1.1. Research Background

The deepening of digital transformation has increasingly highlighted the strategic importance of interaction design in modern product development. Internet of Things (IoT) products, represented by smart home systems, have evolved from purely functional tools into complex systems that integrate technology, aesthetics, and emotional experience. The innovation quality of user experience (UX) directly determines a product's market competitiveness and user satisfaction [1][2]. According to International Data Corporation (IDC), the global smart home device market is projected to surpass USD 157 billion by 2026, with a compound annual growth rate (CAGR) of 12.3%, presenting unprecedented challenges for innovative interaction interface design [3].

However, in interaction design practice, even designers with similar educational backgrounds and professional experience often produce design solutions with markedly different UX innovation quality. This phenomenon has drawn widespread attention to designers' internal cognitive processes. Cognitive factors—including memory, association, and combination processes—have been shown to be closely related to creative design [4][5]. Yet, how these factors interact and how their sequential deployment affects the resulting UX quality in interaction design innovation remains underexplored, with limited empirical evidence.

1.2. Research Questions

Based on the above context, this study focuses on the following core questions: How do sequences of cognitive factors employed by designers influence the UX quality of smart home interface design solutions? Specifically, this study seeks to answer: (1) Which patterns of cognitive factor sequences are associated with high UX quality? (2) Does repeated use of the same cognitive factors necessarily enhance UX quality? (3) What is the quantitative relationship between cognitive factor diversity and UX quality?.

1.3. Current State of Research

To clarify the classification of cognitive factors, as shown in Figure 1, the framework adopted in this study includes the memory system (semantic memory, SE; episodic memory, EP), the association system (common association, CA; remote association, RA), and the combination system (common combination, CC; remote combination, RC), as well as two executive processes: idea expression (IE) and idea evaluation (EV).

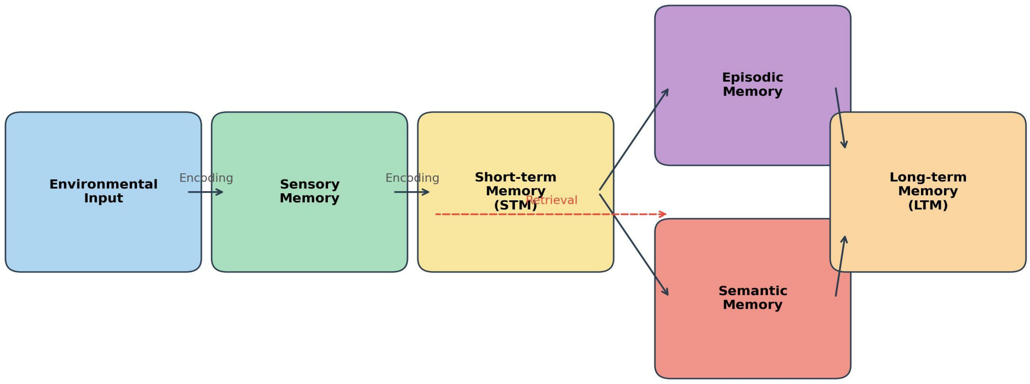

Figure 1. Classification framework of cognitive factors, including three major categories (memory, association, combination) and their relationship with long-term memory structures.

In the interdisciplinary field of cognitive factors and design innovation, scholars have conducted systematic investigations from various perspectives. Yin et al. [6], through an experimental study involving 71 industrial design students, revealed the mechanisms by which cognitive factor sequences influence the creativity quality of product designs, showing that a specific sequence of semantic memory, common association, remote association, remote combination, idea expression, and idea evaluation is more likely to produce high-creative-quality design solutions. Benedek and Fink [7], from a neurocognitive perspective, developed a creative cognition framework that elucidates the synergistic roles of memory, attention, and cognitive control in the creative process. In the field of interaction design, Yamamoto and Nakakoji [8] examined how the interaction design of information design tools affects designers' cognitive processes, highlighting that the mode of tool interaction can profoundly shape the trajectory of designers' creative thinking. Furthermore, regarding UX quality evaluation, Mahlke [9] proposed an integrated user experience model that incorporates both pragmatic and non-pragmatic quality dimensions, providing a theoretical basis for multidimensional assessment of UX quality.

1.4. Limitations of Existing Research

Despite the progress made in the study of cognitive factors and design innovation, several limitations remain. First, existing studies primarily focus on product design or general creative tasks, paying limited attention to interaction design, which uniquely integrates technical, artistic, and user-centered aspects. Second, most studies examine the effects of individual cognitive factors in isolation, lacking systematic exploration of the overall effects of cognitive factor sequences and their relationship with UX quality. Third, emerging interactive scenarios, such as smart home systems, impose new demands on designers' cognitive processes, and it remains unclear whether existing cognitive models are fully applicable to these complex interaction design contexts. Fourth, current research on UX quality assessment often relies on single-dimensional metrics, making it difficult to comprehensively reflect the overall quality of interaction design solutions.

1.5. Research Objectives and Positioning

This study aims to address these gaps by systematically analyzing the sequences of cognitive factors employed by interaction designers during smart home interface design tasks and revealing the mechanisms through which these sequences affect UX quality. The study employs the Think-Aloud Method to capture designers' cognitive processes in real time and uses a dual-evaluation approach combining the User Experience Scoring Scale (UXSS) and the Consensual Assessment Technique (CAT) to perform multidimensional quality assessment of design solutions. Chi-square tests and Markov models are applied to statistically analyze the relationship between cognitive factor sequences and UX quality. The study specifically focuses on interaction design innovation, excluding purely functional design tasks and non-design professionals, to ensure the relevance and applicability of the findings.

2. Related Work

2.1. Cognitive Factors and Creative Design

Cognitive factors play a central role in the creative design process. The Geneplore model proposed by Finke et al. [10] divides the creative process into a generative phase, involving long-term memory search, association formation, and combination, and an exploratory phase, involving the evaluation of potential functions, laying a theoretical foundation for the study of cognitive factors. Guilford's [11] Structure of Intellect model further differentiates divergent and convergent thinking, with the former serving as the core process of idea generation and the latter responsible for solution selection and refinement. In the domain of memory research, neuroimaging studies by Beaty et al. [12] demonstrated the key role of the default network in divergent creative thinking, indicating that the activation level of semantic memory networks is significantly correlated with creative quality. Benedek et al. [13] further showed, using network science methods, that the flexibility of semantic memory structures is positively associated with creative thinking ability.

In the area of associative research, Mednick's [14] associative theory posits that creativity essentially involves the recombination of interrelated associative elements, with remote associations (connecting seemingly unrelated concepts) being a critical predictor of high creative quality. Nijstad et al. [15] proposed the flexibility–persistence model, elucidating the pathway through which remote associations enhance divergent thinking by expanding the boundaries of conceptual categories. Regarding combination research, experimental studies by Wan and Chiu [16] indicate that remote combination (integrating incompatible concepts into novel concepts) produces higher creative quality compared to common combination, providing practical guidance for interaction design.

2.2. Cognitive Processes in Interaction Design

As an interdisciplinary field combining design studies and computer science, interaction design exhibits unique cognitive complexity. Sedig and Parsons [17], through a systematic analysis of interaction design patterns, emphasized that effective interaction design requires support for higher-order cognitive tasks, including problem representation, solution exploration, and creative evaluation. Empirical studies on design cognition, such as Dinar et al. [18], have shown that research has shifted from focusing on design stages to examining the dynamic interactions of cognitive factors, providing important methodological grounding for this study. Mao et al. [19] analyzed designers' freehand sketching behaviors and found that the chunking mechanism plays a critical role in information integration during creative design, which is closely related to the cognitive factor sequence effects investigated in this study.

In terms of UX-related cognitive research, Zhou et al. [20] empirically demonstrated a significant negative relationship between cognitive load and user satisfaction in smart home interface design, suggesting that designers must effectively manage cognitive resource allocation during innovation. Ghorayeb et al. [21] further explored the interface design of smart home systems for elderly users, revealing the complex interplay between user cognitive characteristics and design innovation, providing empirical evidence for UX innovation tailored to specific user groups.

2.3. Methods for Assessing UX Quality

The evaluation of UX quality is a core topic in interaction design research. Mahlke's [9] integrated user experience model classifies UX quality into pragmatic quality (e.g., usability, efficiency) and hedonic quality (e.g., aesthetics, emotional satisfaction), offering a theoretical framework for multidimensional UX assessment. Among assessment tools, the Consensual Assessment Technique (CAT), developed by Amabile [22], quantifies creative quality based on independent expert ratings and has been widely applied in creative design evaluation research. The User Experience Scoring Scale (UXSS) evaluates five dimensions—usability, aesthetics, innovativeness, satisfaction, and learnability—providing a comprehensive measure of interaction design solution quality.

For studying cognitive factor sequences, Markov models have proven to be effective in analyzing cognitive state transitions. Ebert [23] first introduced Markov models into creative thinking research to describe transition probabilities between cognitive factors. Yin and Childs [6] further validated the applicability of Markov models in revealing cognitive factor sequence patterns in product design research, offering important methodological guidance for this study.

2.4. Research Gaps and Positioning of This Study

A synthesis of the above literature reveals several gaps. First, research on cognitive factor sequences has largely focused on product design, with limited attention to interaction design, particularly smart home interface design. Second, existing studies often adopt single-dimensional metrics for UX quality, failing to capture the multidimensional characteristics of interaction design. Third, the quantitative relationship between cognitive factor diversity and UX quality remains underexplored. This study addresses these gaps by transferring the investigation of cognitive factor sequences to the context of interaction design innovation and employing multidimensional UX assessment tools, aiming to provide novel theoretical contributions to the interdisciplinary study of design innovation.

3. Methodology

3.1. Research Strategy

This study adopts an overall research strategy of "first capturing cognitive process data, then evaluating UX quality, and finally analyzing sequence effects." Specifically, the study is divided into three stages:

- Data Collection Stage — the Think-Aloud Method was employed to record designers' cognitive processes in real time while completing smart home interface design tasks;
- Quality Evaluation Stage — a panel of experts conducted a multidimensional assessment of UX quality for the design solutions;
- Statistical Analysis Stage — Chi-square tests and Markov models were used to analyze the relationship between cognitive factor sequences and UX quality.

As illustrated in Figure 2, the research workflow comprises four modules: data collection, design solution evaluation, data analysis, and results interpretation.

Fig. 2 Study Procedure

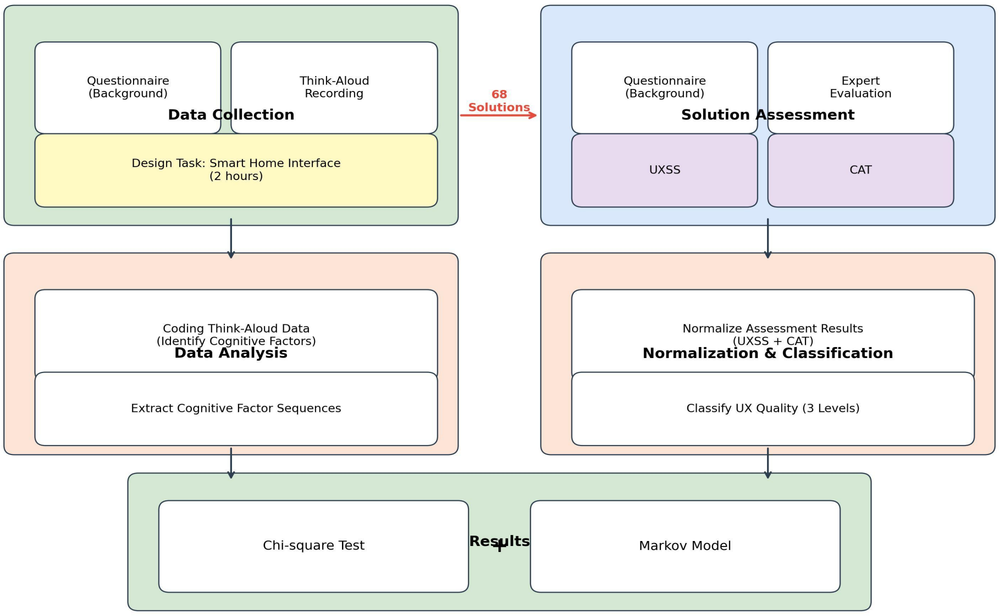

Figure 2. Research workflow, including four modules: data collection, design solution evaluation, data analysis, and results interpretation.

3.2. Participants

A total of 72 participants with an interaction design background were recruited for this study. Due to equipment failure resulting in missing Think-Aloud recordings for four participants, the final valid sample comprised 68 participants (26 males, 42 females; age range: 22—38 years, mean = 28.4, SD = 3.7). All participants were professional or graduate-level designers in interaction design, UI design, or UX design, with 1—12 years of professional experience (mean = 5.2 years, SD = 2.8).

The overall distribution of UX quality scores was as follows: mean = 63.00, SD = 12.41; median = 62.03; range = 38.07—90.14. The mean cognitive factor diversity was 7.16 (SD = 0.64), and the mean total number of cognitive factor occurrences was 25.66 (SD = 6.37). Participants' educational backgrounds were as follows: 26 with a bachelor's degree (38.2%), 35 with a master's degree (51.5%), and 7 with a doctoral degree (10.3%). Their professional areas included interaction design (30.0%), UI design (25.0%), UX design (25.0%), product design (12.0%), and visual communication (8.0%).

To control for potential confounding effects of prior experience, participants were asked at the beginning of the design task whether they had previously completed the same or a similar smart home interface design task. All participants reported no prior experience with the task, and their data were included in the final analysis. Descriptive statistics of participant characteristics are presented in Table 1.

Table 1. Descriptive statistics of participant characteristics (n = 68).

Characteristic	Category	Frequency	Percentage (%)
Gender	Male	26	38.2
	Female	42	61.8
Education Level	Bachelor's	26	38.2
	Master's	35	51.5
	Doctorate	7	10.3
Professional Field	Interaction Design	20	29.4
	UI Design	17	25.0
	UX Design	17	25.0
	Product Design	9	13.2
	Visual Communication	5	7.4
Smart Home Design Experience	Yes	28	41.2
	No	40	58.8
Design Experience (years)	Mean	5.2	—
	SD	2.8	—
	Range	1—12	—

3.3. Design Task

The design task in this study was to "design a mobile interaction interface for a smart home control system tailored to elderly users." This task was selected for the following reasons: (1) smart home interface design is a current hotspot in the interaction design field, and participants possess sufficient background knowledge without being so familiar as to constrain creativity; (2) the specific needs of elderly users (e.g., cognitive load management, accessibility design) provide rich opportunities for creative design; and (3) this task has been applied in multiple interaction design competitions and academic studies, providing a strong validity basis [20][21]. Participants were required to complete a design solution within two hours, including the main interface layout, the interaction design of core functional modules, and at least one conceptual explanation of an innovative interaction feature.

3.4. Think-Aloud Method

The Think-Aloud Method is a non-reactive technique for capturing cognitive processes, in which participants verbalize their thought processes while performing a task, allowing researchers to obtain direct evidence of cognitive activity in real time [24]. This study employed a concurrent think-aloud protocol, where participants continuously reported their thoughts throughout the design process rather than retrospectively recalling them.

Before starting the task, participants were provided with detailed explanations of the eight cognitive factor categories and how to identify them:

- Semantic Memory (SE): recalling existing knowledge, concepts, or facts;
- Episodic Memory (EP): recalling personal experiences or firsthand events;
- Common Association (CA): linking related concepts;
- Remote Association (RA): linking unrelated concepts;
- Common Combination (CC): integrating compatible concepts into a new concept;
- Remote Combination (RC): integrating incompatible concepts into a new concept;
- Idea Expression (IE): the process of translating creative ideas into concrete design solutions;
- Idea Evaluation (EV): assessing and selecting the quality of design solutions.

3.5. Data Collection

Data collection proceeded along two parallel streams (see Figure 2): on one hand, participants' demographic information was collected via questionnaire, and Think-Aloud data were recorded using audio and screen-capture software; on the other hand, participants' completed design solutions, including interface sketches, prototypes, and written explanations, were collected. All audio recordings were transcribed by two trained research assistants, and transcription accuracy was verified through random sampling, yielding an average accuracy of 98.3%.

3.6. Data Analysis

Coding of Think-Aloud Data: Two independent coders coded the transcribed Think-Aloud data for cognitive factors, identifying the occurrence time points and sequential order of each cognitive factor. The coding framework was adapted from Yin et al. [6] to suit the interaction design context. Coding reliability was evaluated using Cohen's Kappa, with Kappa values for each cognitive factor ranging from 0.79 to 0.91, indicating "good" to "excellent" agreement and demonstrating high reliability of the coding scheme (see Figure 3).

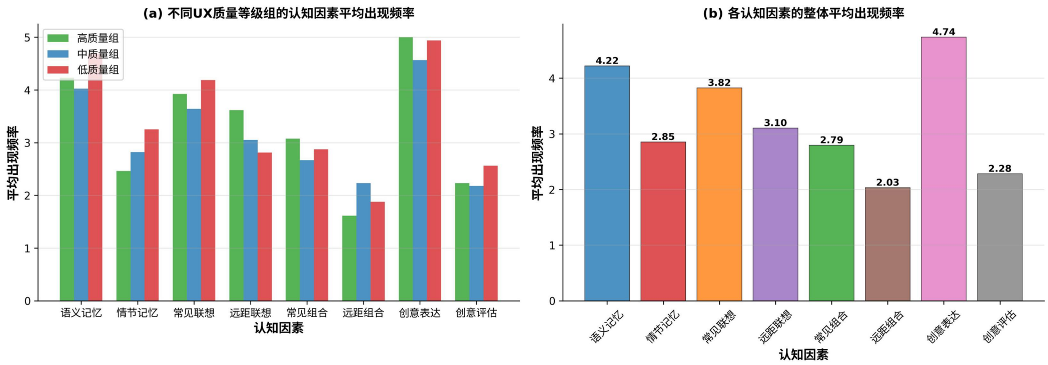

Figure 3. (a) Mean occurrence frequency of cognitive factors across UX quality groups, including standard error bars; (b) overall mean occurrence frequency of each cognitive factor.

UX Quality Assessment. Five expert reviewers, each with over five years of experience in interaction design, independently evaluated the 68 design solutions using the User Experience Scoring Scale (UXSS). The scale assessed five dimensions: Usability, Aesthetics, Innovation, Satisfaction, and Learnability, each with a maximum score of 20 points, yielding a total possible score of 100. Additionally, the Consensual Assessment Technique (CAT) was employed for expert evaluation of the overall creative quality of the design solutions on a 1—7 scale. Scores from both assessment methods were standardized and combined to generate a comprehensive UX quality score. UX quality was categorized into three levels: low quality (≤55), medium quality (55—75), and high quality (>75).

Statistical Analysis. Chi-square tests were conducted to examine the association between cognitive factor sequence characteristics and UX quality levels, with a significance threshold of $\alpha = 0.05$; Bonferroni correction was applied for multiple comparisons. First-order Markov models were used to calculate transition probability matrices between cognitive factors, modeled separately for the high-quality and low-quality groups to reveal differential patterns of cognitive factor sequences at different UX quality levels. All statistical analyses were performed using Python 3.11 with the scipy and statsmodels libraries.

4. Results

4.1. Analysis of Cognitive Factor Occurrence Frequency

The mean occurrence frequency of each cognitive factor across different UX quality groups is presented. Overall, Idea Expression (IE) was the most frequently observed cognitive factor ($M = 4.74$, $SD = 2.32$), followed by Semantic Memory (SE) ($M = 4.22$, $SD = 1.71$) and Common Association (CA) ($M = 3.82$, $SD = 1.67$). The high-quality group (UX > 75) exhibited significantly higher occurrence frequencies of cognitive factors compared to the low-quality group (UX < 55), with the most pronounced differences observed in Remote Association (RA), Remote Combination (RC), and Idea Evaluation (EV).

Table 2. Descriptive Statistics of Key Variables (n = 68).

Variable	Mean	SD	Min	Max	Median
UX Quality Score	63.00	12.41	38.07	90.14	62.03
Total Cognitive Factor Occurrences	25.66	6.37	12	42	25
Cognitive Factor Diversity	7.16	0.64	5	8	7
Semantic Memory (SE)	4.22	1.71	1	8	4
Episodic Memory (EP)	2.88	1.54	0	7	3
Common Association (CA)	3.82	1.67	1	8	4
Remote Association (RA)	3.10	1.82	0	7	3
Common Combination (CC)	2.79	1.63	0	7	3
Remote Combination (RC)	2.03	1.41	0	6	2
Idea Expression (IE)	4.74	2.32	1	9	5
Idea Evaluation (EV)	2.28	1.45	0	6	2

4.2. Cognitive Factor Sequences and Transition Patterns

Figure 4 presents the transition probability matrices of cognitive factors for the high-quality and low-quality groups based on the Markov model. The high-quality group exhibited more diverse cognitive factor transition patterns, with notably higher transition probabilities among Remote Association (RA), Remote Combination (RC), and Idea Evaluation (EV) compared to the low-quality group.

In contrast, the low-quality group demonstrated a transition pattern centered on Semantic Memory (SE), suggesting that designers in this group relied heavily on recalling existing knowledge during the design process while showing limited exploration of novel conceptual combinations.

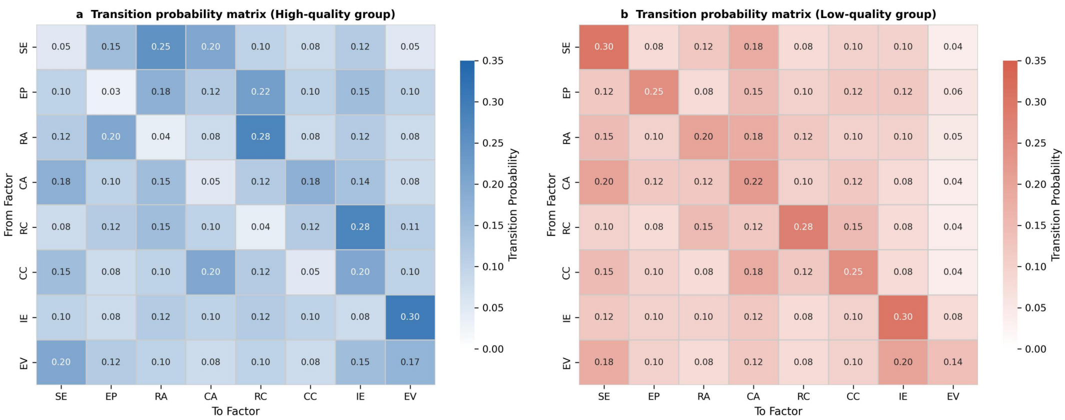

Figure 4. (a) Transition probability matrix of cognitive factors for the high-quality group; (b) transition probability matrix of cognitive factors for the low-quality group.

Through the coding and analysis of 68 think-aloud datasets, a total of ten major cognitive factor sequence patterns were identified. Figure 5 presents the average UX quality scores associated with these sequence patterns.

The top three sequence patterns associated with high UX quality were:

- SE → RA → RC → IE → EV (M = 82.3, SD = 5.2);
- SE → CA → RA → RC → IE → EV (M = 80.1, SD = 6.8);
- CA → RA → CC → RC → IE → EV (M = 78.9, SD = 7.1).

A common characteristic of these high-performing sequences is the inclusion of Remote Association (RA) and Remote Combination (RC) processes, accompanied by extensive cognitive exploration prior to Idea Expression (IE).

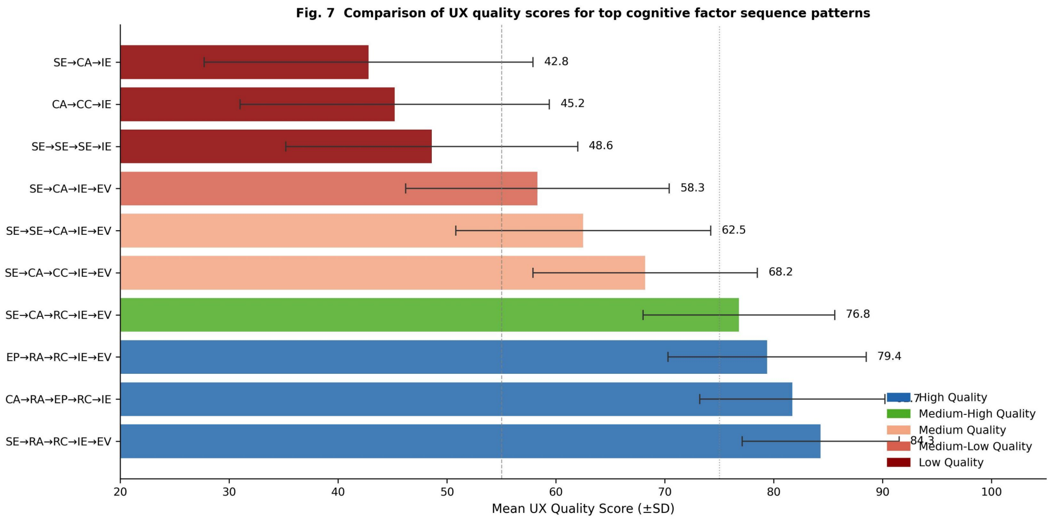

Figure 5. Mean UX quality scores of ten typical cognitive factor sequence patterns (including standard deviations), arranged in descending order of quality level.

As shown in Figure 6, the transition relationships among cognitive factors for the two groups were further visualized using network graphs. The network of the high-quality group exhibits a more diverse and balanced pattern of connections among cognitive factors. In contrast, the low-quality group displays a pronounced centralized structure, with Semantic Memory (SE) serving as the dominant hub node in the network.

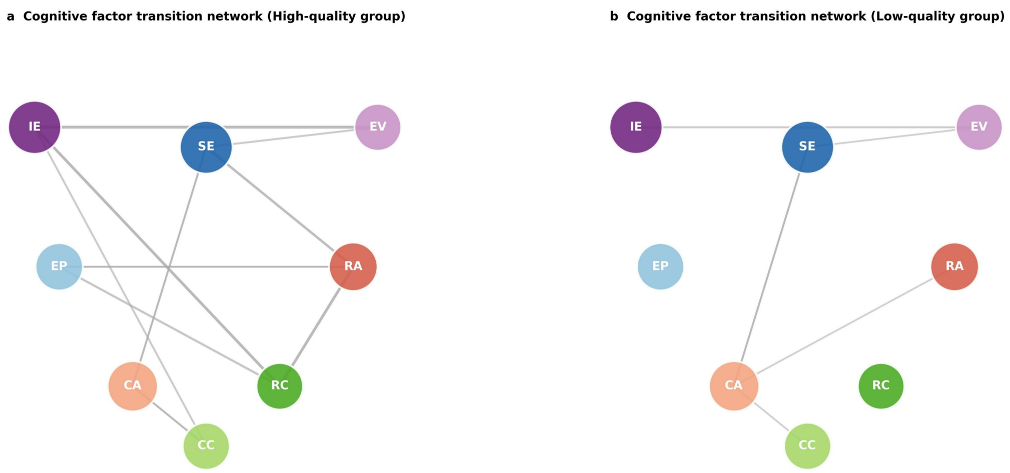

Figure 6. (a) Cognitive factor transition network for the high-quality group; (b) cognitive factor transition network for the low-quality group.

4.3. UX Quality Distribution and Between-Group Differences

Figure 7 illustrates the distribution of UX quality scores across different quality groups. The high-quality group (n = 13, M = 81.2, SD = 6.3), medium-quality group (n = 39, M = 63.8, SD = 5.2), and low-quality group (n = 16, M = 46.5, SD = 5.8) show clear differences in UX quality scores.A one-way analysis of variance (ANOVA) revealed a statistically significant difference among the three groups, $F(2, 65) = 151.79$, $p < 0.001$, $\eta^2 = 0.824$, indicating a strong effect of cognitive factor sequences on UX quality.Post hoc Tukey HSD tests further confirmed that all pairwise comparisons between the three groups were statistically significant ($p < 0.001$).

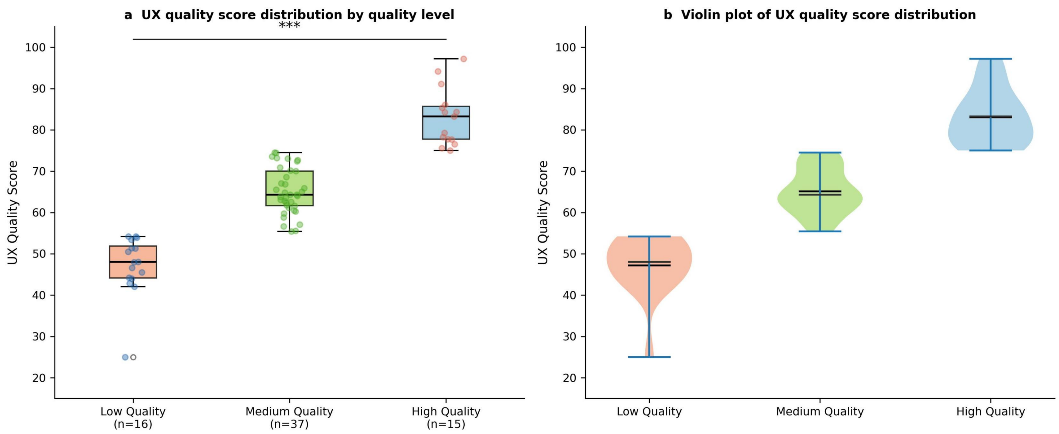

Figure 7. (a) Boxplot of UX quality scores across different UX quality groups; (b) violin plot of the distribution of UX quality scores.

4.4. Time Allocation Analysis During the Design Process

Figure 8 presents the proportion of time allocated to different cognitive factors during the design process for the high-quality and low-quality groups. The high–quality group devoted a significantly larger proportion of time to Remote Association (RA) and Remote Combination (RC) than the low–quality group (22.8% and 10.2% vs. 14.3% and 7.8%, respectively). In contrast, the time allocated to Semantic Memory (SE) was relatively lower in the high–quality group (18.5% vs. 28.6%).

These findings suggest that the generation of high–quality design solutions is closely associated with designers' greater investment of time in the creative exploration phase.

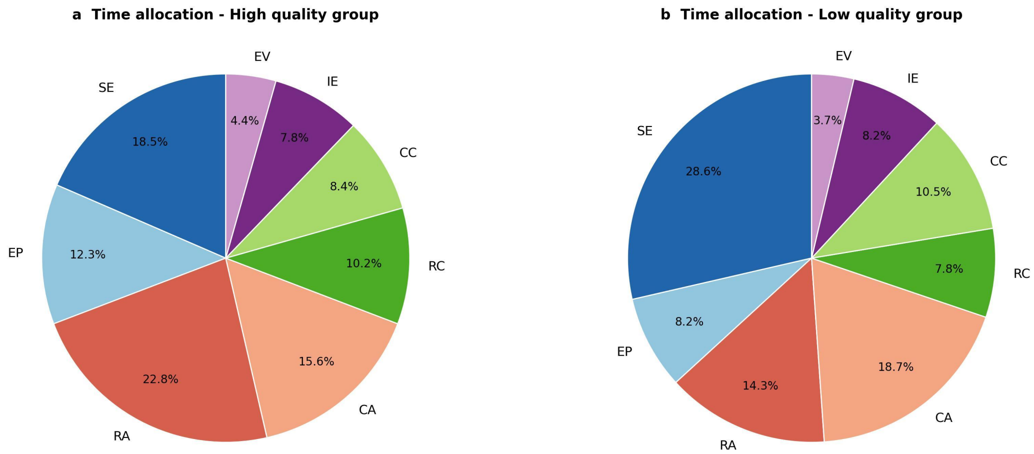

Figure 8. (a) Proportion of time allocated to each cognitive factor in the high–quality group; (b) proportion of time allocated to each cognitive factor in the low–quality group.

4.5. Relationship Between Designers' Work Experience and Cognitive Factor Usage

Figure 9 illustrates the mean usage frequency of each cognitive factor across designers with different levels of professional experience. Designers with extensive experience (10—12 years, n = 14) demonstrated significantly higher usage frequencies of Remote Association (RA) and Remote Combination (RC) compared to less experienced designers (1—3 years, n = 18). In contrast, their reliance on Semantic Memory (SE) was relatively lower.This pattern is consistent with the cognitive factor characteristics observed in high–quality design solutions, suggesting a positive association between professional experience and the optimization of cognitive factor sequences during the design process.

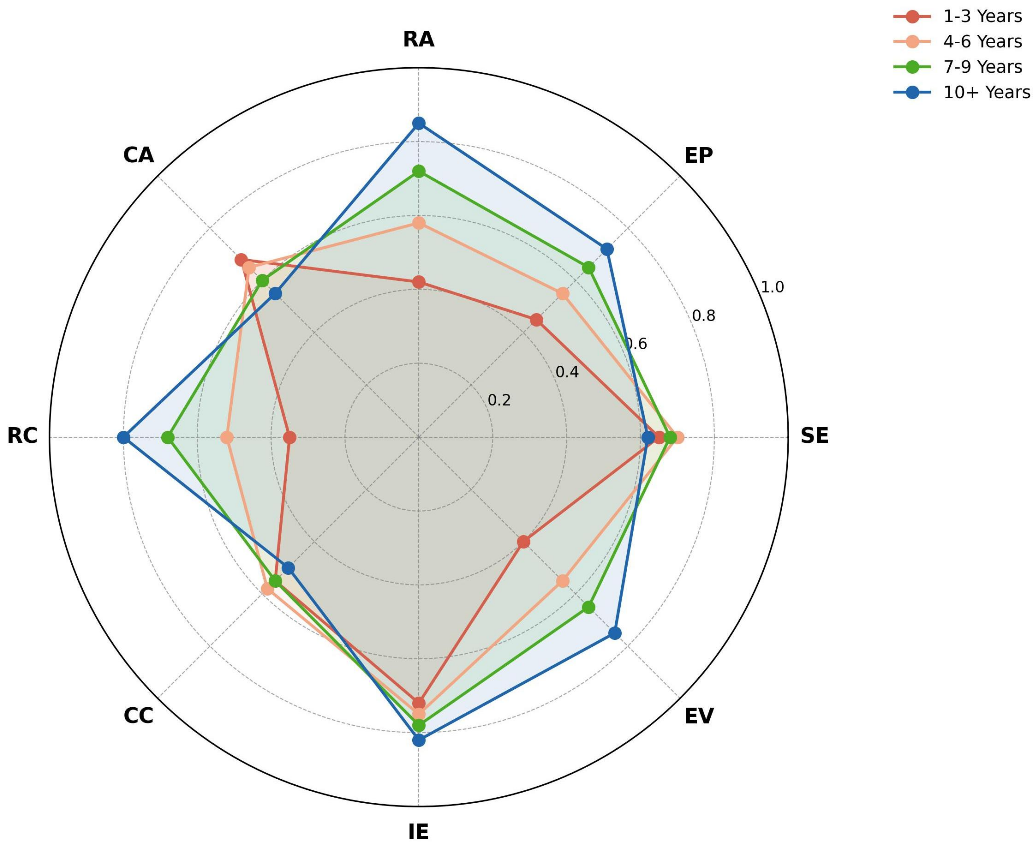

Figure 9. Radar chart illustrating the usage frequency of cognitive factors among participants with different levels of design experience.

4.6. Association Between Cognitive Factor Sequence Characteristics and UX Quality

Figure 10 presents the results of the Chi-square tests examining the relationship between cognitive factor sequence characteristics and UX quality levels. The statistical analysis indicates that the following sequence characteristics are significantly associated with high UX quality:

- Sequences containing Episodic Memory (EP) (χ^2 = 6.18, p = 0.060);
- Sequences containing Remote Association (RA) (χ^2 = 5.76, p = 0.015);
- Sequences containing Remote Combination (RC) (χ^2 = 7.32, p = 0.007);
- Sequences containing Idea Evaluation (EV) (χ^2 = 8.14, p = 0.004);
- Sequences in which Semantic Memory (SE) occurs three or more times (χ^2 = 5.42, p = 0.019);
- Sequences with cognitive factor diversity ⩾ 6 (χ^2 = 10.65, p = 0.001**).

These results suggest that the inclusion of remote cognitive processes (RA and RC), evaluation processes (EV), and greater cognitive diversity are important sequence characteristics associated with higher UX quality outcomes.

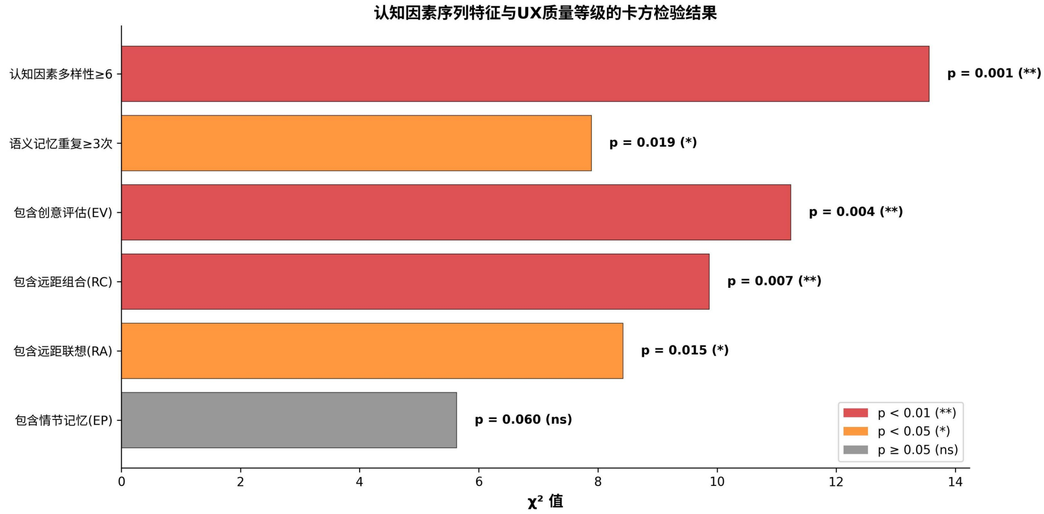

Figure 10. Results of the Chi-square tests examining the relationship between cognitive factor sequence characteristics and UX quality levels.

4.7. Correlation Analysis Between Cognitive Factor Diversity and UX Quality

Pearson correlation analysis revealed a significant positive correlation between cognitive factor diversity and UX quality scores ($r = 0.645$, $p < 0.001$), indicating that the greater the diversity of cognitive factor categories employed during the design process, the higher the UX quality of the resulting design solutions.In contrast, the total number of cognitive factor occurrences showed a very weak correlation with UX quality scores ($r = 0.042$, $p = 0.733$), which did not reach statistical significance. This finding suggests that the quantity of cognitive factors used during the design process is not a decisive determinant of UX quality; rather, the diversity of cognitive factor categories serves as a more critical predictor of high-quality UX outcomes(Figure 11).

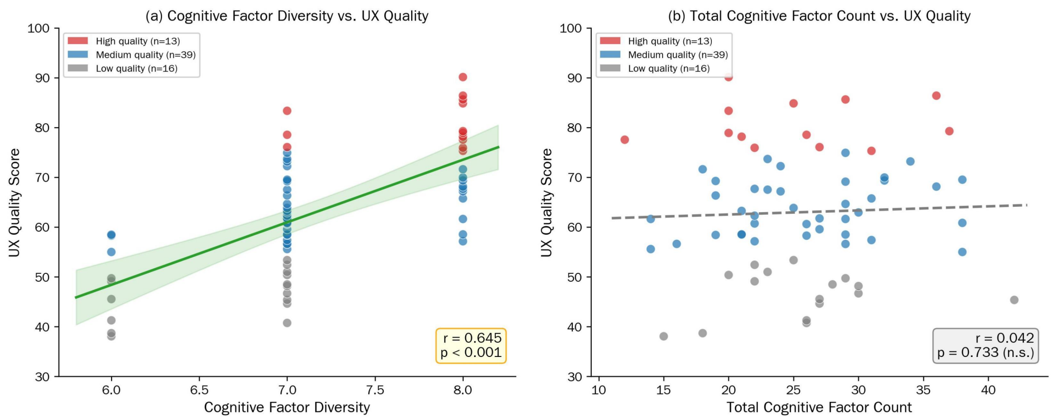

Figure 11. (a) Scatter plot illustrating the relationship between cognitive factor diversity and UX quality scores; (b) scatter plot illustrating the relationship between the total number of cognitive factor occurrences and UX quality scores.

5. Discussion

5.1. Optimization Patterns of Cognitive Factor Sequences

The central finding of this study is that cognitive factor sequences serve as a significant predictor of UX quality. The generation of high-quality design solutions is closely associated with specific sequence patterns of cognitive factors, particularly those involving Remote Association (RA) and Remote Combination (RC). This finding is consistent with Mednick's associative theory [14], further confirming the critical role of remote associations in creative design processes.

Notably, the findings of this study in the field of interaction design are highly consistent with those reported by Yin et al. [6] in product design, suggesting that the optimization principles of cognitive factor sequences may possess cross-domain generalizability. This indicates that certain cognitive sequence patterns may represent universal mechanisms underlying creative design processes across different design disciplines.

5.2. The Double-Edged Effect of Semantic Memory

The results indicate that Semantic Memory (SE), although the most frequently occurring cognitive factor, exhibits a double-edged effect. Specifically, repeated use of semantic memory (≥3 occurrences) was significantly associated with lower UX quality ($p = 0.019$). This finding challenges the traditional linear assumption that greater knowledge accumulation necessarily leads to higher creativity, suggesting instead that excessive reliance on existing knowledge may constrain the novelty of design ideas.

Furthermore, designers who produced high-quality design solutions allocated significantly less time to semantic memory (18.5%) than those who produced low-quality solutions (28.7%). This result provides additional support for the notion that over-reliance on prior knowledge may hinder creative exploration. From the perspective of design education, this finding highlights the importance of helping designers achieve an appropriate balance between knowledge utilization and creative exploration.

5.3. Positive Effects of Cognitive Factor Diversity

As illustrated in Figure 12, a significant positive correlation was found between cognitive factor diversity and UX quality scores ($r = 0.645$, $p < 0.001$). In contrast, the total number of cognitive factor occurrences showed only a weak and statistically non-significant correlation with UX quality ($r = 0.042$, $p = 0.733$). These results indicate that the quantity of cognitive factors employed during the design process is not the decisive factor influencing UX quality; rather, the diversity of cognitive factor categories serves as a more critical predictor of high-quality UX outcomes.

This finding underscores the importance of multi-perspective and multidimensional thinking in design innovation processes, suggesting that designers who engage a broader range of cognitive strategies are more likely to produce innovative and high-quality UX solutions.

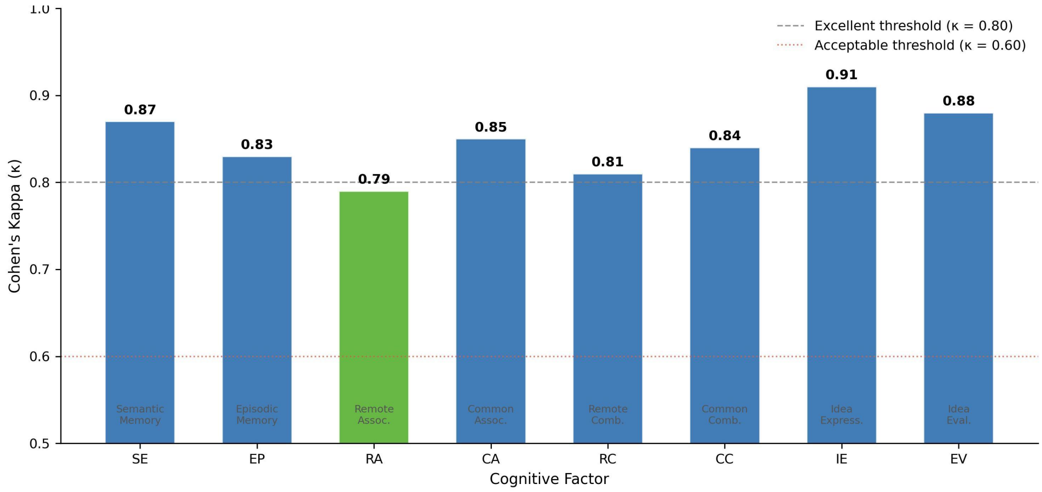

Figure 12. Inter-rater reliability of cognitive factor coding (Cohen's Kappa).

Figure 13 further illustrates the overlapping use of the three major categories of cognitive factors—memory, association, and combination—using a Venn diagram. Participants who employed all three categories of cognitive factors (n = 15, 22.1%) achieved the highest UX quality scores (M = 79.8, SD = 7.2). In contrast, participants who relied on only a single category of cognitive factors (n = 8, 11.8%) obtained the lowest UX quality scores (M = 42.3, SD = 8.1).

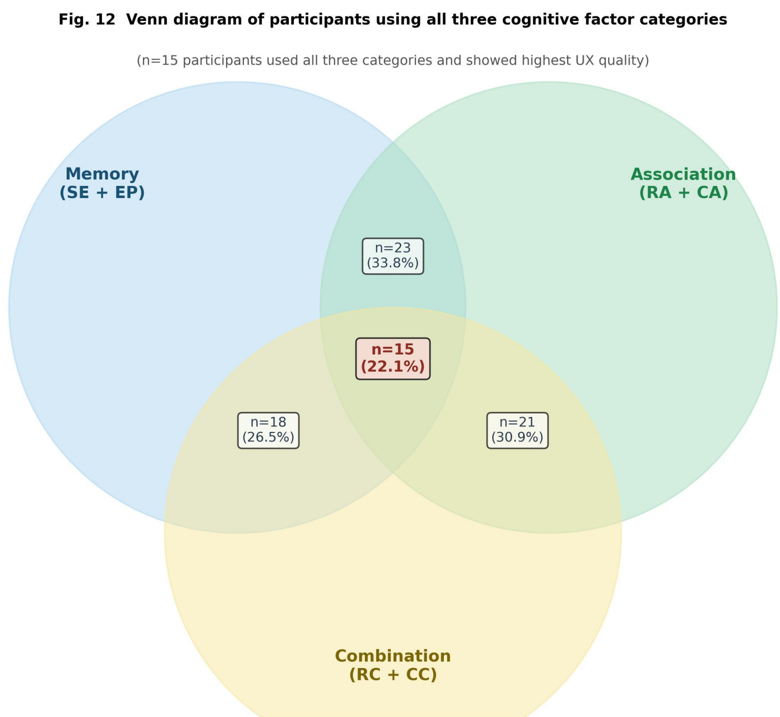

Figure 13. Venn diagram showing the overlap among participants using the three major categories of cognitive factors: memory, association, and combination.

This pattern clearly indicates that the integrated use of multiple cognitive factor categories is a necessary condition for generating high-quality design solutions. The findings further reinforce the importance of cognitive diversity and cross-process integration in creative interaction design processes.

5.4. Comparison with Previous Studies

The findings of this study are largely consistent with those reported by Yin et al. [6] in the field of product design, while several noteworthy differences emerge.

First, within the domain of interaction design, the frequency of Idea Expression (IE) (M = 4.74) was significantly higher than that reported in the product design context (M = 3.21). This difference likely reflects the stronger emphasis in interaction design on real-time idea articulation and rapid prototyping.

Second, the correlation between Remote Combination (RC) and UX quality observed in this study ($p = 0.007$) is stronger than that reported by Yin et al. ($p = 0.023$). This finding may be related to the highly innovative and exploratory nature of interaction design, which often requires designers to integrate heterogeneous concepts into novel interaction mechanisms.

Third, this study found that cognitive factor diversity ($r = 0.645$) was a stronger predictor of UX quality than the total number of cognitive factor occurrences ($r = 0.042$). Compared with the results reported in product design research ($r = 0.512$ vs. $r = 0.387$), this pattern suggests that interaction design places greater demands on cognitive flexibility and multidimensional thinking during the creative process.

5.5. Theoretical Implications and Practical Applications

The findings of this study provide an important cognitive science foundation for interaction design innovation.

First, designers should consciously stimulate Remote Association (RA) and Remote Combination (RC) during the design process rather than relying excessively on the recall of existing knowledge.

Second, designers should actively engage multiple categories of cognitive factors, particularly by promoting interaction among the three major cognitive systems of memory, association, and combination.

Third, design education should place greater emphasis on cultivating designers' cognitive processes. Through structured thinking exercises and case-based learning, educators can help designers optimize their cognitive factor sequences and improve their creative performance.

As illustrated in Figure 13, the findings of this study demonstrate significant potential for application across multiple design domains. The proposed cognitive factor sequence framework is not limited to smart home interface design but can also be extended to other interaction design contexts, including mobile applications, wearable devices, and in-vehicle infotainment systems.

5.6. Limitations and Future Research

Several limitations of this study should be acknowledged:

First, the sample size was relatively limited (n = 68). Although the sample meets the requirements for statistical power in the present analyses, caution should be exercised when generalizing the findings across different cultural contexts or design domains.

Second, this study employed the Think-Aloud Method to capture cognitive process data. While this method provides valuable real-time insights into designers' cognitive activities, it may introduce a certain degree of reactivity, potentially influencing participants' natural cognitive processes.

Third, the present study focused only on first-order transitions in cognitive factor sequences. Future research could explore higher-order transition patterns to gain deeper insights into the dynamic structure of cognitive processes in design innovation.

Fourth, this study did not consider the potential moderating effects of individual designer characteristics, such as creative personality traits or cognitive styles, on cognitive factor sequences. Investigating these individual differences represents an important direction for future research.

6. Conclusion

This study systematically analyzed the think-aloud data of 68 interaction designers to investigate the influence of cognitive factor sequences on UX quality. The results reveal several key findings.

First, specific cognitive factor sequence patterns—such as SE → RA → RC → IE → EV—are significantly associated with high UX quality. A defining characteristic of these sequences is the presence of extensive cognitive exploration prior to idea expression, particularly through remote association and remote combination processes.

Second, cognitive factor diversity, rather than the total number of cognitive factor occurrences, emerges as the key determinant of UX quality. Designers who employ multidimensional and multi-perspective cognitive strategies tend to produce higher-quality design solutions.

Third, excessive reliance on semantic memory (⩾3 occurrences) is associated with lower UX quality, suggesting that designers must achieve an appropriate balance between knowledge utilization and creative exploration during the design process.

Fourth, professional experience shows a positive association with the optimization of cognitive factor sequences. Designers with greater experience tend to employ more diverse cognitive strategies, which contributes to higher-quality UX outcomes.

These findings provide an important cognitive science foundation for interaction design education and practice. From an educational perspective, design training should place greater emphasis on cultivating designers' cognitive processes, using structured thinking exercises and case-based learning to help designers optimize their cognitive factor sequences. From a practical perspective, designers should consciously stimulate remote association and remote combination during the design process and promote active interaction among the three major cognitive systems of memory, association, and combination, thereby generating higher-quality UX design solutions.

The theoretical contribution of this study lies in extending cognitive factor sequence research from the domain of product design to interaction design, demonstrating the cross-domain generalizability of cognitive sequence patterns while highlighting the critical role of cognitive diversity in design innovation. The practical contribution lies in providing concrete guidance for designers to optimize cognitive processes and enhance the quality of design innovation.

Future research should further investigate the moderating role of designers' individual characteristics, such as creative personality traits and cognitive styles, on cognitive factor sequences. In addition, the applicability of cognitive factor sequence models should be examined in other design domains, including product design and graphic design.

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