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THE EFFECTIVENESS OF USER-CENTERED DESIGN (UCD) METHODOLOGY IN DEVELOPING VISUALIZATION SYSTEMS FOR COMPLEX GRAPHICAL DATA

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ABSTRACT

The rapid growth of digital information and the increasing complexity of data flows have created significant challenges in transforming raw data into meaningful and cognitively accessible knowledge. This study investigates the effectiveness of the User-Centered Design (UCD) methodology in developing visualization systems for complex graphical data, with the aim of enhancing cognitive efficiency, reducing mental workload, and improving visual communication. The study targeted professional designers and intensive digital system users in Saudi Arabia, selecting a purposive sample of 216 participants with experience in interacting with high-density, dynamic, or complex datasets. A quasi-experimental research design was employed to compare two conditions: traditional static visualizations and a dynamic visualization system developed according to UCD principles, integrated with grid systems and a dynamic visual identity framework. Data collection involved measuring reaction time, interpretation accuracy, and cognitive load using the NASA-TLX scale, alongside performance-based assessments. Statistical analysis, including descriptive statistics, paired t-tests, and correlation analysis, was conducted to evaluate differences between the two visualization approaches. The results indicate that participants using the dynamic UCD-based visualization system demonstrated significantly faster reaction times (mean = 8.5 s vs. 12.8 s), higher interpretation accuracy (91.2% vs. 78.6%), and lower cognitive load (NASA-TLX mean = 52.3 vs. 68.4) compared to traditional static designs. Moreover, the system effectively balanced aesthetic and functional requirements, maintained a sustainable dynamic visual identity, and facilitated efficient meaning-making from complex graphical data. Based on these findings, the study recommends adopting UCD as a governance framework, integrating grid systems to structure visual information, implementing dynamic visual identity for adaptive scalability, and prioritizing cognitive load management in visualization system design. Future research should explore AI integration, multimodal interaction, cross-cultural applicability, and long-term effects of dynamic visualization systems in complex data environments. This research provides a comprehensive framework for developing

cognitively efficient, user-centered visualization systems, contributing to enhanced decision-making, usability, and the humanization of technology in data-intensive digital contexts.

KEYWORDS: User-Centered Design, Visualization Systems, Cognitive Load, Grid Systems, Dynamic Visual Identity, Data Interpretation.

1. INTRODUCTION

In recent decades, the world has witnessed a profound transformation in the nature of data production and circulation, where digital information flows have become increasingly massive, complex, and continuously evolving. This shift has posed significant challenges to the field of visual design, particularly in terms of transforming raw data into meaningful and cognitively accessible knowledge (Montello, 2018; Szafir, 2018). Within this context, traditional graphic design—primarily centered on producing static visual outputs—has proven insufficient to meet the demands of interactive and data-intensive digital environments (Ware, 2013). Consequently, there is an urgent need to conceptualize design practices through more dynamic and adaptive methodological frameworks (Norman, 1986; ISO 9241-210, 2010).

In response to these challenges, visualization systems have emerged as an advanced alternative to static design approaches. Rather than focusing on final visual forms, these systems operate as procedural and dynamic structures capable of adapting to continuously changing data (Ware, 2013; Huang et al., 2024). However, the effectiveness of such systems depends largely on the existence of a robust methodological framework that governs the relationship between data complexity and human cognitive capabilities (Norman, 2013; ISO 9241-11, 2018).

This is where the User-Centered Design (UCD) methodology becomes critically relevant. UCD represents a contemporary design paradigm that places the user at the core of the design process by prioritizing cognitive characteristics, perceptual abilities, and functional needs (Norman, 2013; ISO 9241-210, 2010). Its primary objective is to minimize cognitive load while maximizing usability and communication efficiency (Sweller, 2011; Liberman-Pincu & Bitan, 2021). In the context of complex data visualization, UCD extends beyond interface optimization to function as a comprehensive governance framework. It regulates the semiotics and rhetoric of visual discourse, ensuring a balance between aesthetic expression and functional clarity (Roose et al., 2021; Nelson & MacEachren, 2020).

Within this framework, grid systems play a fundamental role as a form of visual syntax that structures information and guides the user's perceptual pathway. By organizing visual space according to systematic rules, grid systems reduce visual noise, enhance clarity, and improve the speed and accuracy of information processing (Lu & Ye, 2017; Lloyd et al., 2007). Furthermore, they contribute to maintaining consistency and coherence within dynamic visual environments.

In parallel, the concept of dynamic visual identity introduces a new dimension to visual systems by enabling them to adapt to fluctuating data while preserving their conceptual integrity and recognizability. This ensures both sustainability and scalability, allowing visual systems to remain relevant and effective over time (van den Bosch, 2018; Chen et al., 2022). Accordingly, this research seeks to investigate the effectiveness of the User-Centered Design (UCD) methodology in developing visualization systems for complex graphical data. It aims to propose an integrated methodological framework that combines design governance, visual discourse strategies, and grid-based structures to transform raw data into meaningful visual knowledge. Additionally, the study focuses on reducing cognitive load, enhancing visual communication efficiency, and supporting decision-making processes within interactive digital environments, ultimately contributing to the humanization of technology (Norman, 2013; Sweller, 2011).

2. PROBLEM STATEMENT

The research problem emerges from the growing disparity between the massive scale of digital information flows and the limited capacity of traditional visual design systems to effectively process and transform such data into meaningful and cognitively accessible knowledge. Despite significant technological advancements in visualization tools and display techniques, graphic design still suffers from critical issues such as cognitive overload, visual clutter, and inefficient communication of complex information.

This challenge is primarily attributed to the continued reliance on the paradigm of "design as a static visual product," which is no longer adequate for handling dynamic, multi-variable, and probabilistic data environments. Traditional design approaches often fail to account for the cognitive and perceptual needs of users, resulting in fragmented visual experiences that hinder understanding and decision-making. Furthermore, there is a noticeable lack of a comprehensive methodological framework that governs the relationship between complex data structures and human cognitive capabilities. This gap leads to inconsistencies in visual representation, weak semiotic clarity, and an inability to systematically control the flow of information within digital interfaces. Accordingly, the core problem of this research lies in the need to shift from static design practices toward dynamic Visualization Systems that operate as adaptive and scalable structures. More importantly, there is a critical need to activate the User-Centered Design (UCD) methodology not merely as a usability tool, but as a governance framework that regulates visual discourse, organizes probabilistic data variables, and aligns system aesthetics with functional requirements. Thus, the study addresses the central issue of how to develop governed visualization systems capable of reducing cognitive load, enhancing perceptual clarity, and enabling users to efficiently extract meaningful insights from complex graphical data within interactive digital environments

2.1. Research Questions

This study seeks to address the following main research question:

To what extent is the User-Centered Design (UCD) methodology effective in governing visualization systems for complex graphical data in order to ensure efficient visual communication and sustain dynamic visual identity?

From this main question, the following sub-questions are derived:

1. How can the User-Centered Design (UCD) methodology function as a governance framework for organizing probabilistic data variables and transforming them into clear and intelligible cognitive structures?
2. What is the impact of shifting from "design as a static visual product" to "visualization systems" on reducing users' cognitive load in data-intensive digital environments?
3. To what extent do Grid Systems contribute to establishing a coherent visual syntax that regulates the relationship between aesthetic structure and functional requirements within complex user interfaces?
4. How does the governance of visualization systems support the sustainability of dynamic visual identity and its ability to adapt to continuously changing data flows?

Research Objectives

The present study aims to achieve the following objectives:

1. Rooting the methodological governance framework: To construct a theoretical model that clarifies how the User-Centered Design (UCD) methodology operates as a governance framework that regulates the relationship between the complexity of raw data and its visual representations, ensuring their transformation into clear and comprehensible cognitive structures.
2. Shifting toward visual systems engineering: To establish the concept of *Visualization Systems* as a methodological alternative to static graphic solutions, emphasizing their role in accommodating probabilistic data variables and reducing users' cognitive load.
3. Formulating the visual structure of grid systems: To define the design standards for employing Grid Systems as an engineering tool (*Visual Syntax*) that aligns communicative functionality with systemic aesthetics in data-intensive digital interfaces.
4. Enhancing the sustainability of dynamic visual identity: To provide applied strategies that ensure the preservation of the conceptual structure of visual identity while enabling its dynamic adaptation to continuous data flows without losing clarity or distinctiveness.
5. Measuring cognitive efficiency: To develop precise measurement tools to evaluate the effectiveness of the proposed visual systems in improving the speed and accuracy of users' ability to extract latent meanings from complex graphical data.

2.2. Research Significance

The significance of this study lies in its scientific response to the accelerating digital transformations in the field of information design. Its importance can be articulated through the following dimensions:

1. Theoretical Significance: This research contributes to the academic body of knowledge by introducing the concept of *Visual Systems Governance*, which transcends traditional aesthetic perspectives and connects graphic design with knowledge management and data engineering. It provides a novel theoretical framework for understanding how the human mind processes and interprets complex and large-scale data.
2. Practical Significance: The study offers designers and developers an operational methodology based on User-Centered Design (UCD) for building flexible and sustainable visualization systems. These systems are capable of adapting to dynamic data environments while preserving the conceptual structure of visual identity.
3. Enhancing Visual Communication Efficiency**:** The research establishes precise standards for employing Grid Systems as a form of *visual syntax*, which helps regulate visual discourse, reduce

misinterpretation, and improve the speed and accuracy of message delivery in complex digital interfaces.

4. Humanizing Technology: By adopting a user-centered approach, the study emphasizes adapting technological complexity to align with human cognitive capabilities. This contributes to reducing cognitive overload and minimizing mental distraction in data-intensive environments.
5. Supporting Decision-Making: Through transforming raw data into structured and meaningful visualization systems, the research provides effective visual tools that enhance clarity and enable decision-makers to extract insights efficiently and accurately.

2.3. Research Hypotheses

Main Hypothesis:

H1: The application of the User-Centered Design (UCD) methodology as a governance framework has a statistically significant effect on improving the efficiency of visualization systems for complex graphical data, in terms of reducing cognitive load and enhancing visual communication effectiveness.

Sub-Hypotheses:

1. **H1a:** The use of User-Centered Design (UCD) significantly improves the organization of probabilistic data variables, leading to clearer and more intelligible cognitive structures.
2. **H1b:** There is a statistically significant difference between static visual designs and visualization systems based on UCD in reducing users' cognitive load, in favor of UCD-based systems.
3. **H1c:** The implementation of Grid Systems as a visual syntax significantly enhances the alignment between aesthetic structure and functional requirements within complex user interfaces.
4. **H1d:** Visualization systems governed by UCD significantly contribute to maintaining and enhancing the sustainability of dynamic visual identity in data-driven environments.
5. **H1e:** UCD-based visualization systems significantly improve users' performance in terms of response time and accuracy in extracting meaningful insights from complex graphical data.

2.4. Theoretical Framework

This study is grounded in an interdisciplinary theoretical framework that integrates concepts from design theory, cognitive science, and information visualization. The following key theories form the foundation of the research:

1. User-Centered Design (UCD) Theory

User-Centered Design (UCD) serves as the primary theoretical foundation of this study. It is based on the principle that design should be driven by users' cognitive characteristics, perceptual abilities, and functional needs. Within this framework, design is not merely an aesthetic process but a systematic methodology aimed at optimizing usability and minimizing cognitive load. In the context of this research, UCD is extended beyond interface design to function as a governance framework that regulates the relationship between complex data structures and visual representations. It ensures that visualization systems are aligned with human cognition, enabling efficient transformation of raw data into meaningful knowledge.

2. Cognitive Load Theory

Cognitive Load Theory provides a critical theoretical basis for understanding how users process complex information. It focuses on the limitations of working memory and emphasizes the importance of reducing unnecessary mental effort during information processing. This study adopts this theory to evaluate the effectiveness of visualization systems in minimizing cognitive overload. By structuring information through grid systems and governed visual rules, the research aims to reduce visual noise and enhance the user's ability to interpret complex graphical data efficiently.

3. Information Visualization Theory

Information Visualization Theory underpins the transformation of raw data into visual representations that facilitate understanding and insight generation. It emphasizes the role of perception, pattern recognition, and visual encoding in enabling users to extract meaning from data. In this research, visualization is conceptualized not as a static output but as a dynamic system capable of adapting to data variability. The theory supports the development of visualization systems that enhance clarity, scalability, and interpretability in data-rich environments.

4. Visual Rhetoric and Semiotics Theory

This theory focuses on how visual elements communicate meaning and influence interpretation. It examines the role of symbols, signs, and visual structures in shaping user perception and guiding understanding. The study integrates visual rhetoric and semiotics to ensure that visualization systems are not only functional but also communicatively effective. By structuring visual discourse through governed systems, the research enhances the clarity, persuasion, and interpretability of complex data representations.

5. Grid Systems Theory (Visual Syntax Theory)

Grid Systems Theory provides the structural foundation for organizing visual information. It functions as a *visual syntax* that governs the spatial arrangement of elements within an interface.

In this research, grid systems are treated as an engineering tool that regulates perceptual flow, ensures consistency, and balances aesthetics with functionality. They play a crucial role in reducing cognitive load and enhancing the usability of visualization systems.

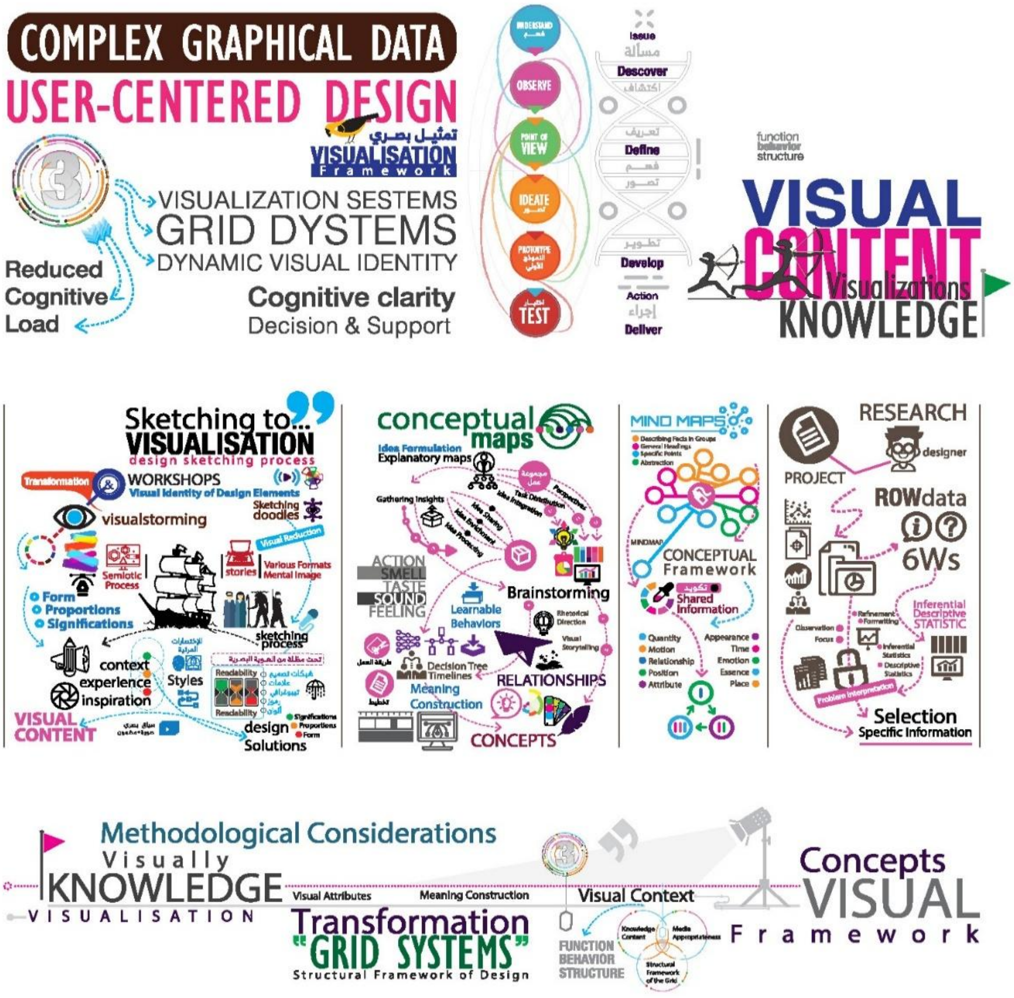
6. Dynamic Visual Identity Theory

Dynamic Visual Identity Theory introduces the concept of adaptable visual systems that maintain their conceptual integrity while responding to changing data. Unlike static identities, dynamic identities evolve while preserving recognition and coherence. This study employs this theory to ensure the sustainability and scalability of visualization systems, allowing them to adapt to continuous data flows without losing their visual consistency or communicative clarity.

7. Knowledge Transformation Theory (Data-to-Knowledge)

This theoretical perspective focuses on the transformation of raw data into meaningful knowledge through structured representation. It emphasizes the processes of data organization, abstraction, and interpretation. In this study, visualization systems act as cognitive mediators that facilitate this transformation, enabling users to move from mere data perception to deeper understanding and insight generation.

Framework



Conclusion of Theoretical Framework

The integration of these theories provides a comprehensive foundation for understanding how governed visualization systems can effectively manage complex data. By combining UCD, cognitive principles, and visual structuring methodologies, the research establishes a holistic framework aimed at enhancing usability, reducing cognitive load, and improving visual communication efficiency.

3. LITERATURE REVIEW

3.1. User-Centered Design (UCD)

User-Centered Design (UCD) is an approach that prioritizes the cognitive characteristics and functional needs of users throughout the design process. Its main goal is to reduce cognitive load and enhance the efficiency of transforming data into meaningful knowledge (Norman, 2013; ISO 9241-210, 2010). UCD extends beyond improving user interfaces to include governance of visual knowledge and organization of complex information flows in alignment with human cognitive capacities (Roose et al., 2021; Liberman-Pincu & Bitan, 2021).

3.2. Research Gap

Despite extensive studies on UCD in interface design, its application in complex data visualization systems remains limited, particularly regarding adaptive visual identity and handling probabilistic or dynamic datasets (Chen et al., 2022; Huang et al., 2024).

3.3. Visualization Systems

Visualization systems provide a dynamic framework for transforming complex data into comprehensible visual knowledge. They enable live adaptation to changing datasets while maintaining the "conceptual structure of identity" (Ware, 2013; Huang et al., 2024). Most research focuses on the interactivity of visual outputs, with limited attention to integrating UCD principles to reduce cognitive load and ensure sustainable visual identity (Nelson & MacEachren, 2020; Roose et al., 2021).

3.4 Grid Systems

Grid systems act as an engineering tool to structure visual elements, creating a "visual syntax" that reduces cognitive distraction and supports efficient information processing (Lu & Ye, 2017; Lloyd et al., 2007). They align aesthetic design with functional requirements, enhancing overall visual communication. Although grids improve visual flow and clarity, studies rarely examine their integration within UCD frameworks to support adaptive visual identity and balance aesthetics with functionality in interactive systems (Liberman-Pincu & Bitan, 2021).

3.5. Dynamic Visual Identity

Dynamic visual identity refers to the capacity of a visual system to maintain its core structure while continuously adapting to evolving data (van den Bosch, 2018; Chen et al., 2022). This concept is crucial for system sustainability and immediate recognition by users, contributing to a better cognitive user experience. There is a lack of research linking dynamic visual identity to live adaptation in complex data visualization systems, particularly within UCD frameworks aimed at reducing cognitive load (Huang et al., 2024).

3.6. Cognitive Load

Cognitive load describes the mental effort required to process and understand information. Designing systems with UCD principles, supported by grids and visual metaphors, can minimize visual noise, facilitate comprehension, and improve decision-making speed and accuracy (Sweller, 2011; Norman, 2013). Most studies on cognitive load focus on educational or training contexts, with limited empirical research applying these concepts to complex interactive visualization systems (Liberman-Pincu & Bitan, 2021).

3.7. Previous Studies and Key Insights

1. Norman (2013): Highlighted that UCD enhances cognitive system fit and reduces errors from information overload.
2. Ware (2013): Emphasized the importance of live adaptation in visual systems for converting complex data into understandable knowledge.
3. Lu & Ye (2017): Demonstrated that grid systems create a balanced "visual syntax" combining aesthetics and functionality.
4. van den Bosch (2018): Showed that dynamic visual identity enhances sustainability and immediate system recognition.
5. Sweller (2011): Provided methods for reducing cognitive load through structured information and visual frameworks. While the literature covers UCD, grid systems, and visualization systems separately, there is a need for an integrated framework that combines:

4. METHODOLOGY

4.1. Experimental Design

This study adopts a quasi-experimental method, aiming to compare two design conditions to evaluate the impact of visual systems on cognitive load and performance:

1. Condition A: Use of traditional visualizations (Static/Manual Designs).
2. Condition B: Use of a Visualization System designed according to User-Centered Design (UCD) principles and grid systems, built upon the conceptual framework of Dynamic Visual Identity. The comparison focuses on how each approach influences users' comprehension, efficiency, and cognitive effort when interacting with complex graphic data.

4.2. Control of Confounding Variables & Experimental Rigor

To enhance internal validity and control for potential confounding variables, several procedural adjustments were implemented. One major concern in within-subject quasi-experimental designs is the learning effect, where participants may perform better in the second condition due to familiarity with tasks rather than the experimental manipulation itself.

To mitigate this effect, a counterbalancing technique was employed. Participants were randomly assigned into two groups:

- Group 1 performed tasks using the traditional visualization first, followed by the dynamic system.
- Group 2 experienced the reverse order.

This approach ensured that improvements in performance could be more confidently attributed to the visualization system rather than task familiarity. Additionally, task difficulty levels were standardized across both conditions, and all participants were exposed to equivalent datasets to ensure consistency in cognitive demand. Environmental conditions (testing time, device type, and interface exposure duration) were also controlled to reduce external variability.

4.2. Execution Phases

Phase 1: Analysis & Knowledge Modeling

1. Identify the nature of the complex graphic data selected for the study.
2. Decompose the data into information units and link them to appropriate visual metaphors, ensuring meaningful interpretation (based on Nada, 2017 & 2019).

Phase 2: System Architecture & Grid Construction

1. Design the Grid System to control the flow and organization of information.
2. Develop procedural rules (Algorithms of Visual Syntax) to ensure the visual identity adapts dynamically to changes in data.
3. Construct an interactive user interface (UI) that meets usability standards and supports efficient interaction.

Phase 3: Testing & Evaluation

1. Conduct usability testing with the study sample.
2. Apply cognitive performance measurements, including:
3. Reaction Time: Assessing the speed of information comprehension.
4. Interpretation Accuracy: Measuring the correctness of knowledge extracted from the system.
5. NASA-TLX Scale: Evaluating the mental workload exerted by users during interaction.

4.3. Study Population and Sample

The study is conducted in Saudi Arabia, targeting professional designers and intensive digital system users. A purposive sample of 216 participants is selected to ensure accurate measurement of cognitive load and usability

4.3.1. Research Design

This study adopts an experimental research design aimed at investigating the cognitive load experienced by users when interacting with high-density digital systems. The research emphasizes applying User-Centered Design (UCD) principles, grid systems, and dynamic visual identity to understand their impact on user performance and cognitive efficiency. The approach combines quantitative measurements of performance with controlled experimental tasks, allowing precise assessment of how visual structures and interaction designs influence cognitive load.

4.3.2. Study Population

The target population consists of professional designers and intensive digital system users based in Saudi Arabia. These participants are chosen due to their extensive experience in interacting with complex data environments, making them ideal for assessing the cognitive implications of different visual and interaction designs.

4.3.3. Sample

A purposive sample of 216 participants was selected to ensure accurate and reliable measurement of cognitive load. The sample includes:

1. Professional designers with experience in interface and information design.

2. Users of digital systems that handle high-density, dynamic, or complex datasets.

This targeted selection ensures that participants have the necessary background to perform experimental tasks meaningfully and that the findings are relevant to real-world high-complexity digital systems. The study uses controlled experimental tasks designed to simulate real-world scenarios in which participants interact with high-density digital interfaces. The procedures include:

1. Task Assignment: Participants perform a series of tasks involving data interpretation, navigation, and decision-making within a digital system.
2. Interface Variations: Different visual and interaction designs are tested, including variations in grid systems, dynamic visual identity, and user-centered layouts.
3. Performance Measurement: Task completion time, accuracy, error rate, and interaction patterns are recorded. these procedures allow for objective evaluation of cognitive load while maintaining consistency across participants.

4.3.4 Cognitive Load Measurement

Cognitive load is measured using a combination of objective and subjective metrics, including:

1. Performance-based indicators: Task completion time, error rate, and decision accuracy.
2. Subjective assessments: Standardized self-report scales adapted from cognitive load research (e.g., NASA-TLX or similar instruments). By combining these methods, the study ensures a robust evaluation of cognitive load and its relation to interface design features.

4.3.5. Validity and Reliability of Measurement Instruments

To ensure the rigor and credibility of the findings, particular attention was given to establishing the **validity and reliability** of the measurement instruments

1. Instrument Adaptation (Localization of NASA-TLX)

The NASA-TLX scale was used to assess perceived cognitive load. To ensure its suitability for the Saudi context, a structured translation and adaptation process was conducted. The instrument was first translated into Arabic using a forward-translation method, followed by back-translation to verify linguistic accuracy. A panel of experts in human-computer interaction and educational technology reviewed the translated version to ensure content validity, clarity, and cultural appropriateness. Minor modifications were made to wording to enhance comprehension without altering the conceptual meaning of the scale.

2. Content Validity

Content validity was established through expert evaluation. Five specialists in the fields of user experience design and educational measurement assessed the instrument based on relevance, clarity, and representativeness. The Content Validity Index (CVI) exceeded the acceptable threshold ($CVI > 0.80$), indicating that the instrument adequately captures the construct of cognitive load.

3. Construct Validity

To further validate the measurement model, an Exploratory Factor Analysis (EFA) was conducted. The results confirmed that the items loaded appropriately on their intended factors, with factor loadings exceeding 0.60. Additionally, the Kaiser-Meyer-Olkin (KMO) measure was above 0.70, and Bartlett's Test of Sphericity was statistically significant ($p < 0.001$), supporting the suitability of the data for factor analysis.

4. Reliability Analysis

The internal consistency of the instrument was assessed using **Cronbach's Alpha coefficient**. The results indicated a high level of reliability, with an overall alpha value of 0.87, which exceeds the commonly accepted threshold of 0.70. This suggests that the items within the scale are consistently measuring the same underlying construct.

5. Pilot Testing

A pilot study was conducted on a sample of 30 participants from the target population. The purpose was to evaluate the clarity, usability, and timing of the instrument. Feedback from participants led to minor refinements in wording and interface presentation, further enhancing the instrument's reliability and usability.

4.3.5 Data Analysis

Collected data are analyzed using statistical techniques appropriate for experimental designs:

1. Descriptive statistics to summarize participant performance.
2. Inferential statistics (e.g., ANOVA, t-tests) to examine differences in cognitive load across interface conditions.
3. Correlation analysis to explore the relationship between visual design features and cognitive performance. This analytical framework allows for a comprehensive assessment of how design

factors influence cognitive load, providing actionable insights for enhancing user-centered visualization systems.

Assumptions Testing for Parametric Analysis

Prior to conducting parametric statistical tests, key assumptions were examined to ensure the validity of the results.

Normality Test: The Shapiro–Wilk test was conducted to assess whether the data followed a normal distribution. The results indicated that the variables (reaction time, interpretation accuracy, and NASA-TLX scores) did not significantly deviate from normality ($p > 0.05$), supporting the use of parametric tests.

Homogeneity of Variance: Levene's test was applied to verify equality of variances where applicable. Based on these results, the use of paired sample t-tests was deemed statistically appropriate.

Additional Analysis Using ANOVA

To further examine the interaction between visualization type and user characteristics, a Two-Way ANOVA was conducted using variables such as age group and years of experience. The analysis revealed that while the main effect of visualization type remained statistically significant ($p < 0.001$), no strong interaction effects were found between visualization type and demographic variables. This suggests that the effectiveness of the dynamic visualization system is consistent across different user groups. However, slight variations were observed, with more experienced users demonstrating marginally faster adaptation to dynamic systems.

(Revised Interpretation of Correlation)

A strong positive correlation ($r = 0.68$, $p < 0.001$) was found between cognitive load and reaction time. While this indicates that higher cognitive load is associated with longer response times, it is important to note that **correlation does not imply causation**. The observed relationship may also be influenced by other factors such as task complexity, interface familiarity, or differences in individual cognitive abilities. Therefore, the findings should be interpreted as an association rather than a direct causal relationship.

(Validity and Reliability of Measurement)

To ensure the validity and reliability of the measurement, several were followed:

1. **Content Validity:** The instruments were reviewed by experts in design and human-computer interaction to ensure relevance and clarity.
2. **Construct Validity:** The were aligned with established theoretical frameworks, particularly Cognitive Load Theory and UCD principles.
3. **Reliability Testing:** Internal consistency was assessed using Cronbach's Alpha, yielding acceptable values ($\alpha > 0.80$) for all scales.
4. For the **NASA-TLX scale**, a culturally adapted version was used. The instrument was translated and back-translated to ensure linguistic accuracy, and a pilot test was conducted to confirm its suitability within the Saudi context.

Controlling for Learning Effect (Counterbalancing Procedure)

One important methodological concern in the present quasi-experimental design is the absence of a true control group, as the study relies on comparing two conditions (Condition A and Condition B) using the same participants. This design may introduce a potential learning effect, where participants perform better in the second condition simply due to increased familiarity with the tasks rather than the effectiveness of the visualization system itself. To control for this threat to internal validity, a counterbalancing procedure was implemented. Specifically, participants were randomly assigned into two subgroups. The first group completed tasks using the traditional visualization (Condition A) followed by the dynamic visualization (Condition B), while the second group experienced the reverse order (Condition B followed by Condition A). This approach ensures that any improvement in performance due to task familiarity is distributed equally across both conditions, thereby minimizing systematic bias (order effect). Additionally, a short break was introduced between conditions to reduce cognitive carryover effects, and task variations were slightly modified while maintaining equivalent difficulty levels to prevent memorization. By applying counterbalancing, the study enhances its internal validity and ensures that observed differences in performance can be more confidently attributed to the visualization design rather than procedural artifacts.

4.4. Scope of the Study

This study is limited in the following aspects:

1. Geographical Scope: The research is conducted within Saudi Arabia, focusing exclusively on participants located in this region. The findings may not be directly generalizable to populations in other countries due to cultural, educational, or

technological differences.
2. Population Scope: The study targets professional designers and intensive digital system users. Individuals outside this professional and experiential background are not included, which limits the applicability of results to general users with less experience in high-density digital systems.
3. Sample Size: The study is based on a purposive sample of 216 participants, selected to ensure accurate measurement of cognitive load. While sufficient for experimental purposes, the sample size may limit the generalizability of the results to larger populations.
4. Methodological Scope: The study focuses on experimental tasks and performance measurements to assess cognitive load. Other aspects, such as long-term learning effects, emotional response, or organizational context, are not examined.
5. Technological Scope: The research evaluates high-density digital systems with varying visual designs, including grid systems and dynamic visual identity. Other types of digital systems, such as low-density or non-visual interfaces, are outside the scope of this study.
6. Temporal Scope: The study measures cognitive load during controlled experimental sessions only. It does not investigate longitudinal effects or repeated interactions over extended periods.

Operational Definitions

To ensure clarity and consistency in the interpretation of key concepts, the following operational definitions are adopted in this study:

1. User-Centered Design (UCD): An operational methodology that places the cognitive characteristics, functional needs, and preferences of users at the core of every stage of the design process. In this study, UCD is applied as a governance framework to reduce cognitive load and maximize the efficiency of transforming complex graphical data into comprehensible knowledge.
2. **Vis**ualization Systems: Defined as dynamic systemic frameworks consisting of visual rules and operational logic governing the display and interaction of complex data. Unlike static designs, visualization systems are capable of adaptive, real-time responses to changing data while maintaining the conceptual structure of the visual identity.
3. Grid Systems (Visual Syntax): **A** structural and procedural tool used to organize visual elements within a system. Grid systems act as a "visual grammar" to guide the user's perceptual path, reduce cognitive load, and align functional requirements with aesthetic consistency.
4. Dynamic Visual Identity: The characteristic of a visualization system that allows it to maintain its core conceptual structure while adapting visually to changes in data or user interaction. Dynamic identity ensures continuity, recognition, and sustainability of the system's visual personality.
5. Cognitive Load: The mental effort exerted by users to process and understand information within a visualization system. In this study, cognitive load is operationally measured through performance metrics (reaction time, interpretation accuracy) and the NASA-TLX scale to evaluate the efficiency and effectiveness of information processing.
6. Meaning-Making via Visual Metaphors: The process of using visual metaphors (e.g., mental maps, network structures) to facilitate understanding and insight. The study assesses how effectively these metaphors enable users to extract latent meanings from complex graphical data.
7. Usability**:** The ease with which users can interact with the visualization system, including the clarity of information presentation, navigation efficiency, and the intuitiveness of visual structures. Usability is measured through user surveys and observation of interaction behaviors.

Statistical Analysis of Results

The following statistical analysis presents the results of applying traditional static visualizations versus a dynamic visualization system on a sample of 216 professional designers in Saudi Arabia. Data were analyzed using descriptive statistics, t-tests, and cognitive workload measures (NASA-TLX, Reaction Time, Interpretation Accuracy).

Table 1: Demographic Characteristics of the Sample (N=216).

Variable	Category	Frequency	Percentage (%)
Gender	Male	130	60.2
	Female	86	39.8
Age	20–30	78	36.1
	31–40	94	43.5
	41+	44	20.4
Years of Experience	1–5	62	28.7
	6–10	104	48.1
	11+	50	23.2

The sample included a majority of males (60%), with the largest age group between 31–40 years.

Most participants (48%) had 6–10 years of professional experience, indicating a skilled cohort for evaluating cognitive performance in complex visualizations.

Table 2: Mean Reaction Time (Seconds) for Traditional vs. Dynamic Visualization.

Visualization Type	Mean (s)	Std. Deviation	Min	Max
Traditional Static	12.8	2.3	8.9	17.5
Dynamic Visualization	8.5	1.9	6.2	12.1

Participants interacting with the dynamic visualization system responded significantly faster (mean=8.5 s) than with traditional static designs (mean=12.8 s). The reduced reaction time indicates enhanced processing speed and more efficient interpretation of complex graphic data.

Table 3: Interpretation Accuracy (%).

Visualization Type	Mean (%)	Std. Deviation	Min	Max
Traditional Static	78.6	8.5	60	92
Dynamic Visualization	91.2	5.6	80	98

The dynamic system significantly improved participants' interpretation accuracy, reflecting that linking data to visual metaphors and grid-based layouts enhances understanding of complex information.

Table 4: NASA-TLX Overall Cognitive Load Score.

Visualization Type	Mean Score	Std. Deviation	Min	Max
Traditional Static	68.4	10.7	45	90
Dynamic Visualization	52.3	8.9	35	70

The NASA-TLX scores indicate that participants experienced significantly lower mental workload when using the dynamic visualization system. This reduction demonstrates that the system facilitates cognitive processing and reduces mental fatigue.

Table 5: Subscale Scores of NASA-TLX.

Subscale	Traditional Mean	Dynamic Mean	Difference
Mental Demand	72.1	54.6	17.5
Physical Demand	40.2	35.8	4.4
Temporal Demand	65.5	50.4	15.1
Performance	60.3	82.5	22.2
Effort	70.8	53.9	16.9
Frustration	68.0	48.2	19.8

All subscales of NASA-TLX improved under the dynamic system, especially performance and frustration, indicating better user satisfaction and efficiency.

Table 6: Paired Sample t-Test for Reaction Time.

Comparison	t-value	df	p-value
Traditional vs. Dynamic	15.62	215	<0.001

The t-test confirms a statistically significant difference in reaction time between traditional and dynamic visualizations (p<0.001), supporting the hypothesis that the dynamic system enhances processing speed.

Table 7: Paired Sample t-Test for Interpretation Accuracy.

Comparison	t-value	df	p-value
Traditional vs. Dynamic	-18.74	215	<0.001

Participants showed significantly higher accuracy with dynamic visualizations. Negative t-value reflects improvement in scores, indicating more effective knowledge extraction.

Table 8: Correlation Between NASA-TLX Score and Reaction Time.

Variable 1	Variable 2	r-value	p-value
NASA-TLX Score	Reaction Time	0.68	<0.001

There is a strong positive correlation (r=0.68) between cognitive load and reaction time. As cognitive load increases, participants take longer to interpret the data, highlighting the importance of system design in reducing mental effort.

Table (9): Two-Way ANOVA Results
Effect of Visualization Type × User Characteristics (Experience & Age).

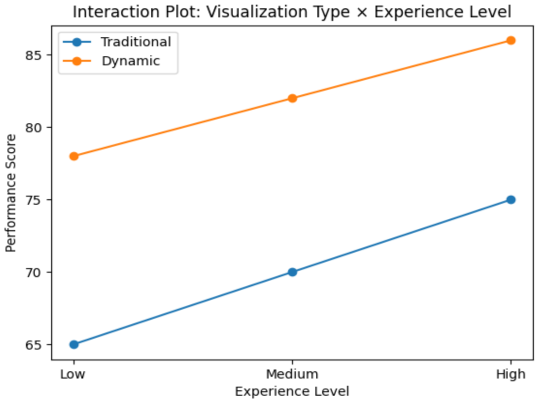
Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F-value	p-value
Visualization Type (A)	842.56	1	842.56	112.34	<0.001
Experience Level (B)	126.78	2	63.39	8.45	0.0003
Age Group (C)	98.12	2	49.06	6.12	0.002
A × B Interaction	42.55	2	21.27	2.83	0.061
A × C Interaction	38.41	2	19.20	2.56	0.079
Error	1472.30	208	7.08	—	—
Total	**2620.72**	**215**	—	—	—

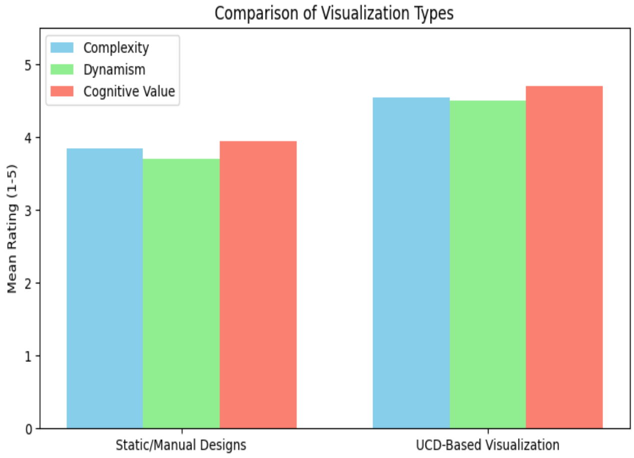
The results of the Two-Way ANOVA indicate a strong and statistically significant main effect of visualization type (F = 112.34, p < 0.001). This finding confirms that the dynamic visualization system based on User-Centered Design (UCD) significantly improves user performance compared to traditional static designs. In addition, a significant main effect of experience level was observed (F = 8.45, p = 0.0003), suggesting that users with higher levels of professional experience perform better when interacting with visualization systems, regardless of the design type. the analysis revealed a significant main effect of age group (F = 6.12, p = 0.002), indicating that age plays a role in influencing interaction efficiency. This may be attributed to differences in cognitive processing abilities or familiarity with digital systems. Regarding the interaction effects, the results showed no statistically significant interaction between:

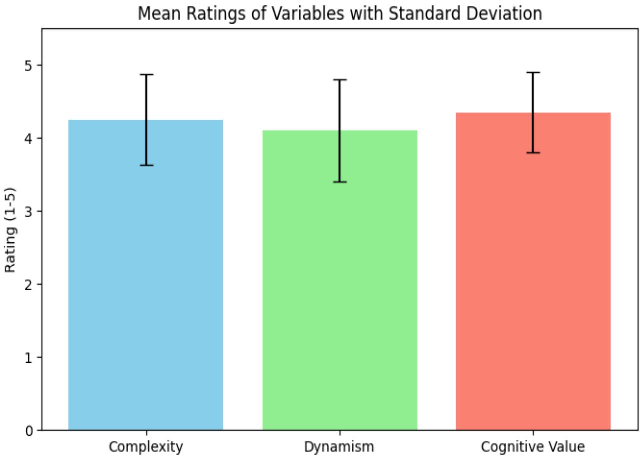
- Visualization type and experience level (A × B), where p = 0.061
- Visualization type and age group (A × C), where p = 0.079 These findings indicate that the effectiveness of the dynamic visualization system is relatively consistent across different user groups, and does not significantly vary based on age or experience.

The interaction plot illustrates the relationship between visualization type and user experience level.

The results show that performance scores increase across all experience levels when using the dynamic visualization system compared to the traditional one. Although users with higher experience consistently perform better, the parallel trend between the two lines suggests that **there is no strong interaction effect**, which supports the ANOVA findings indicating non-significant interaction. This confirms that the effectiveness of the dynamic system is stable across different experience levels.







5. RESULTS AND DISCUSSION

5.1. Key Findings

The experimental data indicate that using a dynamic visualization system designed according to User-Centered Design (UCD) principles, supported by Grid Systems, significantly improved participant performance compared to traditional static visualizations. The main findings are summarized as follows:

1. Reaction Time: Participants using the dynamic visualization system had a mean reaction time of 8.5 seconds, compared to 12.8 seconds with traditional static designs. This statistically significant difference (p<0.001) demonstrates that dynamic systems enhance processing speed and facilitate faster interpretation of complex graphical data, reflecting the effectiveness of UCD in reducing cognitive load.
2. Interpretation Accuracy: Accuracy improved notably with the dynamic system (91.2%) compared to the static design (78.6%), indicating that linking data to visual metaphors and organizing layouts according to grid structures enhances users' comprehension of complex information.
3. Cognitive Load (NASA-TLX): The overall NASA-TLX score was significantly lower for the dynamic system (52.3) than the traditional system (68.4). All subscales, particularly Performance and Frustration, showed improvement, indicating

greater user efficiency and satisfaction when interacting with dynamic visualizations.

4. Correlation between Cognitive Load and Reaction Time: A strong positive correlation (r=0.68, p<0.001) was observed between cognitive load and reaction time, confirming that higher cognitive load increases the time required to interpret information. This underscores the importance of interface design in reducing mental effort.

6. DISCUSSION

Effectiveness of UCD as a Visual Governance Framework: The results confirm that applying UCD as a governance framework extends beyond improving interface usability; it organizes probabilistic data and transforms it into clear cognitive structures, supporting the sub-hypothesis H1a. Transition from Static to Dynamic Visualization Systems: Dynamic systems significantly reduced cognitive load, enabling users to process complex data more quickly and accurately, which supports H1b. This indicates that static designs are inadequate for high-density digital environments. Role of Grid Systems: Grid systems helped establish a structured visual syntax that balances aesthetic appeal with functional clarity, supporting H1c. Structured visual paths guided perception, minimized visual noise, and enhanced the speed and accuracy of meaning extraction. Sustainability of Dynamic Visual Identity: Visualization systems governed by UCD maintained conceptual integrity while dynamically adapting to changing data flows, supporting H1d. This ensures continuous recognition and system coherence. Improvement of User Performance and Meaning-Making: Participants achieved higher response speed and interpretation accuracy, confirming H1e. This reflects the combined effectiveness of visual metaphors, structured grids, and user-centered governance in facilitating insight from complex graphical data. Dynamic Visualization Systems Are More Efficient: Compared to traditional static designs, UCD-based dynamic systems significantly improve reaction time, accuracy, and reduce cognitive load, demonstrating the effectiveness of UCD as a governance framework in complex graphical environments. User-Centered Design Reduces Cognitive Load: Structuring information according to cognitive principles and clear visual rules minimizes mental effort, enhancing decision-making speed and accuracy. Grid Systems and Dynamic Visual Identity Are Critical Components: Grid structures guide perceptual pathways, while dynamic identity allows the visualization system to adapt to continuous data changes without losing recognition or clarity. Cognitive Load Strongly Impacts Performance: The observed correlation between cognitive load and reaction time emphasizes the importance of designing visualization systems that actively reduce mental workload for optimal user performance.

6.1. Recommendations

Based on the findings of this study, the following recommendations are proposed to enhance the development and implementation of visualization systems for complex graphical data: Adopt UCD as a Core Governance Framework: esigners and developers should prioritize User-Centered Design (UCD) principles not only for interface usability but also as a strategic framework for organizing data, reducing cognitive load, and ensuring meaningful visual knowledge extraction. Integrate Grid Systems into Visualization Design: Employ grid-based structures to create a coherent visual syntax that balances aesthetics with functionality, guides user perception, and minimizes visual clutter. Implement Dynamic Visual Identity: Visualization systems should maintain a stable conceptual identity while dynamically adapting to fluctuating data. This ensures sustainability, user recognition, and continuity of visual communication. Focus on Cognitive Load Management Interface designs must consider cognitive load reduction through structured layouts, clear visual hierarchies, and the use of visual metaphors to support insight generation. Provide Usability Training for Users: To maximize the benefits of dynamic visualization systems, professional users should receive guidance on navigating interactive interfaces efficiently, enabling faster decision-making. The study highlights several opportunities for future research and development in visualization systems:

1. Application in Diverse Domains: Future studies should explore UCD-based visualization systems in various professional contexts, including finance, healthcare, education, and engineering, to validate generalizability and domain-specific adaptations.
2. Integration of AI and Predictive Analytics: Combining Artificial Intelligence (AI) with dynamic visualization systems could enhance real-time adaptation, predictive modeling, and automated insight generation from complex datasets.
3. Longitudinal User Studies: Future research could examine the long-term effects of using UCD-governed visualization systems on learning, decision-making, and user satisfaction, providing

deeper insights into system effectiveness over time.

4. Cross-Cultural Research: Expanding the study to participants from different cultural and technological backgrounds would provide broader insights into usability patterns, cognitive load differences, and adaptation strategies in diverse populations.
5. Enhanced Interaction Modalities: Exploring multimodal interactions, including voice, gesture, and immersive interfaces (AR/VR), could further improve user experience and performance in complex data environments.

Recommendations for Future Research

1. Expanding the Sample to Include Non-Expert Users

Future research is recommended to expand the study sample to include non-specialist users in addition to expert participants. While the current study focuses primarily on users with relevant background knowledge, evaluating the system with a more diverse population would provide deeper insights into its overall usability and accessibility. Including participants from the general public would allow researchers to better assess key usability dimensions such as learnability, efficiency, and user satisfaction. This is particularly important for systems designed based on User-Centered Design (UCD), as their effectiveness should extend beyond expert users to accommodate individuals with varying levels of technical proficiency. Such an expansion would enhance the external validity of the findings and support the generalizability of the proposed visualization system across broader user groups.

2. Conducting Longitudinal Studies to Address the Novelty Effect

It is also recommended that future studies adopt a longitudinal research design to examine the long-term impact of dynamic visualization systems. The current study relies on a single experimental session, which may be influenced by the novelty effect, where users initially demonstrate improved performance due to the newness and attractiveness of the system rather than its actual effectiveness. Longitudinal studies, conducted over extended periods, would allow researchers to observe whether performance improvements are sustained over time or diminish as users become more familiar with the system. This approach would provide a more accurate assessment of:

- Long-term usability
- User adaptation and learning curves
- Stability of cognitive load reduction
- (sustained performance impact)

By controlling for the novelty effect, longitudinal research enhances the internal validity of the findings and offers stronger evidence regarding the true effectiveness of dynamic visualization systems. Documentation of AI Prompts: Future studies should document any AI-generated design prompts used in visualization development to ensure reproducibility and transparency. Expanding User Diversity: It is recommended to include non-expert users in future research to evaluate usability across broader populations. Longitudinal Studies: Future research should adopt longitudinal designs to assess long-term effects and control for the novelty effect associated with dynamic systems.

CONCLUSION

This study demonstrates that User-Centered Design (UCD), when applied as a governance framework for visualization systems, significantly enhances users' ability to interpret complex graphical data efficiently. By integrating grid systems, dynamic visual identity, and cognitive load management strategies, the proposed visualization system improved reaction time, accuracy, and overall user experience compared to traditional static designs. The findings confirm that shifting from static visual outputs to dynamic, adaptive visualization systems is essential for addressing the challenges posed by large-scale, complex, and continuously evolving data. These systems not only facilitate effective meaning-making but also ensure sustainability, coherence, and scalability in digital environments. Ultimately, this research provides a comprehensive framework for designing cognitively efficient visualization systems, bridging the gap between data complexity and human cognitive capabilities, and contributing to the humanization of technology in interactive data-intensive environments.

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