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Adaptive Visualization Framework for Real-Time User Engagement in Big Data

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ABSTRACT

With the growth of data and the diversification of users' needs, traditional dashboards cannot support real-time interaction and multiple opinions. In this paper, a double closed-loop framework of "user perception-component scheduling" is proposed, which combines semantic-behavior fusion and Bandit-Mermaid algorithm to dynamically optimize the visualization of big data. An 8-week experiment with 3.8 TB logs and 1250 surveys shows that the delay is reduced by 97 milliseconds, the attention is increased by 28.4%, and the task completion rate is improved by 16.2%. There is a linear positive correlation between scheduling frequency and satisfaction ($r = 0.41$, P < 0.01). Bandit parameter $\varepsilon = 0.06$ optimizes the stability and click rate. The research results show that the framework can be applied to financial monitoring, e-commerce, and smart cities and provides a replicable model for adaptive visualization.

KEYWORDS

Adaptive Visualization, User Demand Perception, Multi-Armed Bandit, Dynamic Interface Optimization, Big Data Interaction

INTRODUCTION

In the big data era, visual dashboards were originally designed to extract and present data insights. However, with the growing demand for data real-time performance and decision-making agility, traditional static interfaces struggle to capture rapidly evolving business dynamics (Bach et al., 2022; Marreiros et al., 2022; Sultana, 2025). Through enterprise interviews and online gray-scale monitoring, we found that decision-makers need to identify key anomalies within 10 seconds, but current dashboards require manual view switching and size adjustment, leading to an average response delay exceeding 200 milliseconds (Dzreke, et al., 2025; Weidner & Broll, 2022). Additionally, user focuses vary significantly by role—operation managers prioritize abnormal indicator trends, while data analysts emphasize detailed data (Olayinka, 2021; Saura et al., 2024). Failure to adapt to such differences forces users to rely on external methods like data export, resulting in data fragmentation and security risks (Kristiana et al., 2025; Nie & Ahmad, 2025).

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Prior research primarily focuses on offline static graphic recommendation or template generation, ignoring semantic clues and real-time behavioral feedback (Subramaniam, 2025). Most methods also lack closed-loop verification, limiting them to single-round optimization. Addressing these gaps, this study proposes a cybernetics-inspired double-loop framework of real-time user demand perception-dynamic interface component scheduling, paired with a bandit-based algorithm to achieve millisecond-level adaptive visual layout. An eight-week rolling experiment with 3.8 TB of interaction logs and 1,250 questionnaires verified the framework's efficacy in reducing latency, improving user satisfaction, and boosting click-through rate (CTR), while confirming its cross-domain applicability. The research aims to construct a replicable adaptive visualization paradigm, clarify the internal mechanism of the double-loop system, and provide empirical support for subsequent intelligent visual analysis.

LITERATURE REVIEW

In recent years, the research of adaptive visualization has developed rapidly along three main lines: user modeling, component rearrangement, and interpretable mechanism. Yáñez et al. (2025) pointed out through systematic review that truly effective adaptation needs to capture tasks, situations, and cognitive loads at the same time. However, most of the existing methods remain at the level of offline rules, and no real-time closed loop is established. In view of the high concurrency e-commerce scenario, Valencia-Arias et al. (2024) summarized the latest trend of the intersection of artificial intelligence and recommendation systems, emphasizing the importance of combining the interaction log with the depth model to maintain the conversion efficiency in the secondary traffic fluctuation. However, this paper does not solve the dynamic scheduling problem at the visual component level. Zhengyang et al. (2025) expanded the application of artificial intelligence and big data in e-commerce, integrated these technologies, formulated a dynamic pricing strategy for e-commerce marketing and product management, and demonstrated the value of adaptive algorithms in optimizing business decisions. However, like the work of Valencia-Arias et al. (2024), their research focuses on the pricing mechanism rather than the dynamic adjustment of the visual interface that directly affects the user's data perception.

In the field of complex system decision-making, Nayak and Pradhan (2025) proposed an event-driven adaptive visualization framework and verified the advantages of real-time visualization analysis in abnormal response. However, their experiments were limited to a single business field, and their universality remains to be tested. Jiang et al. (2024) empirically proved that the interactive dashboard driven by artificial intelligence can significantly reduce users' cognitive load, but it is difficult to explain the mechanism behind the lack of quantification of satisfaction and behavior chain. To improve the accessibility of vulnerable groups, Kristić et al. (2025) summarized the application points of machine learning in accessible adaptive interfaces and put forward the importance of interpretable output for inclusive design. However, the data dimension is still limited to static preferences.

Under the background of recommendation systems and adaptive intervention, the dobby bandit algorithm and reinforcement learning show considerable potential, although their applications in visualization are still rare. Aramayo et al. (2022) used the method of multi-armed robbers to recommend housing advertisements, which achieved an effective balance between exploration and utilization in content distribution. Alkhateeb and Solaiman (2026) constructed a context-aware visual interpretation scheme for social media recommendations, which proved the feasibility of adjusting the interpretation granularity according to the user level but failed to form an iterative closed loop with real-time interaction logs. Brunner (2021) further explored the reinforcement learning model in real-time adaptive intervention recommendation systems through doctoral research, emphasizing the ability of the algorithm to respond to real-time user needs, but focused on intervention recommendation rather than visual component scheduling. In the field of medical care, Švihrová et al. (2025) made a