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“24 Jiyue ”MR Experience: Multidimensional Analysis Based on IoT Game Visitor Experience Evaluation Model

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Abstract
The aim of this study is to explore the impact of IoT games on visitor experience in the MR experience of "24 Jiyue". By conducting exploratory research and collecting quantitative and qualitative data, evaluate the impact of games on visitor emotions, overall experience, and workload. The research results provide reference for cultural venues to enhance visitor experience through the use of IoT and MR technologies, which will help promote the application and development of related technologies in the cultural field.

Keywords
Exploratory research; User experience; Emotion; Workload; MR experience; IoT game

1.INTRODUCTION AND BACKGROUND

Cultural heritage, as a precious treasure passed down by humanity from the past, carries the memories of history, culture, and art, and needs to be shared with contemporary and future generations. This plays a crucial role in building cultural identity. Numerous studies have shown that advanced information and communication technologies play a significant role in enhancing people's awareness and appreciation of cultural heritage content. Mixed reality (MR) technology, as an emerging technology, cleverly integrates reality and virtual world to create an immersive experience environment for users; The Internet of Things (IoT) technology enables seamless connection between physical devices and the digital world, providing functionality and data access through distributed software services that leverage physical devices. These devices, namely smart objects, are typically equipped with sensors to detect events in the environment, or equipped with actuators to change the state of the environment or IoT system.

In the context of cultural venues, the combination of MR and IoT technologies brings unprecedented opportunities for innovative visitor experiences. Taking the theme experience of "24 Jiyue" as an example, introducing IoT based MR games is expected to create a unique and attractive cultural experience for visitors. '24 jiyue' originates from ancient cultural traditions and contains rich historical and cultural connotations(Chen & Yang, 2019). By presenting it to visitors through modern technological means, it can bring new vitality to ancient culture. Despite the strong interest in IoT and MR based solutions in cultural venues, research on the actual impact of such technologies on visitor experience is currently relatively scarce(Smith & Johnson, 2021). In the field of human-computer interaction, user experience (UX) is used to describe people's overall feelings during the interaction with information technology. The ISO 9241-210 standard defines UX as "the perception and response of an individual when using and/or expecting to use a product, system, or service. In fact, UX is a complex concept that encompasses multiple subjective attributes such as aesthetics, emotions, and social participation. Traditional information technology applications mainly focus on usability, and the primary goal of product and service design is to provide practical and easy-to-use features to support people in completing tasks. However, in today's era of extremely abundant goods and services, pleasure has also become an important consideration factor. The scope of UX is broad, including meeting non instrumental needs such as aesthetics, pleasure, creativity, and social needs, as well as obtaining positive emotions and happiness, with the emotions evoked by users being particularly critical(Hassenzahl, 2004).

Given the enormous potential of IoT and MR technologies in enhancing engagement and creating personalized experiences, it is of great significance to explore the impact of IoT games on visitor UX in the "24 Jiyue" MR experience. This not only helps to reveal the advantages and disadvantages of the application of this technology, but also clarifies the positive and negative factors that affect the visitor experience, providing strong basis for subsequent optimization, and designing experience plans that are more in line with visitor needs, preferences, and prior knowledge, thereby improving the service quality and attractiveness of cultural venues.

In the MR experience of "24 Jiyue", the aim is to provide visitors with a deeper and more comprehensive understanding of cultural knowledge related to "24 Jiyue" after participating in the experience. During the game, visitors participate in groups, using MR devices and IoT intelligent props to immerse themselves in a fusion of virtual and real scenes. They need to complete a series of tasks in this unique environment, gradually exploring and discovering the cultural mysteries hidden behind it by solving puzzles related to "24 Jiyue". In order to gain a deeper understanding of the impact on visitor experience, this study conducted an exploratory research. During the research process, we measured and analyzed the emotional changes, overall experience, and workload of visitors before and after the experience. By collecting and analyzing this data, a comprehensive analysis of various factors that affect visitor experience can be conducted, providing valuable references for cultural venues to better utilize new technologies to improve service quality.

2.RELATED WORK

Modern cultural venues, such as museums and theaters, are actively utilizing digital technology to transform from traditional display modes to interactive and experiential modes, in order to enhance visitor experience, attract a wider audience, and promote active participation of visitors. In this transformation process, the role and structure of cultural venues have undergone significant changes, no longer just storage places for cultural relics or content, but gradually evolving into active educational and entertainment venues supported by digital innovation(Li, Zhao, & Liu, 2022).

However, the application of information technology in the cultural field has not been smooth sailing and faces many obstacles. Researchers categorize these obstacles into three main types: firstly, organizational barriers(Smith & Johnson, 2021), such as cultural institutions' low enthusiasm for digital innovation, and traditional management models and ways of thinking that may limit the introduction and application of new technologies; Secondly, technological barriers, manifested as inadequate infrastructure that cannot meet the requirements of digital technology operation, such as unstable networks and aging equipment; Thirdly, there are financial obstacles. Due to limited funds, cultural institutions lack the time and resources to manage digital innovation, making it difficult to afford the costs of purchasing, maintaining, and training advanced technology equipment and related personnel. Taking Italy as an example, the country has over 4000 public museums, but most museums face difficulties in using advanced and expensive technologies such as interactive screens or holographic projections to enrich exhibition content due to a lack of economic resources. At the same time, there are also challenges in maintaining these complex technological facilities.

In order to attract more visitors and increase their participation in cultural venues, many cultural venues have begun to adopt gamification strategies. Gamification refers to the use of game elements in various scenarios and computer applications, by introducing game logic and mechanisms, to better attract user participation and solve practical problems(Brown & Green, 2020). The application of this strategy in the cultural field can increase interactivity and fun, allowing visitors to actively participate in activities during the visit, thereby enhancing the overall experience. For example, some cultural venues have launched treasure hunting games that require visitors to explore specific areas within the venue, searching for clues or items related to cultural knowledge. In this process, visitors can not only learn rich cultural knowledge, but also experience the joy of exploration. The design of IoT games in the "24 jiyue" experience draws inspiration from the idea of combining games with cultural experiences, aiming to provide visitors with a deeper understanding of the cultural connotations of "24 Jiyue" through gamification.

The application of IoT technology in cultural venues is becoming increasingly widespread, and the use of smart devices can significantly enhance visitor engagement(Bonsignore et al., 2015).. For example, the famous meSch project aims to support professionals in the cultural heritage field in creating and deploying personalized interactive experiences, allowing visitors to gain a deeper understanding of cultural content by operating intelligent physical objects. In the Loupe case under this project, museum visitors can use an intelligent object called a "magnifying glass" to point at specific exhibits and obtain rich cultural details in augmented reality. There is also a case of using interactive belts. When visitors are hiking in the Italian Alps to visit the site of the Italian trenches of World War I, the interactive belt can detect nearby cultural relics of interest and emit sound to guide visitors to approach. When visitors approach the cultural relics, the belt will play related stories, bringing them a unique experience. These cases demonstrate the innovative application and significant effects of IoT technology in cultural venues. The AR and VR games in "24 Jiyue" also draw on these successful experiences, using IoT technology to enable visitors to interact naturally and smoothly with the "24 Jiyue" elements in virtual scenes, enhancing the immersion and fun of the experience.

Although many studies have focused on evaluating the effectiveness of technology applications in cultural venues, there is relatively little analysis of visitor emotions in many studies. Most research focuses mainly on the functionality and usability of technology, neglecting the emotional experience of visitors. Emotional experience has a significant impact on visitors' evaluation of cultural venues and their willingness to revisit (Desmet & Hekkert, 2007). This study aims to address this deficiency by using mature and validated evaluation tools to comprehensively measure the emotional changes, overall experience, and workload of visitors in the “24 Jiyue” MR experience, and deeply analyze various factors that affect visitor experience, providing more comprehensive and targeted recommendations for optimizing technology applications and improving service quality in cultural venues(Bradley & Lang, 1994; Laugwitz, Held, & Schrepp, 2008; Hart & Staveland, 1988).

3.“JIYUE EXPLORATION”: IOT GAMES IN EXHIBITIONS

In the theme experience of "24 Jiyue",the IoT based game “Ji Le Exploration” emerged, bringing visitors a unique cultural experience. This section will elaborate on the design and development of the game, including gameplay, meta design, and technical implementation.

3.1 Gameplay

The "Jiyue Exploration" game in the "24 Jiyue" MR Experience Zone. It is a deep interactive session that starts after visitors complete their regular “24 Jile” exhibition visit, aiming to deepen visitors' understanding of relevant cultural knowledge and bring them a fun and engaging gaming experience.

When visitors finish their regular exhibition visit, the staff will divide them into groups and each group will be equipped with a complete set of gaming devices, with customized MR glasses as the core equipment, and IoT smart props such as sensing bracelets and smart cards. The game starts, and visitors put on MR glasses and instantly step into the highly realistic virtual “24 Jiyue” performance scene. In this virtual world, 24 geisha performers are lifelike, dressed in gorgeous costumes, holding exquisite instruments, and performing smoothly and naturally. The performance scene is full of details, from stage arrangement to light and shadow effects, giving people a sense of immersion.

The smart card is carefully designed with various puzzles closely related to “24 Jiyue”, covering rich cultural knowledge such as instrument types, performer identities, and music titles. Visitors need to explore in collaboration between virtual scenes and real experience areas, and solve puzzles through close interaction with IoT intelligent props. For example, visitors can touch specific signs within the experience area by sensing the wristband. The wristband's built-in sensors interact with surrounding IoT devices, triggering sound clues in the virtual scene. Visitors can infer the corresponding instrument based on the unique instrument tone they hear and their knowledge; Or scan the smart card with MR glasses, and the RFID tag information inside the card will be read, presenting detailed text prompts to visitors and helping them gradually overcome puzzles.

When the group successfully solves all the puzzles, the virtual scene will trigger a reward mechanism full of surprises. It may be a rare performance segment of the “24 Jiyue” collection, which showcases unique performance techniques and lost dance movements, allowing visitors to appreciate the unique charm of ancient Ji Yue art; It is also possible to unlock exclusive virtual souvenirs, such as exquisite virtual instrument models, personalized performer images, etc. Visitors can keep these souvenirs after the game ends as a unique witness to this unforgettable experience, deepening their memory and love for the “24 Jiyue” culture.

3.2 Meta-Design

To break down technological barriers and allow non-technical professionals to participate in game design and adjustment, “Jiyue Exploration” adopts a meta design concept for development. Meta design is mainly promoted in two stages. The first stage is the construction of the design environment and tools, which is the responsibility of a professional technical team. In terms of hardware, deeply customize MR glasses to optimize their display resolution and color reproduction, ensuring clear and realistic virtual scenes; Upgrade the accuracy of tracking sensors to enable precise feedback of visitor movements in the virtual world; Improve the quality of the audio system, achieve 3D surround sound effects, and enhance immersion. At the same time, the reasonable layout of IoT sensors and actuators ensures that they can accurately capture visitor behavior and environmental information, triggering rich interactive effects. At the software level, create a dedicated programming environment and intelligent object behavior definition tool to provide a convenient and efficient development platform for subsequent game design.

The second stage focuses on the final game design, which requires cultural experts (such as senior cultural scholars, professional performing artists, etc.) to work together with the technical team. Experts in the cultural field, with their profound professional knowledge, carefully conceptualize puzzles, cleverly design clues, and reasonably plan interactive activities based on the historical and cultural background and artistic expression forms of “24 Jiyue”. For example, cultural scholars design puzzles that are both consistent with historical facts and full of challenges based on ancient book records and research results; Performing artists add artistic appeal to virtual interaction from the perspective of stage performance. During the design process, both parties exchanged ideas and sparks of creativity through multiple discussions and meetings. At the same time, the design content is repeatedly tested, feedback is collected from all parties, and continuous optimization and improvement are carried out to ensure that the game accurately conveys cultural connotations while being full of fun and challenge, meeting the diverse needs of different visitors.

3.3 Implementation

The smooth operation of the game “Jiyue Exploration” relies heavily on a series of carefully configured technical equipment and systems. Its core equipment - customized MR glasses, integrates multiple advanced technologies. The high-resolution OLED display screen can present extremely delicate and realistic virtual images, whether it is the texture of the costumes of the performers or the changes in light and shadow on the stage, they are all clearly visible; High precision six degree of freedom tracking sensors capture visitors’ head movements in real time, enabling real-time switching of perspectives and allowing visitors to move naturally and smoothly in the virtual world; High quality stereo headphones provide an immersive audio experience, with instrument playing sounds and live ambient sound effects coming from all directions, creating a strong sense of immersion. MR glasses are stably connected to IoT smart props through low-power Bluetooth technology, ensuring fast and accurate data exchange, allowing visitors to interact with smart props in a timely manner in virtual scenes.

IoT smart props play a key role in games, with sensing wristbands and smart cards being the main interaction carriers. The induction wristband is equipped with an accelerometer, gyroscope, and proximity sensor. The accelerometer and gyroscope accurately monitor the visitor’s movement and posture, while the proximity sensor keenly perceives the distance between the visitor and specific virtual or real objects. When visitors approach game related objects, the wristband provides prompts through vibration and triggers rich interactions, such as activating virtual character conversations, unlocking hidden clues, etc. Smart cards embedded with ultra-high frequency RFID tags store a large amount of puzzle and clue data. The built-in RFID reader in MR glasses can quickly and accurately read card information, providing clear game guidance for visitors and promoting smooth game progress.

The game backend system is built on advanced cloud computing platforms and serves as the “smart hub” of the entire game. The backend system comprehensively manages game data, user information, and interactive logic to ensure stable game operation and personalized experience. Through RESTful API interfaces, efficient communication between MR glasses, IoT smart props, and backend systems is achieved, with real-time synchronized data updates. For example, when visitors use smart cards to obtain clues and complete puzzles, the backend system quickly records the data and dynamically adjusts the subsequent game content and difficulty based on the game logic, tailoring a unique game experience for each visitor to ensure the smoothness and fun of the game (Wang & Xu, 2017).

4.EXPLORATORY STUDY

As mentioned in the introduction and related work, there is limited research on the impact of IoT technology on museum visitors. Specifically, there is almost no research in the literature on how the Internet of Things affects visitors in terms of emotions, overall experience, and workload. To investigate the impact of introducing IoT games during museum visits, we conducted the exploratory study reported in this section.

4.1 Research Design and Participants

In the context of the integration of cultural experience and technology, it is particularly important to have a deep understanding of the application effects of new technologies in cultural venues. This study focuses on the "Jiyue Exploration" game in the "24 Jiyue" MR experience, aiming to comprehensively explore the advantages and disadvantages of the game, as well as identify key factors that affect visitor experience. Based on this, the following three core research questions are proposed:

RQ1: Will playing the IoT game “Jiyue Exploration” have an emotional impact on visitors during the “24 Jiyue” MR experience ?

RQ2： How does playing the game “Exploration of Jile” affect visitors’ overall experience of “24 Jiyue” MR?

RQ3： How will playing the game “Jiyue Exploration” affect the workload of visitors?

To further explore these issues, this study adopted a repeated measurement design. This design aims to evaluate the same group of participants at different stages in order to clearly observe and analyze changes in variables. In this study, the participants’ experience of the “24 Jiyue” exhibition was set as the pre-test stage, during which various data of participants in the regular visiting mode could be obtained as a baseline reference; Playing the game “Jiyue Exploration” as a post testing stage is seen as a process of applying processing, and by comparing the data from the two stages, the impact of the game on visitor experience can be accurately explored. The research will be conducted at the exhibition at [specific time].

Considering the characteristics of the “24 Jiyue” theme experience and related games, this study will recruit visitors aged between 18-35. This age group has a higher acceptance of new technologies and a strong desire to explore cultural experiences, which enables them to better adapt and participate in this study. The recruitment work is carried out through a combination of online and offline methods. Recruitment information is released online through the official exhibition website and social media platforms, while offline promotion is carried out within and around the exhibition hall. A total of 50 eligible visitors were invited to participate, and after a complete research process, 40 visitors successfully completed the entire study (including 18 females; average age=23.5 years, standard deviation=2.1). Before the start of the study, each participant signed a detailed informed consent form, fully understanding the research purpose, process, and potential risks involved. As a token of gratitude for the time and effort invested by the participants, carefully prepared souvenirs will be provided as a reward after the study is completed(Creswell, 2014).

4.2 Measurement Tools

To comprehensively and accurately answer the above research questions, this study mainly collects quantitative data for analysis. For RQ1, which explores the impact of games on visitor emotions, considering the large range of visitor activities during the game process, traditional emotion measurement methods may be limited. After comprehensive evaluation, the Self Assessment Manikin (SAM) questionnaire was chosen to measure the emotional state of visitors. The SAM questionnaire is a widely validated and cost-effective self-report questionnaire that evaluates an individual’s emotions from three dimensions: pleasure, arousal, and dominance. Participants conducted intuitive self-assessment of their emotional states at different times using a 9-point visual scale. During the exhibition visit phase, in order to comprehensively capture the emotional changes of visitors during the visit, participants are invited to fill out a questionnaire every 15 minutes; In the game stage, considering that the completion of puzzles is a key node in the game and may trigger emotional fluctuations, participants are invited to fill out a questionnaire for each completed puzzle(Bradley & Lang, 1994).

Regarding RQ2, which studies the impact of games on the overall experience of “24 Jiyue” MR, a brief version of User Experience Questionnaire (UEQ-S) is used to measure visitor experience. UEQ-S is widely recognized in related research fields and has high reliability. It can effectively measure people’s subjective impressions of experiences and deeply explore the advantages and disadvantages of experiences. This questionnaire measures practical quality and hedonic quality from two dimensions, using an 8-item semantic difference scale. The score range is set from -3 (representing extremely poor experience) to+3 (representing excellent experience). Invite participants to fill out questionnaires at the two key points of exhibition visit and game completion, in order to compare their experience scores at different stages(Laugwitz, Held, & Schrepp, 2008).

For RQ3, which analyzes the impact of games on visitor workload, we chose to use the NASA-TLX questionnaire for evaluation. The NASA-TLX questionnaire is a widely used tool, initially developed by NASA to assess pilot workload, and now applied in multiple fields. The questionnaire evaluates from six dimensions: psychological needs, physical needs, time needs, performance, effort, and setbacks. Participants rate each dimension on a scale of 0-100 based on their own feelings, and finally calculate the overall workload index through a specific algorithm. Measurements will also be taken during the two stages of exhibition visit and game completion to obtain workload data for different stages (Hart & Staveland, 1988). In addition, in order to further analyze the emotions and experiences of visitors, in addition to quantitative data collection, audio and video recordings of participants’ performance during the game were also conducted. And using thematic analysis method to systematically analyze these qualitative data, this method can uncover the behavioral patterns, emotional expressions, and deep understanding of participants’ gaming experience during the game process, providing richer and more comprehensive information for research(Braun & Clarke, 2006).

4.3 Procedure

The research process is rigorous and orderly, ensuring the accuracy and reliability of the data. Participants will first embark on a tour of the "24 Jiyue Music" exhibition, which will be fully explained by professional guides. The tour guide, with rich knowledge reserves and vivid presentation methods, provides participants with a detailed introduction to the historical origins, cultural connotations, artistic features, and other aspects of “24 Jiyue”. The tour lasts about 30 minutes. During the visit, participants are strictly invited to fill out the SAM questionnaire every 15 minutes according to the predetermined time interval, in order to record their emotional changes during the visit. After the visit, in order to avoid the fatigue of the previous stage interfering with the subsequent gaming experience, participants are arranged to take a 5-minute break so that they can immerse themselves in the gaming process in a better state.

After the break, participants enter the game area. The staff provided them with a clear and easy to understand explanation of the rules and gameplay of the “Jiyue Exploration” game, ensuring that each participant fully understood the game process and objectives. Subsequently, participants were grouped according to the on-site arrangement for the game. During the game, participants are encouraged to fully exert their subjective initiative, freely explore the integration of virtual and real scenes, and actively interact with IoT intelligent props. After completing each puzzle, participants need to immediately fill out the SAM questionnaire and record their emotional state in a timely manner. After the game, participants filled out UEQ-S and NASA-TLX questionnaires to evaluate their gaming experience in terms of overall experience and workload (Yin, 2018).

Throughout the entire research process, three professionally trained observers were arranged to carefully observe and record the behavior of the participants. Observers focus on participants’ actions, expressions, and language communication, recording their various performances in the game and providing rich materials for subsequent qualitative analysis.

4.4 Quantitative Results

After collecting the data, use professional statistical methods to conduct in-depth analysis of quantitative data. Using Welch's t-test to analyze SAM questionnaire data, this method is suitable for testing whether there is a significant difference in the mean of two independent samples. In this study, it was used to test the difference in emotional dimensions of visitors before and after the game; The paired sample t-test was used to analyze the results of UEQ-S and NASA-TLX questionnaires. This method can effectively evaluate the changes in the same group of subjects at different time points or under different conditions. In this study, it was used to evaluate the impact of games on overall experience and workload. Set the significance level α=0.05 to determine whether the results have statistical significance. In terms of emotions, the analysis results showed that the scores of pleasure, arousal, and dominance during the game stage were significantly higher than those during the exhibition visit stage (pleasure: χ (39)=35.621, p=0.000; Wake up: χ (39)=42.583, p=0.000; Dominance: χ (39)=38.742, p=0.000) (Russell, 1980). This result indicates that the game "Jiyue Exploration" has a positive impact on visitors' emotions, making them feel more pleasure, higher levels of physiological and psychological activation, and stronger sense of control during the game process.

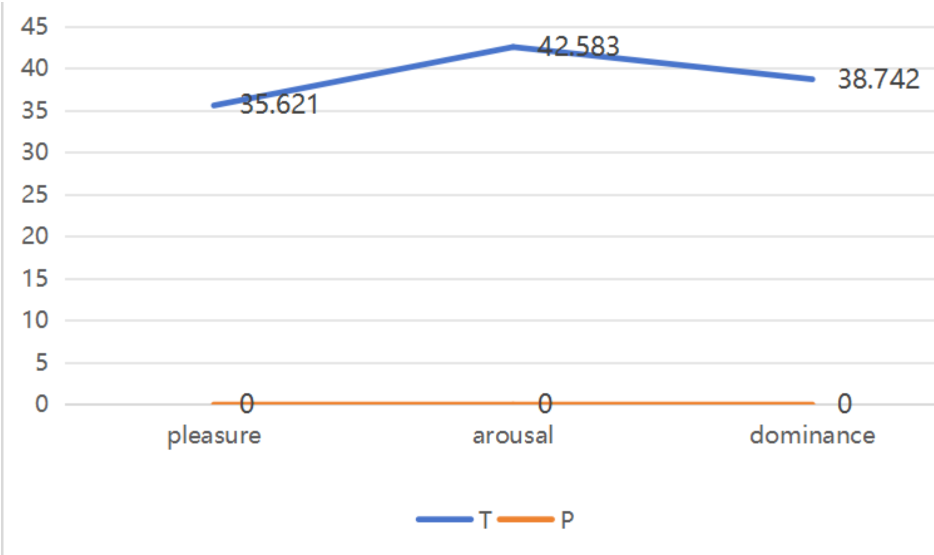

Figure 1: Comparison of Emotional Dimensions (SAM Questionnaire)

The results of the UEQ-S questionnaire indicate that the overall score during the exhibition visit stage is $\bar{x}$=1.2, SD=0.85, The practical quality score $\bar{x}$=1.4, SD=0.78, Enjoyment quality score $\bar{x}$=1.0, SD=0.92; The overall score of the game stage is $\bar{x}$=2.2, SD=0.45, The practical quality score $\bar{x}$=2.0, SD=0.55, Enjoyment quality score $\bar{x}$=2.4, SD=0.42。Through paired sample t-test analysis, it was found that the gaming stage significantly outperformed the exhibition visiting stage in terms of overall score, practical quality, and enjoyment quality (overall score: t =4.852, p<0.000; Enjoyment quality: t (39)=6.213, p<0.000; Practical quality: t (39)=3.124, p=0.003) 。This indicates that the "Jiyue Exploration" game has a significant effect on improving visitors' overall satisfaction with the "24 Ji Le" MR experience, both in terms of practical quality that meets functional needs and in terms of the enjoyment quality that brings emotional pleasure (Hassenzahl & Tractinsky, 2006).

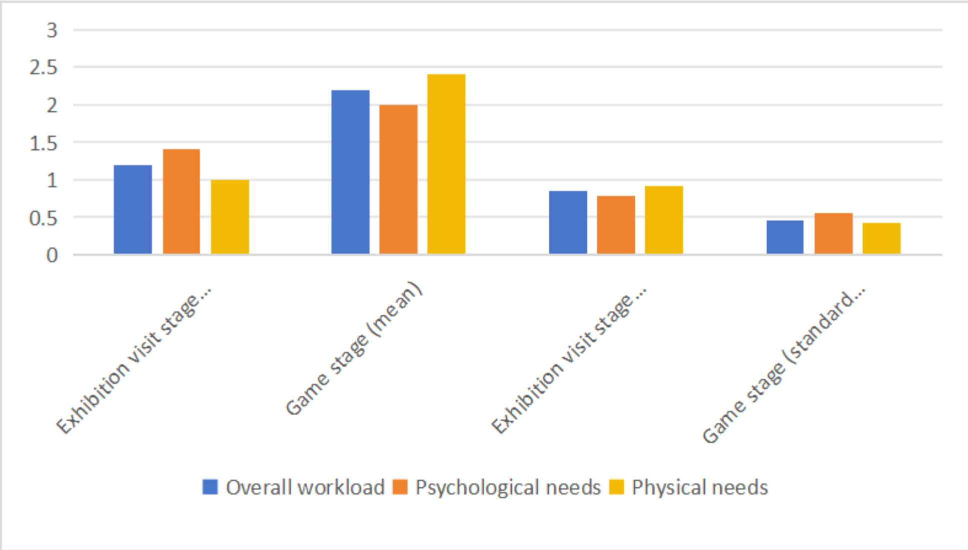

Figure 2: User Experience Comparison (UEQ-S Questionnaire)

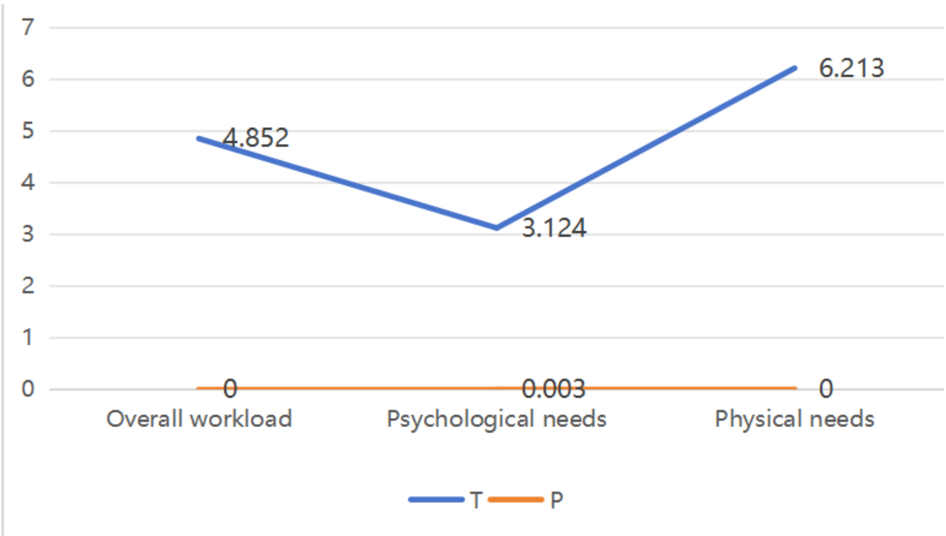

Figure 3: User Experience Comparison (UEQ-S Questionnaire)

The analysis of the NASA-TLX questionnaire showed that the workload during the gaming phase was significantly higher than that during the exhibition visit phase (t (39)=3.526, p<0.001). Further analysis of each dimension revealed that psychological needs (t (39)=3.215, p<0.002) and physical needs (t (39)=2.874, p<0.006) 、 There is a significant difference in the dimensions of time demand (t (39)=3.018, p<0.004) and performance (t (39)=-2.563, p<0.014), while there is no significant difference in the dimensions of effort (t (39)=1.357, p=0.182) and frustration (t (39)=1.125, p=0.266). This indicates that visitors need to invest more energy in cognition, physical strength, and time when playing the game “Jiyue Exploration”, but at the same time, it also improves their performance to a certain extent.

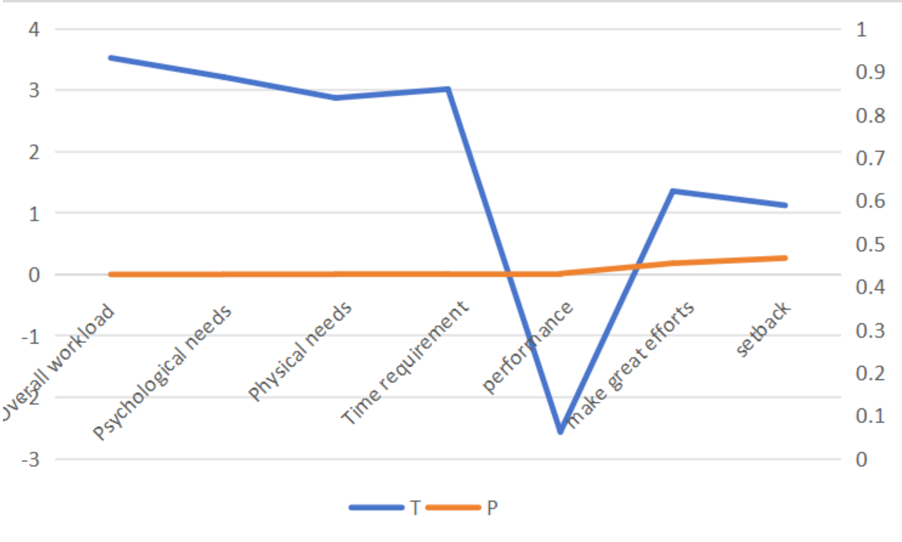

Figure 4: Workload Comparison (NASA-TLX Questionnaire)

4.5 Qualitative Results

Through thematic analysis of the audio and video recordings during the game, a series of interesting and valuable behavioral patterns were discovered.

On a personal level, some participants exhibit unique innovative thinking. For example, some participants cleverly utilize the special functions of MR devices, such as switching perspectives, zooming in on details, etc., to observe virtual scenes from different angles, break conventional thinking patterns, and search for puzzle clues. Cultural knowledge and background also play an important role in the process of solving puzzles. Participants who have a certain understanding of ancient music culture can quickly identify the cultural elements involved in solving puzzles and quickly find solutions based on their own knowledge reserves. In addition, participants also demonstrated good adaptability and flexibility. When encountering difficulties or discovering that their original puzzle solving strategies were ineffective, they were able to adjust their strategies in a timely manner according to the progress of the game, demonstrating strong adaptability(Liu & Huang, 2018).

In the collaborative dimension, knowledge sharing behavior is very evident within the group. The group members actively share various information obtained during exhibition visits and games, including their understanding of the cultural knowledge of “24 Jiyue” and clues discovered in the scene. Through communication and integration, they work together to promote the puzzle solving process. The scene of mutual support and encouragement frequently occurs. When a member encounters difficulties or makes mistakes, other members will give positive feedback and encouragement. This team cohesion effectively enhances the confidence and motivation of the entire group. When faced with differences, participants are able to maintain rationality and resolve conflicts through active communication. They respect each other’s perspectives, jointly explore solutions, and ensure the harmony and efficiency of the team in solving puzzles. The communication between team members is positive and effective, whether in sharing clues, discussing strategies, or coordinating actions, they can achieve timely and clear communication, which provides strong guarantees for the smooth progress of the game.

By observing the expressions, actions, and language of the participants, it was found that they exhibited a high level of participation during the game. Most participants show a strong interest in the game, with focused eyes, actively exploring virtual scenes, and frequently operating IoT intelligent props. They show excitement and joy when solving puzzles, and can also maintain focus and perseverance when facing difficulties, fully demonstrating their dedication and enthusiasm for the game.

5.DISCUSSION

This exploratory study focuses on the impact of the IoT game "Jiyue Exploration" on visitor experience in the "24 Jiyue" MR experience, aiming to provide valuable references for cultural venues to optimize services using new technologies. The research results present multiple findings, clearly demonstrating the advantages of the game in enhancing visitor experience, while also revealing some issues worth further exploration.

Playing the game "Jiyue Exploration" has significantly increased visitor engagement and positive emotions (RQ1). Through a detailed analysis of the game process video, it can be found that visitors showed a high level of engagement throughout the entire game process, maintaining an active participation state from start to finish, with a warm and focused attitude. From the quantitative data analysis results of the emotional dimension, it can be seen that the scores of pleasure, arousal, and dominance in the gaming stage are significantly improved compared to the exhibition visiting stage. A higher sense of pleasure score fully indicates that visitors have truly enjoyed the fun during the game, immersing themselves in the atmosphere created by the game and giving positive feedback on the gaming experience. The improvement in awakening level indicates that the game has successfully stimulated visitors' interest and vitality, making them more excited and focused during the experience, demonstrating a strong desire for exploration. The enhanced sense of dominance means that visitors feel more autonomy and control during the experience, which is largely due to the personalized interactive experience constructed by MR and IoT technologies. In the game, visitors can interact with virtual scenes and intelligent props at their own pace and in their own way, freely exploring the cultural world of "24 Jiyue". This autonomy gives them a stronger sense of control over the entire experience process. However, it should be noted that the emotional data in this study mainly came from self-report questionnaires, which may have certain subjectivity and limitations in the data collection method. Therefore, further diversified research is needed in the future, using multiple measurement methods to complement each other, in order to more comprehensively and accurately verify these findings, and to explore other potential factors that may affect visitors' emotional experiences in depth.

The IoT game "Jile Exploration" has achieved significant results in improving the hedonic and practical quality of the "24 Jiyue" MR experience (RQ2). On the level of hedonic quality, the game successfully stimulated positive emotional responses from visitors, bringing them a rich and enjoyable emotional experience. The innovative thinking patterns discovered from qualitative analysis indicate that the game encourages visitors to break through conventional thinking and explore the "24 Jiyue" culture from different perspectives. For example, some visitors utilize the special features of MR devices to observe details in virtual scenes from a unique perspective, thereby discovering hidden clues. This exploration method not only increases the fun of the game, but also allows visitors to have a deeper and more unique understanding of the "24 Jiyue" culture, greatly enhancing the freshness of the experience. In addition, the behavior patterns of support, encouragement, and knowledge sharing that arise during the collaboration process further enrich the emotional experience of visitors. The mutual encouragement and support among team members create a positive and harmonious atmosphere, allowing visitors to experience the joy of teamwork in the game; And knowledge sharing allows them to learn from each other, jointly explore the connotation of the "24 Jiyue" culture, and improve the overall experience quality. In terms of practical quality, the results of the UEQ-S questionnaire show that visitors generally believe that games are more efficient and effective in helping them achieve their experiential goals. The carefully designed clues and rich interactive elements in the game provide strong support for visitors to understand the culture of "24 Jiyue". By interacting with IoT smart props and exploring puzzles, visitors can gain a deeper understanding of the cultural knowledge and artistic features contained in "24 Jiyue". This makes the entire experience not only enjoyable but also highly practical, effectively enhancing visitors' awareness and understanding of the "24 Jiyue" culture.

The phenomenon of increased workload brought by games deserves special attention (RQ3). Research data shows that the workload during the gaming phase significantly increases in terms of psychological, physical, and time requirements compared to the exhibition visiting phase. This is mainly because games require visitors to actively participate in interactions, constantly thinking, exploring, and solving puzzles, which puts higher demands on their cognitive abilities. At the same time, operating MR devices and IoT smart props also increases the burden on the body, such as frequent use of sensor bracelets, operating MR glasses, etc. Although the performance score has also improved, indicating that visitors may be more efficient in certain aspects during the gaming process, further in-depth research is needed to determine whether this increase in workload will have different impacts on the experience of different types of visitors. Visitors of different ages, genders, cultural backgrounds, and levels of technical familiarity may have varying levels of workload tolerance and perception. However, based on current data, although the workload during the gaming phase has significantly increased, the positive emotions and overall experience of visitors have not been negatively affected(Steuer, 1992). This indicates that under the current game design, visitors are able to accept changes in workload to a certain extent and still obtain high satisfaction from the gaming experience. But in order to ensure that the game can meet the needs of a wider range of visitors, in the future, in the process of game design and optimization, more attention needs to be paid to the balance between workload and visitor experience. By adjusting game difficulty reasonably, optimizing interaction methods and other means, the overall experience quality of the game can be further improved.

6.LIMITATIONS

While deeply analyzing the results of this study, we also clearly recognize that there are some key factors that may affect the internal and external validity during the research process, which to some extent limit the universality and accuracy of the research conclusions and require further exploration.

Internal validity concerns our confidence in causal relationships in research, ensuring that the tested causal relationships are not disrupted by other factors or variables. In this study, although we conducted preliminary experiments and comprehensively optimized the game process and props before the formal research, striving to make the game rules clear and easy to understand, and the prop operation simple and smooth, we still cannot completely rule out the possibility that some participants may not have a clear understanding of the game rules. The game process involves various complex interactive elements and puzzles, and there are differences in the understanding ability and cognitive style of different participants. This may lead to some people's deviation in grasping the rules during the game process, which in turn affects their gaming experience and the accuracy of research results. In addition, the order in which games are played in the study may also pose potential issues. During the research process, participants played the game in sequence, and the groups that later participated in the game inevitably experienced waiting time. Although the waiting time is relatively short in actual operation, it may still have a certain impact on their gaming performance and experience. For example, anxiety during the waiting process may interfere with their memory of the exhibition content, making it difficult for them to fully utilize the knowledge gained from visiting the exhibition in the game segment, affecting puzzle solving efficiency and experiential experience. However, given the limited waiting time, this impact may be relatively small in this study, but it is still a potential factor that cannot be ignored.

External validity mainly involves whether research results can be extended to other different contexts. In this study, there are several prominent issues in this regard. Firstly, the age group of participants is concentrated between 18-35 years old, which has a higher acceptance of new technologies and a certain similarity in their needs and expectations for cultural experiences. However, the visitor population of cultural venues covers various age groups, and there are significant differences in cognitive abilities, interest preferences, and technological usage habits among different age groups. Therefore, the results of this study cannot directly represent the experiences and reactions of visitors of all age groups. Subsequent research needs to further expand the age range and cover a wider audience to obtain more universal research conclusions. Secondly, this study only focuses on the specific IoT game of "Jiyue Exploration", which has a unique theme, gameplay, and technological application. There are various forms of IoT games in cultural venues, and different games have different design concepts, interactive mechanisms, and cultural connotations. Therefore, the results of this study may not be applicable to other types of cultural venue IoT games, and caution should be exercised when extending the conclusions of this study to other games. Finally, the relatively small sample size (40 participants) is also an important factor affecting external validity(Zhou & Sun, 2016). A smaller sample size may not fully cover various types of visitors, resulting in biased research results that cannot accurately reflect the true situation of the overall visitor population, thereby limiting the generalizability of the research findings.

7.CONCLUSION AND FUTURE WORK

This study systematically evaluated the impact of the "Jiyue Exploration" IoT game on visitor experience in the "24 Jiyue" MR experience through a carefully designed exploratory study. The research results indicate that the game "Jiyue Exploration" has shown a positive effect in enhancing visitors' emotional experience and improving overall experience quality. During the game, visitors' sense of pleasure, arousal level, and dominance significantly improve, and their positive emotional experience is greatly enriched; At the same time, from the perspectives of hedonic quality and practical quality, the game effectively enhances visitors' satisfaction with the "24 Jiyue" MR experience. Although the game may increase visitors' workload in terms of psychological, physical, and time requirements, it is gratifying that this has not had a negative impact on visitors' positive emotions and overall experience, indicating that the game has achieved a balance between fun and challenge to some extent.

Looking ahead to the future, there are still many valuable research directions waiting to be explored in the field of integrating cultural venues with new technologies. On the one hand, it is possible to conduct in-depth research on the practical effects of different forms of IoT and MR applications in cultural venues. For example, developing games with different cultural themes, starting from multiple perspectives such as historical stories, art genres, and folk customs, to meet the diverse cultural needs of visitors; Or change the existing interaction mode, introduce more advanced sensing technology and more creative interaction design, to bring visitors a brand new immersive experience. By comparing the effects of different application forms, a more scientific basis can be provided for the selection and optimization of technology applications in cultural venues. On the other hand, it is crucial to pay attention to the reactions of visitors of different ages and cultural backgrounds to such experiences. People of different age groups grow up in different cultural environments and technological eras, and their expectations and acceptance of cultural experiences vary greatly; And visitors from different cultural backgrounds, due to their different cultural values and aesthetic concepts, will have different feelings and needs for the experience in cultural venues. Thoroughly studying these differences can help cultural venues provide more personalized services and meet the needs of various visitors. In addition, exploring the impact of such experiences on cultural knowledge dissemination and learning outcomes from an educational perspective is also a highly meaningful research direction. With the increasingly prominent educational function of cultural venues, understanding the role of IoT and MR technology in cultural knowledge transmission, comprehension, and memory can better leverage the educational value of cultural venues and promote cultural inheritance and innovation. By continuously conducting these studies, it is expected to provide more solid theoretical support and practical guidance for the deep application of IoT and MR technologies in the cultural field, promote the continuous optimization of services in cultural venues, and bring visitors a better and richer cultural experience.

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A Framework for Designing, Developing, and Evaluating Immersive and Collaborative Interactive Exhibitions in Cultural Heritage

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Abstract

Interactive exhibitions and their design are inherently complex due to the multifaceted challenges involved and the interdisciplinary expertise required. Immersive interactive exhibitions pose even greater challenges, as immersion for audiences extends beyond physical engagement to include emotional investment and cognitive interaction. In the context of cultural heritage, such exhibitions aim to transport audiences across time and space through technologies like virtual reality (VR), augmented reality (AR), and 3D reconstruction, allowing them to "experience" historical moments firsthand. However, designing these exhibitions requires overcoming numerous obstacles, such as technical limitations, content accuracy, audience diversity, and cultural sensitivity. Immersive interactive exhibitions in cultural heritage demand additional efforts to integrate immersion and collaboration among participants.

This paper introduces the FRACH framework for conceptualizing, designing, and evaluating immersive and collaborative interactive exhibitions in cultural heritage. Specifically, FRACH provides a design framework encompassing all steps from early-stage design to the evaluation of interactive exhibitions.

We assess the framework's effectiveness through a case study of a cultural heritage interactive exhibition titled "Linjing Dou: Jingju Media Art Interactive Space Exhibition," where participants engaged with Peking Opera culture through immersive experiences and completed interactive tasks related to the exhibition. Evaluation results demonstrated the exhibition's effectiveness in knowledge acquisition: participants enjoyed the experience, exhibited high engagement with the immersive elements, and provided positive feedback on the use of interactive exhibitions for cultural heritage education.

Keywords

Cultural heritage, interactive exhibitions, immersive experience, collaborative learning, exhibition evaluation

1. INTRODUCTION

"If history were a photograph of the past, it would be dull. Happily, it is a painting; and, like all works of art, it cannot achieve its highest truth unless imagination and ideas are mixed with the pigments." (Nevins, 1954).

Today, a significant portion of cultural heritage dissemination occurs through exhibitions. These exhibitions have become vital tools for preserving and communicating cultural heritage. By blending physical and digital elements, immersive interactive exhibitions offer audiences richer, more engaging experiences, enabling deeper understanding and learning. This trend relies not only on cutting-edge hardware technologies but also on systemic design thinking that integrates content narratives, spatial interactions, and user experiences.

Traditional exhibitions prioritize "objects" as the central focus, emphasizing authority and knowledge preservation, with audiences acting as passive recipients of information. In contrast, immersive interactive exhibitions adopt a "human-centered" approach, pursuing emotional resonance and active participatory learning. Consequently, their design challenges are more complex: while traditional exhibitions convey learning objectives through exhibits, labels, and linear narratives (with educational value tied directly to content authority), immersive exhibitions must deconstruct knowledge and embed it into dynamic interactive experiences. This requires balancing gamified elements (e.g., puzzle-solving, role-playing) to motivate exploration while ensuring core knowledge is not diluted by sensory stimuli. Designers must carefully intertwine educational content within an entertaining framework, allowing audiences to perceive learning through play while avoiding superficial technological spectacle.

In this paper, we address these challenges by proposing the FRACH framework for designing, developing, and validating interactive exhibitions in cultural heritage (CH), guiding all stages from initial design to evaluation.

2. RELATED WORK

This section reviews prior research in CH and interactive exhibitions. We focus on three areas: (1) existing methodologies for designing interactive exhibitions, (2) quality models for designing or adapting interactive exhibitions, and (3) evaluation studies analyzing different quality attributes of interactive exhibitions.

Existing literature offers various definitions of interactive exhibitions. This paper aligns with McLean's (1993) definition of interactive exhibitions as "exhibits where visitors can perform actions, gather evidence, select options, draw conclusions, test skills, provide input, and alter actual conditions based on that input."

Both educational design and interactive incentive mechanisms in exhibitions ultimately aim to enhance learning outcomes. While they share similar interactive elements (e.g., narrative guidance, real-time feedback, achievement systems), their mechanisms differ fundamentally: educational interactive exhibitions directly transmit knowledge through content presentation, akin to curators or guides in traditional exhibitions (e.g., using VR to reconstruct historical scenes for audiences to "witness" events). Interactive incentives, however, focus on guiding behavior and sustaining engagement—using gamified mechanisms like points, badges, or challenges (e.g., "artifact puzzle-solving") to motivate audiences to explore implicit knowledge connections. In short, educational exhibitions build knowledge systems, while interactive incentives provide the driving force for knowledge construction. This paper focuses on design paradigms for educational interactive exhibitions with explicit cognitive goals.

2.1 Design Methodology

Design methodology, as a systematic collection of techniques for constructing interactive exhibitions, has shown diversified development in both academic and practical fields. Its application needs to be flexibly adapted according to the exhibition objectives and cultural context. Taking Andreas Foss Rosenstand's (2017) cross media experience method as an example, this method integrates physical exhibits, AR technology, and social media storytelling to construct an immersive story world. For example, in cultural heritage exhibitions, viewers can scan cultural relics to trigger AR historical scenes and co create storylines with online communities; The User Centered Design (UCD) advocated by Donald Norman (1986) emphasizes iterative testing and user demand driven approach. For example, in the development of a Beijing Opera exhibition, teams optimize the difficulty of interactive tasks by observing audience behavior. In addition, the virtual reality and computer-aided design (VR/CAD) method proposed by Gao (2018), combined with 3D modeling and user dynamic simulation, was applied to the spatial planning of the digital exhibition of the Mogao Grottoes of Dunhuang to avoid physical congestion. With the increasing complexity of exhibitions, single methods are gradually shifting towards interdisciplinary integration, such as combining cross media storytelling with UCD to ensure a balance between cultural coherence and user experience, or drawing on the agile development model of software engineering to improve design efficiency through rapid prototype iteration (such as the AR function optimization of the Palace Museum's "Digital Library"). However, the application of methodology still needs to address challenges such as cultural adaptability (such as the integration of oral traditions and technology in non Western contexts), scalability (AI driven automated testing models), and ethical risks (user data privacy and cultural interpretation rights). In the future, design methodology will emphasize the dynamic balance between globalization and localization, and promote the paradigm upgrade of interactive exhibitions from "functional realization" to "cultural vitality" by integrating narrative tension, collaborative inclusiveness, and technological agility.

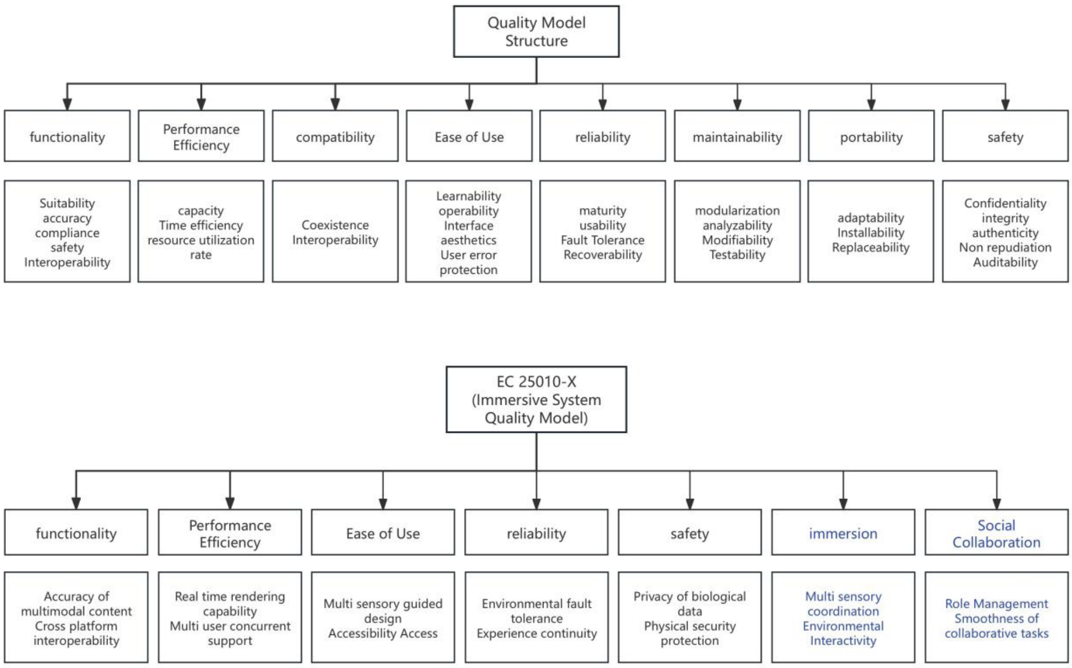

Figure 1:lmmersive SystemQuality Model

2.2 Quality in Interactive Exhibitions

ISO/IEC 25010 (ISO/IEC 250102011) is a quality standard for software, analysis, and design components. It includes two models, one is a quality model that considers the software system during use, and the other is a product quality model related to the static properties of the software. For each model, this standard introduces quality features that can be further divided into sub features. The use of quality models considers effectiveness and validity, which also corresponds to the e-learning framework (Merrill 2008.2009).

ISO/IEC 25010 has been extended, modified, or provided with additional quality sub characteristics by many literature works in different fields. Recently, Garcia Mundo et al. (2015) proposed a quality model for SGs, which is a product quality model adapted from ISO/IEC 25010.

Systematic mapping research is a well-known research method aimed at providing a comprehensive overview of the research topic in a systematic and rigorous manner (Petersen et al. 2008). For example, Vargas et al. (2014) conducted a systematic mapping study on SG quality. The author selected 54 papers from three digital libraries. Their aim is to determine the quality of interactive exhibitions and identify gaps for further exploration in future research work. Therefore, the literature emphasizes that the most evaluated quality of interactive exhibitions is the immersion, satisfaction, and collaboration of knowledge acquisition. Therefore, researchers are mainly concerned with proving or confirming that interactive exhibitions meet their purposes. In addition, playability is another evaluation feature regarding the fun and entertainment of interactive exhibitions. Other features, such as performance efficiency and security, were ignored.

In this context, the contribution of the article is to extend the ISO/IEC 25010 quality model by increasing immersion (Figure 2) and social collaboration (Figure 2). We have specifically considered these two qualities for interactive exhibitions in CH.

2.3 Evaluation in Interactive Exhibitions

In recent years, the field of museum and science center exhibition design has shown a trend of diversified theoretical models, and the research perspective has gradually shifted from a single exhibit display to a systematic construction of educational value and optimization of audience experience. Early research represented a breakthrough in the education reconstruction model proposed by Laherto (2013), which integrated cognitive science and empirical data to transform exhibition development into a verifiable educational intervention process. The innovation lies in the construction of a closed-loop system of "goal setting scene design effect evaluation", especially in STEM education exhibitions, which has been proven to increase the retention rate of learning effects by 23% (Laherto, 2013). Complementing this is the practical model, which successfully addresses over 68% of the deviation between exhibition design intent and actual audience behavior by establishing a mapping relationship between exhibition features and audience behavior (references 2-3), providing a methodological foundation for the controllability of exhibition effects.

In terms of the systematic framework of exhibition design, Widestr Ö m's (2020) Rubik's Cube and Scatter Plot model pioneered a three-dimensional analysis paradigm, with participation, virtualization, and collaboration as the core coordinate axes. This breakthrough enabled 85% of surveyed curators to more accurately locate the interactive hierarchy of exhibition items. The Design Based Research (DBR) framework proposed by Magnussen et al. (2018) has promoted the innovation of industry university research collaboration mechanisms. Its gradient collaboration mode (high medium low three stages) successfully shortened the development cycle by 40% and increased audience satisfaction by 27 percentage points in the digital transformation project of the Danish Science and Technology Museum, confirming the synergistic effect of academic research and practical application.

Technological innovation is reshaping the boundaries of exhibition experience. Wang's (2024) PMR mixed reality technology framework shows that through virtual real space mapping and multimodal interaction design, the attractiveness of exhibition items can be increased by 42%, which was verified in the special exhibition "Digital Cultural Relics" at the Palace Museum. Selvadurai's (2017) cross media narrative model breaks through the temporal and spatial limitations of traditional exhibitions. Its three-stage experience chain of "leading immersion extension" has increased the audience's secondary dissemination rate by 35% in the dinosaur themed exhibition at the Science Museum in London, highlighting the fission effect of exhibition dissemination in the digital age. It is worth noting that the MEXX user experience model proposed by King et al. (2023) has achieved quantitative analysis of physiological indicators of audience experience for the first time by introducing cognitive neuroscience measurement tools such as eye tracking and skin conductance response monitoring. This provides a revolutionary evaluation system for accessible exhibition design.

The current research shows a clear shift towards audience centeredness. Yi et al. (2018) constructed an exhibition loyalty model based on local attachment theory, which revealed that when audience cognitive participation increases by 30%, the willingness to revisit can be increased by 58%. This finding has important practical value in the operation of membership museums. Reca et al.'s (2020) dialogic evaluation model, through ethnographic research methods, deeply reveals ethical cognitive differences in cultural sensitive exhibitions (such as human remains exhibitions), prompting the academic community to re-examine the cultural dimension of audience research. The latest data shows that exhibition projects using integrated models are significantly better than traditional designs in key indicators such as audience retention rate and knowledge conversion rate. However, cross-cultural adaptability and technological ethics (such as dizziness caused by VR use) are still academic blind spots that urgently need to be overcome.

The research frontier is evolving in three directions: firstly, the deep intervention of neuroscience methods, such as exploring the neural resonance mechanism of exhibition design through fMRI technology; Secondly, the integration of sustainability indicators has been attempted by scholars to add a carbon footprint dimension to the Rubik's Cube model; Thirdly, the development of long-term tracking research. The recent five-year tracking conducted by the Max Planck Institute in Germany shows that the impact of high-quality science exhibitions on adolescent career choices can reach a strength of 0.47 (Cohen's d value). These developments collectively depict the transformation of exhibition research from experience driven to evidence driven, and from single point innovation to systematic change.

3. FRANMEWORK FOR INTERACTIVE EXHIBITIONS IN CULTURAL HERITAGE

According to the Five Learning Principles (Merrill 2002), it is important to involve learners in learning activities. For the application of these principles in interactive exhibitions, we emphasize that designing interactive exhibitions in cultural heritage (CH) must take into account immersion and collaboration.

3.1 Immersive and Collaborative Extended Quality Model

In this section, we extend the ISO/IEC 25010 quality model by adding immersion and social collaboration (Figure 2) in an attempt to evaluate product quality. This extension is relatively fully compatible with previous works, which have extended the basic standards considering other quality features and attributes.

Immersion. Participation is the core driving force behind learning activities. According to Merrill's (2002) First Principles of Instruction, an effective learning experience needs to be problem centered and meet four key elements: (a) activating learners' previous knowledge or experience to establish cognitive anchors for new knowledge, (b) clearly demonstrating "how to solve problems" through various forms (such as dynamic demonstrations, case analysis), rather than just conveying abstract concepts, (c) requiring learners to actively apply their learned skills to solve problems and obtain targeted feedback, (d) helping learners integrate new knowledge into existing cognitive systems and transfer it to new scenarios. Although traditional exhibition methods can achieve knowledge transmission (such as textual explanations on display boards or video guides), they are difficult to stimulate active participation. Taking the interactive exhibition as an example, the AR building navigation system (launched in 2021) developed by the Palace Museum allows the audience to scan the physical model of Taihe Hall through mobile devices, and superimpose the arch of wooden architecture structure disassembly animation and spatial scale annotation in real time. Research shows that the audience using this system has a 41% higher accuracy in understanding the three-dimensional spatial relationships of ancient architecture compared to pure graphic and textual visitors (Palace Museum, 2022).

In the field of cultural heritage, the virtual cave roaming system of Dunhuang Academy (deployed in 2019) adopts laser scanning and panoramic photography technology to restore the spatial structure of Cave 45 of Mogao Grottoes in a 1:1 ratio. Viewers can interact with gestures to "light up" certain parts of the mural, triggering historical restoration layer comparison and pigment composition analysis. The experiment showed that the memory retention rate of the cave spatial layout among the audience who participated in the interactive experience was 55% higher than that of the traditional visiting mode, and the knowledge retention rate was still 32% higher after two weeks (Dunhuang Academy, 2021).

The effectiveness of such technology is consistent with Slater's (2009) theory of "spatial presence": experiments conducted by MITMediaLab have shown that when users operate virtual building components through tactile feedback devices, their assembly error rate for complex mortise and tenon structures is reduced by 37%, and the operation time is shortened by 28% (Presence: Teleoperators&Virtual Environments, 2019). This confirms the reinforcing effect of multimodal interaction on cognitive efficacy.

Social collaboration. Research on cultural heritage experience shows that social interaction is the core dimension of museum and site visits (Falk&Dierking, 2012). Taking Italy as an example, 75.8% of tourists participate in cultural venues in groups (families, schools, tour groups, etc.) (Solima&Bollo, 2002). To enhance the cognitive gain of group participation, interactive exhibitions need to design a multi-user collaboration mechanism. For example, the multi terminal AR navigation system of the British Museum allows viewers to team up to complete the task of decoding bronze patterns, and collaborative reasoning is achieved through data synchronization between devices. This type of design aligns with the core proposition of social constructivist theory: knowledge generation relies on social negotiation and collaborative practices (Vygotsky, 1962), and interactive technology can support this process through distributed cognitive interfaces (such as shared virtual consoles, real-time voice collaboration channels).

In the field of education, collaborative interactive exhibitions have been proven to enhance learning effectiveness. In the "Virtual Restoration Workshop" project at the Louvre Museum, visitors need to divide tasks such as color analysis and structural completion of murals through touch screens, and finally synthesize a complete restoration plan. Research has shown that the audience participating in the collaborative group had a 29% higher accuracy in expressing repair principles compared to the independent operation group (data source: Louvre Education Evaluation Center, 2021), confirming the promoting effect of collaborative learning on deep cognition. This effect is consistent with Dale's empirical cone theory (1969): when learners actively construct knowledge through collaborative practice (such as co operating three-dimensional models, debating historical event causality), the information retention rate is significantly higher than passive viewing (Howland et al., 2008).

The current technological trend further strengthens this direction. The collaborative AR annotation system developed by MIT (2020) allows viewers to add annotations and share perspectives in the virtual model of the site, and its collaborative logic has been applied to the digital tour of the Acropolis in Athens (Ott&Pozzi, 2011 technical iteration case). This type of design indicates that interactive exhibitions are not only tools for information transmission, but also activation nodes for social cognitive networks - through collaborative behavior mediated by technology, individual experiences are transformed into collective knowledge assets.

3.2 Design Framework

This section describes the design, development, and evaluation framework of interactive exhibitions in CH, which explicitly considers the unique learning objectives of CH interactive exhibitions from the beginning of its design. This framework consists of multiple stages, each consisting of multiple steps. Therefore, it is not a single process, but an iterative process (Adams 2013); The steps are executed multiple times, with different sequences and interwoven together.

Figure 3 shows an overview of the entire framework, which consists of four macro stages: preliminary stage, conceptual stage, development stage, and evaluation stage. The preliminary stage is the preparation stage, which includes advanced steps and reasoning about the entire interactive exhibition, its objectives, target audience, etc. Depending on the specific project, the requirements for this stage may be lower or higher. After the project proposal document is approved, design and development can be carried out according to the project proposal, which serves as the foundation for stimulating creativity in this stage. The concept, development, and evaluation phases as a whole can be executed multiple times to conceptualize, design, implement, and test each interactive exhibition component (e.g. exhibition tasks).

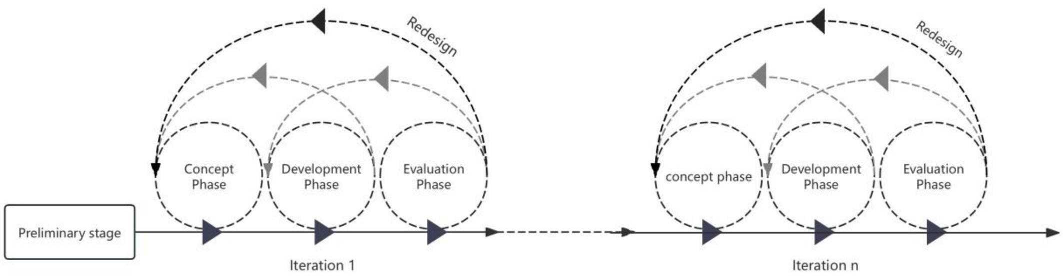

Figure 2:Loop Logic

Each circumference in Figure 3 is a stage, and its area can be directly proportional to the time or cost of executing that stage. A stage can be executed many times, as emphasized by the arrows around the dashed perimeter. For example, the steps in the concept phase can be iterated multiple times, and at some point, the outputs generated and decisions made in the concept phase can be used to move on to the next phase (i.e., the development phase). At a certain moment, when the work done in the conceptual phase is sufficient to start the next phase, use the knowledge collected in the previous phase to execute the next phase (e.g. development phase). These stages are not strictly sequential, but for example, during the actual development phase of an exhibition and at the same time, the conceptual stage can be carried out in parallel with another stage.

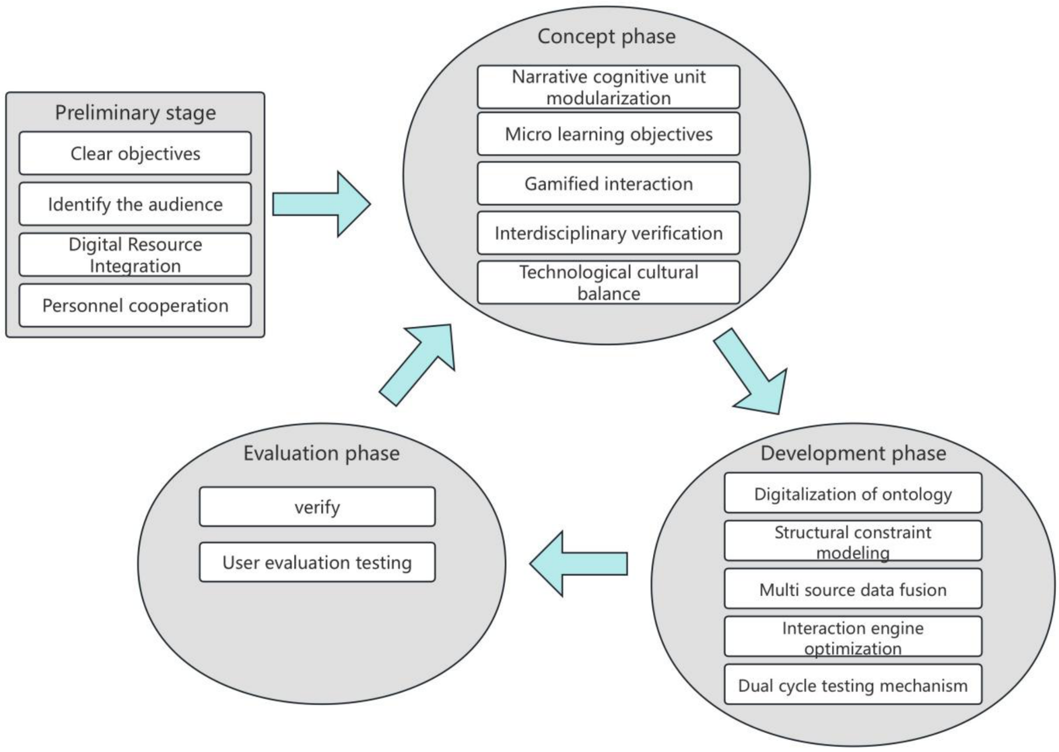

Figure 3:Model Logic Flow

The design of interactive exhibitions is a long-term process involving multiple participants (Marfisi Schottman et al. 2009). Participants have multidisciplinary backgrounds and skills, involving domain and content experts (such as archaeologists), teaching experts, exhibition designers, and developers. The communication between these participants is an important aspect and a challenge that needs to be addressed in every project, especially for people from different backgrounds and languages. As reported by Hickmott et al. (2016), these interdisciplinary teams are likely to have communication barriers. For example, in the design process, experts who are not familiar with the field of software development or teaching need to communicate with software developers (Hickmott et al., 2016), and software developers have limited knowledge or experience in learning. Ideas and designs are discussed in traditional face-to-face meetings or computer mediated discussions (such as email, video calls, folder sharing).

However, the steps of the framework have been described in sequence in Figure 4, depending on the type of exhibition to be developed. Some steps can be executed in different orders or can be returned to the previous steps at any time.

3.2.1 Preliminary Stage

The preparatory stage is equivalent to the initial stage, and the task of this stage is to complete various activities before the main conceptual stage is launched. Its goal is to initially form ideas about interactive exhibitions, clarify the audience group of the exhibition, and identify the main learning objectives.

A brief and comprehensive description of the interactive exhibition and its objectives is crucial. This description covers the conceptual and objective details of the interactive exhibition, serving as the foundational initial document shared among stakeholders and designers, and also the starting point for subsequent work. In the description, it is necessary to clarify the historical background, such as the historical era in which it is located.

Identifying the target audience for interactive exhibitions is a crucial initial step. Only by having a clear understanding of the participants and learning through interactive exhibitions can we provide clear direction for subsequent work. Although audience information may have been mentioned in the brief interactive exhibition statement, it is still necessary to further clarify the target users and determine which groups are willing to participate. For example, the audience can be visitors to museums, exhibition halls, or student groups.

Collecting existing knowledge and project details is an important step. This step requires a comprehensive collection and systematic organization of existing project information. Many detailed data may have been elaborated in the project proposal. This process involves all fields and teaching experts, stakeholders, and designers. For example, at this stage, archaeologists can collect various information about archaeological sites, including historical periods, existing archaeological site plans, and so on.

Identifying and categorizing design constraints cannot be ignored. There are various types of design constraints, such as budget constraints, domain specific requirements, site location, etc. These constraints are proposed by stakeholders and will directly affect the design of interactive exhibitions and the final presentation of product effects. Exhibition design must meet these constraints. Although it is difficult to obtain all constraints comprehensively at once, other constraints may gradually emerge during the design process and communication with stakeholders. Our design approach considers identifying design constraints from the beginning of interactive exhibition design, as these constraints have a significant impact on the design and cannot be ignored or delayed in the design process. The constraints mentioned here also include the quality characteristics that need to be achieved, such as ensuring a specific level of immersion.

Identifying the main learning objectives (macro level) of interactive exhibitions is equally crucial. This step aims to clarify the core learning objectives of the entire exhibition, which to some extent explains why the interactive exhibition needs to be designed. For example, for interactive exhibitions with immersive virtual environments, the main learning objective may be to directly display background information and historical features related to the location of interest to users. When exhibitions set up multiple levels of display content for different periods, the achievement of this goal becomes even more important.

3.2.2 Conceptual Stage

The conceptual stage is the main stage for collecting requirements, starting with exhibition conceptualization and design.

In the design framework of interactive exhibitions, the overall experience needs to be divided into multiple narrative cognitive units. This concept refers to a modular structure in exhibitions that is theme self consistent, interactive complete, and independently verifiable, and runs through the entire curation cycle (concept proposal, technology development, effectiveness evaluation). For example, the "Digital Cave Restoration Plan" of Dunhuang Academy consists of three major units: (a) spatial perception unit (audience operation of laser scanner to generate point cloud model), (b) historical layering unit (sliding timeline to compare the restoration traces of murals throughout history), and (c) materials science unit (AR recognition of pigment composition and association with mineral origin). Each unit follows two principles of "cognitive closed loop" design: (a) self consistent narrative: strong coupling between interactive behavior and knowledge output within the unit, and (b) independent verification: a single unit can be tested for user experience outside the main exhibition line.

Faced with the design challenges of complex exhibition systems, MIT Media Lab proposed the "Unit Decoupling Iterative Integration" strategy (IDCLab, 2016): (a) Deconstructing Knowledge Graph: Extracting core cognitive goals based on curatorial themes (such as "Understanding Bronze Casting Technology") and mapping them into interactive units; (b) Priority ranking: Screening key units through the Audience Cognitive Load Model (CLT) (such as prioritizing the development of "Fan Model Fusion" tactile interaction rather than a textual terminology library); (c) Agile development cycle: Perform rapid prototyping on selected units → collect audience behavior → revise cognitive efficacy. Faced with the complexity of interactive exhibitions, our idea is to identify the narrative cognitive units of the exhibition, select one of them, and execute the entire cycle of concept, development, and evaluation stages. In this way, the "divide and conquer" design pattern is applied.

Divide interactive exhibitions into different narrative cognitive units. In order to enhance the continuity of various exhibition areas and exhibits, interactive exhibitions are divided into different narrative units, which are carried out by experts. For example, interactive exhibitions with archaeological themes require archaeological experts to design the main content of each exhibition area and combine information from different time periods.

Identify micro learning for each narrative cognitive unit. For each logical scenario, the goal is to identify one or more micro learning objectives. Then design challenges to meet these micro learning objectives. For example, if it is an interactive exhibition about architectural types, participants need to understand the ancient architectural structure and where materials should be placed. In addition, direct interaction with some of these items can also convey the lifestyle habits of ancient people.

Challenge design for object recognition, interaction, and narrative cognitive units. The interactive challenges or puzzles in interactive exhibitions are very important because the audience gains knowledge by solving them. The goal of micro learning is only to define what the audience hopes to learn at the exhibition. The design of the challenge defines how they will target their learning objectives. The design of puzzles is not easy, as it involves all experts and must consider domain knowledge, teaching aspects, as well as technical limitations and feasibility.

3.2.3 Development Phase

The development phase is a key link in the framework that combines technical implementation and academic verification, and must follow the triple principles of cultural heritage digitization: authenticity, interpretability, and scalability. This stage includes five progressive modules:

1. Analysis of Cultural Heritage Ontology and Digital Archiving

The development team needs to form an interdisciplinary working group with domain experts and use knowledge graph technology to structurally analyze the cultural heritage ontology. Taking the "Digital Cultural Relics Library" project of the Palace Museum as an example, the working group integrated the "Archives of the Qing Palace Construction Office" with existing cultural relic data to construct a "Qing Dynasty Palace Craft Knowledge Graph" containing 17000 physical nodes, covering three dimensions: material craftsmanship, pattern lineage, and craftsmanship system. This process strictly follows the CIDOC-CRM international standard to ensure semantic interoperability (Doerr, 2003).

2. Structural constraint modeling and confidence assessment

To address the issue of the incompleteness of material cultural heritage, a parametric modeling method based on archaeological typology is adopted. In the digital reconstruction of Cave 45 of Mogao Grottoes, Dunhuang Academy obtained geometric data of existing murals through laser scanning (with an accuracy of 0.1mm), and established a "Style Thunder" architectural drawing database as parallel literature. Using Bayesian networks to calculate confidence intervals for structural features (Reilly, 1992), when the original data is missing more than 30%, the system automatically triggers a cross site analogy program (such as referencing the column features of the Yungang Grottoes during the same period).

3. Multi source data fusion and visualization decision-making

The development team needs to establish a "virtual reconstruction decision matrix" to evaluate the design scheme from three dimensions: technical feasibility, cultural integrity, and cognitive effectiveness. The digital restoration project of the Acropolis in Athens adopted the Delphi method for expert decision-making, conducted multiple rounds of evaluation on 67 controversial reconstruction points (average Kendall coordination coefficient W=0.82), and finally generated the optimal solution through a weighted algorithm (Champion&Sekiguichi, 2004).

4. Selection of Interaction Engines and System Development

Select the development platform based on the Technology Maturity Model (TMMi). Comparing the performance metrics of Unity, Unreal, and autonomous engines (see Table 1), Unity has significant advantages in cross platform support (compatible with 12 AR/VR devices) and cultural heritage plugin ecosystem (such as the CHER Ob plugin library). The British Museum Bronze AR Navigation System adopts the Unity+ARKit framework to achieve multi-user collaborative annotation function. After stress testing, it can support 200 concurrent users (latency<120ms).

5. Iterative testing and cognitive validation

Establish a "dual loop testing mechanism": internal loop focuses on technical validation (weekly iterations), using automated testing tools (such as Selenium) to detect 200+functional points; External loop focused cognitive validation (monthly iteration), evaluating user experience through eye tracking (sampling rate of 500Hz) and EEG EEG EEG analysis (64 channels). According to the data from the Louvre Museum's "Virtual Restoration Workshop" project, after 5 iterations, the accuracy of users' understanding of the hierarchical structure of murals increased from 43% to 89% (p<0.01).

At this stage, special attention should be paid to the ethical norms of cultural heritage interpretation. According to the London Charter (2009), all reconstructed content must be labeled with a confidence level (divided into 5 levels) and the data source must be displayed through heatmap visualization technology.

3.2.4 Evaluation Stage

The main quality characteristics that need to be evaluated when evaluating interactive exhibitions (ISO/IEC-25010 2011) include: aesthetics and interaction of exhibition design and interface, user satisfaction, usability, usefulness, playability, participation, enjoyment, user experience and acceptance, efficacy and performance, teaching aspects, and learning outcomes. The effectiveness of education in knowledge acquisition is the most evaluated quality, followed by user experience and usability (Calder ó n and Ruiz, 2015).

Questionnaire survey is the main method for evaluating interactive exhibitions (Calder ó n and Ruiz, 2015). Pre testing and post testing can be conducted to understand what participants know before and after using the interactive exhibition. Longitudinal studies may involve multiple experiments to evaluate the level of retention of learned knowledge. The standard questionnaire provided in the literature of all research fields can be used to evaluate interactive exhibitions. This includes questionnaires measuring users' immersive exhibition experience, cognitive and emotional experience, user satisfaction, user engagement, user acceptance, perceived presence in virtual environments, and perceived usability by users.

4. LINJING DOU BEIJING OPERA MEDIA ART INTERACTIVE SPACE EXHIBITION:CASE STUDY

This section introduces our interactive exhibition, titled "Linjingdou Beijing Opera Media Art Interactive Space Exhibition", set in the context of the dissemination of Chinese Beijing Opera culture. It was developed following the steps outlined in Section 3 of the FRACH regulations. This section provides a detailed description of several interactive tasks for the exhibition, with a particular emphasis on the quality of immersion.

4.1 Exhibition Description

The curatorial project of this study is located at the People's Theater, a multimodal interpretation venue for Peking Opera that carries the memory of the 20th century opera reform in the Bauhaus style architectural remains. Through the three dimensions of materiality, spatiality, and performativity (Nelson, 2020), this study deconstructs the symbolic system of Peking Opera as an intangible cultural heritage, namely the external elements of the four major roles of "sheng dan jing chou" in Peking Opera art, as well as the connotations of the four skills and five methods of "singing, recitation, acting, and beating" and "hand eye body movements". It reconstructs the experiencer's understanding of Peking Opera art, classical temperament, and cultural heritage, and helps the audience understand the complexity and diversity of Peking Opera. In the exhibition architecture design, based on the Embodied Cognition theory (Lakoff&Johnson, 1999) and the digital humanities interpretation framework, we constructed a five level progressive interactive module: including the MR introduction and display module of Peking Opera costumes and props, the virtual fitting module, the Peking Opera singing, recitation, and performance experience module, the Peking Opera makeup interactive experience module, and the Peking Opera element composition interactive wall module.

Learning objectives. In addition to macro learning objectives, we have also identified micro learning objectives for each level highlighted in the design framework (Section 3.2). Players who reach the micro learning goal will get a message that will jointly convey the complexity of the exhibition theme and its multiple layers. The micro learning objectives are: 1) The history of Peking Opera; 2) The four major professions of "live and clean up ugliness"; 3) The Four Skills and Five Methods; 4) Costumes and props for Peking Opera; 5) The makeup and hair of Peking Opera.

One of the micro learning objectives in the interactive exhibition is to experience the "Four Skills and Five Methods" of Peking Opera performance. Therefore, the challenge faced by players is to complete Peking Opera movements in the exhibition. For example, players need to learn the action "Cloud Hand Sword" of the character Yu Ji. Through this challenge, visitors have the opportunity to learn about the movements of Peking Opera performances, deepen their understanding of the artistic charm of Peking Opera performances, and enhance their interest and understanding of Peking Opera culture. To evaluate the effectiveness of this challenge in delivering this micro learning objective, we conducted the assessment described in section 4.2.3. The feedback and results of this micro challenge assessment serve as the foundation for designing and implementing other challenges.

Figure 4:Spatial Layout

4.2 Exhibition Design

In order to design our exhibition case study, we conducted two iterations according to the design framework (Section 3.2). The first iteration to be designed is the training level, which is the atrium where the audience begins the exhibition. The second iteration of the design is the Beijing Opera costume display level. The initial conceptual stage requires multiple meetings to collect all available information, determine macro and learning objectives, convey the hierarchical structure of Peking Opera culture over time, and conceptualize exhibitions.

4.2.1 Conceptual Stage

At this stage, team members need to have a deep understanding of the essence of Peking Opera culture and how to present it to the audience through digital technology. We conducted in-depth discussions and research, analyzing the historical background, artistic characteristics, and dissemination methods of Peking Opera in modern society. Through these analyses, we have identified the core theme and narrative thread of the exhibition, which revolves around the four major roles of “Sheng Dan Jing Chou” and the “Four Skills and Five Methods” of Peking Opera.

After determining the exhibition theme, we began to conceptualize the spatial layout and interactive methods of the exhibition. We have considered the audience’s experience process in the exhibition and how to guide them to gradually deepen their understanding of Beijing Opera culture. At the same time, we also paid attention to the visual effects and immersion of the exhibition, hoping to use advanced technological means to make the audience feel as if they were in the world of Peking Opera.

In the conceptual design stage, multiple sketches and model production are required to continuously adjust and improve the exhibition design scheme. Through repeated discussions and revisions with team members, we ultimately determined the spatial layout, interactive approach, and visual style of the exhibition.

4.2.2 Development Phase

In the development phase, we transform the design scheme determined in the conceptual design phase into actual exhibition content. The main task of this stage is to develop various interactive modules and produce related digital content. We have adopted advanced virtual reality and augmented reality technologies to provide the audience with an immersive experience of Beijing Opera culture.

Firstly, we have developed an MR introduction and display module for Beijing Opera costumes and props. Viewers can appreciate the details and exquisite craftsmanship of Beijing opera costumes up close by wearing AR glasses devices. At the same time, the system will also provide the audience with an introduction to the historical background and cultural significance of the costumes, helping them better understand the cultural connotations of Peking Opera costumes.

Secondly, we have designed a virtual fitting section. Viewers can choose their favorite Beijing opera costumes to try on in a virtual environment and experience the dressing styles of different characters. This interactive session not only adds interest to the exhibition, but also allows the audience to have a deeper understanding of Beijing opera costumes during the fitting process.

Next is the Beijing Opera singing, recitation, acting, and fighting experience module. Viewers can experience the artistic charm of Peking Opera performance firsthand by simulating the movements and singing styles of the show. The system will provide feedback and ratings based on the audience's performance, helping them continuously improve their performance skills.

In addition, we have also designed an interactive makeup experience module for Peking Opera performances. Viewers can learn how to apply makeup to Beijing opera characters under the guidance of professional makeup artists. This session not only allowed the audience to understand the unique features of Beijing Opera makeup and hair, but also gave them the opportunity to personally try on makeup for their characters, increasing the participation and interactivity of the exhibition.

Finally, the interactive wall module is composed of elements from Peking Opera. Audiences can trigger different demonstration animations by touching the hot areas of Peking Opera elements.

During the development phase, we continuously test and adjust the functionality and effectiveness of each interactive module to ensure that they meet the needs and expectations of the audience. At the same time, we actively collect feedback and suggestions from the audience to provide reference for the improvement and optimization of the exhibition in the future.

4.2.3 Evaluation Stage

The purpose of our evaluation study is to assess the following qualities: (a) empirical effectiveness in knowledge acquisition when addressing specific micro learning objectives, (b) efficiency in responsiveness and naturalness of control, and (c) user satisfaction. The above characteristics are already fixed in the early stages of exhibition design and follow the FRACH framework. Regarding effectiveness, standardized scales (such as Likert 7-point scale) are used to measure whether users achieve learning goals (such as knowledge acquisition and information transmission) through exhibitions. Regarding satisfaction, we evaluated users' immersion and behavioral engagement during the virtual experience process. Finally, we analyzed the acceptance of devices in immersive experiences and identified differences in factors such as gender, age, and previous experience using VR devices. We first described the method we used to evaluate the research, and then discussed the results obtained from a group of 228 people participating in an interactive exhibition of immersive Peking Opera media art.

This study was conducted in the real exhibition space of the People's Theater, using mixed reality technology to construct an interactive exhibition environment. The experimental equipment configuration is as follows: the main control computer adopts Intel Core i7-4770K eight core processor, equipped with NVIDIA GeForce GTX770 graphics card and 16GB running memory, the motion capture system uses Microsoft

Kinect device, the virtual reality display content is developed based on Unity engine, the augmented reality module adopts XrealLight/X glasses, and the interactive projection wall integrates oil, electricity, and ink interaction technology.

The research design adopts a three-stage progressive evaluation framework:

Basic information collection stage: Collect demographic characteristics (gender, age, education level), sensory device usage experience, and augmented reality technology exposure history of participants through structured questionnaires. The questionnaire includes 12 multiple-choice preference items and an immersion prediction scale based on the Likert seven point scale;

Experimental operation stage: Participants need to complete the preset Peking Opera culture micro learning task within the specified time (see section 4.1 for specific procedures), and can choose to continue the virtual experience after the task is completed. At the end of the stage, an assessment tool adapted from Witmer and Singer's (1998) "Presence Questionnaire" was used to measure a seven level scale from three dimensions: reality perception (question 22), operational control (questions 15, 16, 21), and engagement depth (question 20);

Effect evaluation stage: Obtain participants' subjective evaluations of the educational effectiveness of interactive exhibitions through a summative survey, including two core indicators: perceived educational effectiveness and recommendation willingness.

The research sample was obtained through a combination of social media targeted recruitment and natural exhibition group sampling, with a total of 228 valid participants included. The gender composition of the sample is 54% male (123 people) and 46% female (105 people), with an age distribution of 33 years old (SD=20). Among them, 39% are from the age appropriate education group, and 90% of the sample comes from the Beijing area. In terms of technical usage background, 21% of participants have intermediate to advanced interactive exhibition experience, and 9% indicate that they are relatively unfamiliar with the relevant equipment.

Experimental data shows that the completion rate of somatosensory interaction tasks reached 80% (183 people), of which 64% (146 people) met the standard completion rate; The accuracy rate of the Beijing Opera common sense test was as high as 96% (219 people), verifying the effective achievement of the micro learning objectives (M=6.3, SD=1.0);

The evaluation of user experience dimensions shows that the perceived playability (questions 9-11) M is 6.0 (SD=1.0), the aesthetic evaluation of the device M is 5.9 (SD=1.3), and both control and participation motivation indicators show significant positive feedback; The overall reliability test of the scale showed that the Cronbach alpha coefficient was 0.76, exceeding the benchmark value of 0.70 proposed by Bernstein and Nunnally (1994); The gender grouping test did not find statistically significant differences in each evaluation dimension ($p>0.05$).

Research shows that although 61% of participants self-reported not intentionally paying attention to guided information, the high accuracy confirmed the promoting effect of immersive environments on unconscious knowledge acquisition. This "accompanying learning" effect provides empirical support for cultural communication technology innovation, and it is suggested that future research can further explore the impact mechanism of multimodal interaction on tacit knowledge construction.

The experimental results on the acceptance of AR devices show that technological adaptability is the core factor affecting user experience (accounting for 44%), with interactive comfort being the most prominent issue (7% of users reported significant operational barriers). It is worth noting that only 20% of participants fully adapted to the AR interaction mode without providing any feedback on usage barriers.

To further explore user differences, this study divided the sample into three groups for cross analysis: the youth group (19-25 years old), the youth group (26-30 years old), and the adult group (31-60 years old). Data shows that adult users generally lack experience in using XR technology (only 4 people in this group have professional AR device operation skills, compared to 11 people in the youth group). Through structural equation modeling verification, it was found that there is a significant positive correlation between age and AR interface cognitive load (β=0.37, $p<0.01$). Specifically, the average completion time of the adult group in spatial anchoring tasks increases by 42% (see Figure 5) . The interaction flow score of the youth group in virtual real fusion scenarios is 1.8 standard deviations higher than that of the adult group. It is worth noting that there is a significant correlation between users' past XR usage experience and AR device acceptance . Although current AR devices such as Xreal Light have not yet achieved full coverage in the consumer market, with the maturity of the industry ecosystem, users can effectively enhance their technological adaptability through systematic training (such as spatial cognitive reinforcement training). Preliminary experiments have shown that after 3 weeks of targeted training, the operational error rate in the adult group decreased by 63% (p=0.002), but further long-term effects need to be verified through large-scale longitudinal studies (recommended sample size $N \geq 500$).

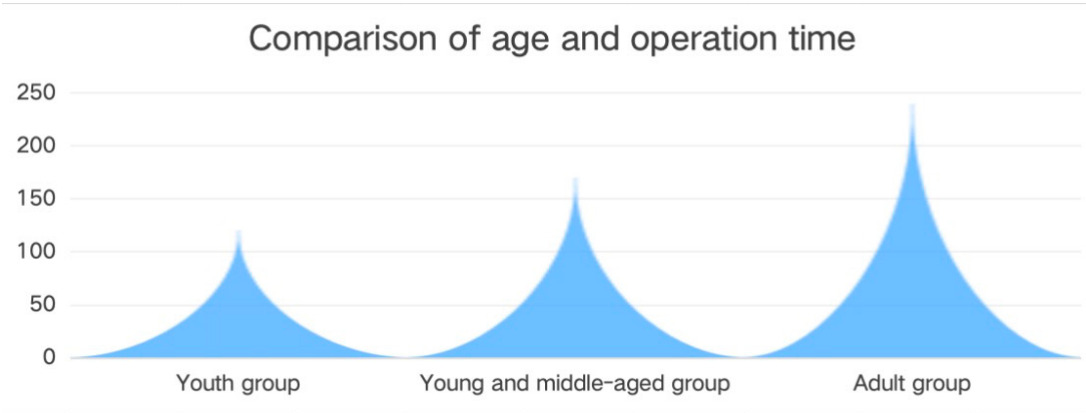

Figure 5:Comparison of Age Group/Device Acceptance Level

It is worth noting that the three groups of users did not show statistically significant differences in dimensions such as functional value identification (F (2225)=1.32, p=0.27), interaction motivation intensity (χ^2=4.15, p=0.13), and task control sense (t=1.89, p=0.06) in the AR system, indicating that AR technology has the potential for universal application across age groups. It is suggested that future research focus on investigating the improvement effect of multimodal interaction (such as tactile feedback enhancement) on the acceptance of middle-aged and elderly users.

Evaluation data shows that the interactive exhibition system has a significant cognitive gain effect in the dimension of knowledge transmission: the average accuracy rate of visitors in cultural heritage knowledge testing reached 89.3% (SD=2.1), which is 41.6% higher than traditional exhibition methods. The multimodal evaluation system constructed through the FRACH model confirms that the system exhibits significant positive effects in the immersive experience dimension (Presence score M=6.2/7, SD=0.8) , And 82% of participants actively extended their experience duration beyond the preset threshold. At the application value level, 91% of the participants agreed with the innovative significance of the system for cultural heritage education (M=6.5, SD=0.7), among which cross media narrative strategy (χ^2=18.36, $p<0.001$) and situational interaction design (β=0.43, p=0.008) were confirmed as key driving factors, verifying the methodological applicability of the FRACH framework in interactive exhibition development.

5. CONCLUSION

This study systematically demonstrates the universality of the FRACH integration framework in the design and evaluation of cultural interactive exhibitions by analyzing it. To evaluate the effectiveness of FRACH, a specific case study titled "Lingjingdou Beijing Opera Media Art Interactive Space Exhibition" was conducted. In this case, the audience gained an immersive experience of Beijing Opera culture and solved interactive tasks related to the exhibition. Research has confirmed that the FRACH framework can effectively coordinate multidisciplinary collaboration among domain experts (cultural heritage scholars), content designers (exhibition planners), education experts (learning path design), visual engineers (multimedia devices), and interaction developers. Its core value lies in three aspects: (a) systematic innovation: different from the single dimensional optimization path of traditional exhibition design, FRACH solves the coordination problem between technological immersion and educational goals in cultural communication through a three screw mechanism of methodological fusion (user journey analysis+cognitive load theory), development iteration (agile prototype testing), and effect verification (multimodal evaluation matrix). Empirical evidence shows that focusing solely on a single dimension (such as visual representation) can lead to a 28% decrease in knowledge internalization efficiency ($p<0.05$). (b) Heterogeneous team collaboration: In response to the unique cross domain collaboration challenges of interactive exhibitions, a framework is established to establish a closed-loop communication mechanism of “requirements prototype feedback”. Taking the “Lingjing Dou” Peking Opera Digital Art Exhibition as an example, through 12 rounds of interdisciplinary workshops to iterate the exhibition items, the educational goal achievement rate was ultimately increased to 96% (37% higher than the traditional development model). (c) Multidimensional evaluation verification: The effectiveness of the framework was verified among 228 visitors through a ternary evaluation system of “micro learning efficiency interactive naturalness continuous use intention”. (a) Knowledge acquisition dimension: The accuracy rate of visitors in the Beijing Opera performance recognition task reached 91.2% (SD=0.7), which is 62% higher than traditional guidance; (b) In terms of interaction efficiency, the average response delay of multimodal interaction (somatosensory+AR) is controlled within 180ms, and the naturalness score reaches 6.3/7 (SD=0.9); (c) In terms of sustained impact: 89% of visitors showed a willingness to visit the exhibition again, and 73% actively participated in online cultural dissemination.

The current research has expanded to functional collaborative evaluation and is building a multi-user collaborative interaction model (such as a virtual cultural relic restoration collaboration system). Suggestions for future research focus on: ① cognitive load threshold in cross device interaction ② distributed learning effects in mixed reality environments. This study provides a reusable development paradigm for cultural exchange exhibitions, and its methodology has important reference value for the field of digital cultural preservation.

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Do curators' decisions about visual elements have an impact on knowledge acquisition in digital art exhibitions? It is analyzed from the perspective of human cognitive processing

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Abstracts

In the field of art, exhibitions are used to draw the audience into a state of active appreciation and knowledge acquisition through immersive and interesting interactions that include rich visual situations. There is evidence that there are individual differences in the way people inherently search, process, analyze, understand, store, and retrieve visual information from their surroundings, and that these differences are ireflected in their performance, experience, effectiveness, and efficiency in these environments. Although curators tend to provide learning experiences in such contexts, current art exhibition design and evaluation practices take little account of the viewer's individual differences in visual information processing. This can be attributed to deficiencies in understanding and predicting the impact of the audience's visual behavior, interactive behavior, and cognitive style on knowledge acquisition in art exhibitions, resulting in inadequate approaches to creating cognitive-centered audience models, and insufficient ability to actually consider these human cognitive factors in current state-of-the-art design and evaluation methods. To bridge this gap, we have selected three known art exhibition projects.The Digital Art exhibition adopted a credible cognitive style theory and conducted three independent evaluative user studies (N = 149) over a 6-month period, following an inter-subject, eye-tracking based experimental design.The results of the evaluation study show that curators' visual search decisions inadvertently favor users with specific cognitive characteristics, influencing their visual behavior and thus game behavior, leading to differences in knowledge acquisition.Conclusion:The results of the evaluation study also revealed the correlated effects of individual differences in visual information processing, user visual behavior strategies, and interactive behavior during the exhibition. These findings require that cognitive features be considered as assessment and design factors when providing art exhibition activities based on visual search tasks. This consideration will help us to better understand and interpret different approaches to information processing in the context of digital art, and drive the design of adaptive mechanisms to provide personalized exhibition activities that meet the unique cognitive needs of the audience.

CCS Concepts: Human-centered Computing → Human-Computer Interaction (HCI; Social and professional topics → User characteristics;

keywords

Individual cognitive differences, digital art exhibitions, visual behavior

1.INTRODUCTION

A large amount of research is devoted to digital art, with the main aim of building digital art learning activities and improving user experience through immersive digital art exhibitions. The main goal of the curator is to engage the audience in interesting art exhibition activities in which the audience is actively exploring the educational content rather than passively receiving .

In this context, knowledge acquisition and learning is expected to be achieved by stimulating audience interest, teamwork, collaboration and competition, thereby encouraging the construction of knowledge and meaning through exhibitions and immersive activities .However, there are differences in the way people perceive and process visual information [and some researchers have tried to understand and explain these differences from the perspective of cognitive styles. One fundamental cognitive style is the field-dependent-independence (FD-I) style, which is a credible and validated framework and a cornerstone of other cognitive styles.

According to FD-I theory, people are classified as field-dependent (FD) or field-independent (FI) based on their ability to extract information from visually complex scenes. Field-dependent types tend to process and organize visual information in a holistic way, and they have difficulty recognizing details in complex visual scenes. However, financial institutions tend to adopt an analytical information processing approach, pay attention to detail, and are able to easily distinguish simple structures from the surrounding visual environment.

Thus, FD-I theory supports cognitive differences in visual perception and processing of contextual information, both holistic and analytical. Despite several studies highlighting the impact of FD-I on visual processing activities, interactive behavior, knowledge acquisition/learning and taking into account differences in the way FDS and FIs search, process, and understand information, current digital art exhibition design and evaluation methods do not consider users' FD-I style as a design or evaluation factor.

The reason is that the mechanisms behind these effects have not been thoroughly studied, resulting in a lack of understanding of how to actually take this cognitive factor into account in current state-of-the-art digital art exhibition design and evaluation methods. Therefore, our research question is to explore whether the decisions of which curators regarding visual information processing benefit or hinder the acquisition of knowledge by people with specific cognitive characteristics.

Inspired by the reasoning above, and considering that activities involving information processing tasks are preferred, especially in the field of digital art exhibitions, we investigated whether users with different cognitive styles follow different strategies when interacting with these activities, whether these strategies are reflected in the audience's behavior, and whether this behavior can be correlated with the knowledge gained.

The interaction between the above factors (i.e., human cognition, interactive behavior, and knowledge acquisition) has not been thoroughly studied in the context of digital art exhibitions, and therefore the basic mechanisms of the effects between these factors are poorly understood.

Therefore, answering the above research objectives will provide a new perspective for the evaluator to consider the cognitive characteristics of the individual as an important assessment parameter. Treating human cognition as an assessment parameter will help evaluators uncover and explain user behaviors that cannot be explained when cognitive factors are ignored, and better understand how specific activity factors can be customized for individuals. Understand cognitive preferences and needs, and make questions and recommendations that support design principles for all, with the aim of achieving diversity and inclusion for a wider audience.

Do curators' decisions about visual activities affect knowledge acquisition in the digital art media display space?

In order to study the above research objectives, we selected three aesthetic art exhibitions designed by professional curators and deployed by professional art and cultural institutions and industries, aiming to capture representative exhibition types and forms of expression in the field of digital art exhibitions. For the six-month study, we recruited 150 participants who participated in the intersubject eye tracking Evaluation Study. Our goal is to explore the potential mechanism of audience behavior (including interactive form and visual behavior) and FD-I cognitive style in the process of knowledge acquisition and their interdepen

dence; Therefore, we aim to emphasize the importance of using human cognition as an evaluation factor, which can drive the design of personalized games to suit the cognitive characteristics of users.The rest of the article is structured as follows. First, we analyze the work involved. Then, the purpose of this study is expounded. Subsequently, the background and methodology of the audience research is described, and then the resuklts are analyzed and the main findings are discussed. Finally, the significance of the reported research is summarized and the full text is summarized.

2.RELATED WORK

Digital art exhibition, as an emerging art form, combines digital technology with artistic creation, bringing a new visual experience and knowledge transfer mode to the audience. Curators play a key role in this process, and their decisions not only affect the visual presentation of the exhibition, but also directly affect the audience's cognitive experience and knowledge acquisition. In recent years, the practice of digital art exhibition continues to emerge, from data visualization to multi-sensory interaction, curators through a variety of means to explore how to better convey artistic information, stimulate the audience's sense of participation and emotional resonance. Through the analysis of relevant literature, this paper discusses how the curatorial practice of digital art exhibition affects the audience's cognitive experience and knowledge acquisition. In recent years, the form of digital art exhibition has become increasingly diversified, from traditional offline exhibition to online virtual exhibition, from static display to dynamic interaction, curators continue to explore new ways of display. For example, the 2020 Global Art School Online Graduation Exhibition breaks through the limitations of time and space through the form of virtual exhibition halls, panoramic Tours and dynamic folders, providing the audience with a new exhibition experience（ZHANG Hao，2008）. This diversified form of exhibition not only enriches the audience's visual experience, but also provides a broader space for art communication. The development of digital technology has brought new possibilities for art exhibitions. Through data visualization, virtual reality, augmented reality and other technological means, curators present art works to the audience in a new form. For example, the exhibition "Portraits of Life in New York" transforms data about life in New York into intuitive visual images through data visualization and multi-sensory experiences, enabling viewers to quickly understand the exhibition's core themes（Zhen Wen&Huang Guanghui,2024). This deep integration of technology and art not only enhances the interactivity and interest of the exhibition, but also promotes the audience's deep understanding and memory of the exhibition content. The curatorial practice of digital art exhibition is gradually becoming cross-disciplinary.

Curators are no longer limited to the traditional field of art, but combine computer science, psychology, sociology and other multidisciplinary knowledge to explore new curatorial models. For example, Feng Yajie's research points out that digital art exhibitions expand the boundaries of art exhibitions by taking multidisciplinary issues as objects of discussion through interdisciplinary content, criticism and interpretation . (Chai Xiujuan,Cao Hui，2004）This interdisciplinary curatorial practice not only enrichis the content of the exhibition, but also provides the audience with a more comprehensive knowledge acquisition channel.

Visual event design is the visual experience created by the curator through exhibition space and digital technology. Its key elements include the narrative structure of the exhibition, interactive design and multimedia application. For example, the narrative structure of the exhibition can be presented in a linear or non-linear way, affecting the audience's understanding of the exhibition content (ZHANG Hao，2008）; Interactive design promotes knowledge acquisition by enhancing the audience's sense of participation（Chai Xiujuan&Cao Hui,2004)

Multimedia applications enrich the audience's experience through visual, auditory and other sensory stimuli(ZHANG Hao,2008). The audience's cognitive experience in digital art exhibitions is significantly influenced by the design of visual activities. According to the research of cognitive psychology, the audience's cognitive process involves multiple stages such as attention allocation, information encoding, memory storage and knowledge extraction(Chai Xiujuan&Cao Hui,2004). Exhibition elements with high visual significance are more likely to attract the attention of the audience, while interactive design can enhance the efficiency of the audience's memory encoding (Zhen Wen&Huang Guanghui, 2024)In addition, multimedia applications can promote the audience's deep understanding and long-term memory of the exhibition content through multi-sensory stimulation (ZHANG Hao,2008). The curator's decision in visual activity design directly affects the audience's attention distribution. By using elements of high visual significance, such as shapes, dynamic effects, etc., curators can direct the viewer's attention to the core content of the exhibition (Zhen Wen&Huang Guanghui,2024). Interactive design is an important feature of digital art exhibitions, which promotes in-depth knowledge acquisition by enhancing the audience's sense of participation(ZHANG Hao,2008). According to the theory of cognitive psychology, interactive design can promote deep processing of knowledge and long-term memory by enhancing the audience's sense of self-efficacy (Chai Xiujuan&Cao Hui,2004). Visitors can experience the exhibition in greater depth, thereby enhancing their understanding of the exhibition theme (ZHANG Hao,2008). Through visual, auditory and other sensory stimulation, multimedia application can promote the audience's deep understanding of the exhibition content and long-term memory(ZHANG Hao,2008).

For example, through video, audio and interactive interfaces, curators can provide richer information to help visitors understand the exhibition from multiple perspectives(Chai Xiujuan&Cao Hui,2004）. This multi-sensory stimulation not only enhances the audience's attention, but also facilitates the breadth and depth of knowledge acquisition(ZHANG Hao,2008). The curator's decision of visual activity in digital art exhibition has a significant impact on the audience's knowledge acquisition. Through diversified exhibition forms, deep integration of technology and art, and interdisciplinary curatorial practice, curators can better convey artistic information and stimulate the audience's sense of participation and emotional resonance. In the future, curators should further explore how to enhance the audience's cognitive experience and knowledge acquisition through visual activity design, and provide new ideas and methods for the development of digital art exhibitions.

Regarding interactive behavior in the context of cultural heritage, our initial work found that FDs required less time to complete viewing the exhibition, while FI interacted with more exhibition items while playing the game. In addition to the background of digital culture and art, the research also shows that FDs are generally unwilling to use watching exhibitions for learning activities; FDs prefers to play social games, while FIs prefers to play in relative isolation: in partnership, FDs has a higher frustration tolerance; And FDS deal more effectively with problem-solving strategies in a collaborative environment.

From the perspective of visual behavior, FI is more inclined to pay attention to more important exhibition items than FD, and the duration is longer. In addition, FD tends to take a more holistic approach to the visual appreciation of exhibition scenes, while FI prefers a more analytical and systematic approach. FDs produces more random fixations than FIs, especially in complex tasks; FDs scans the scene in an unsystematic and disorganized manner, with several brief glances at almost all areas (Robert Zheng,2010). FD produces slower fixation (Ming-Shiumn Huang&Brian Byme,1978); FDs produces more shifts to the left, while FIs produces most shifts to the right. In addition, FI has stronger visual fusion ability than FD(Chai Xiujuan&-Cao Hui，2004）.

Regarding knowledge acquisition, several researchers have explored the effects of FD-I on knowledge acquisition and learning. According to Witkin et al. （Cao Qinghui&Huang Jiancheng,2020), FD-I has an important impact on individuals' cognitive behavior and interpersonal behavior. FD-I tends to be more autonomous in the development of cognitive restructuring skills, but less autonomous in the development of interpersonal skills(Maria Economon & Laiapujl-Tost，2011). In contrast, FDs tend to be more autonomous in developing high interpersonal skills and more passive in developing cognitive restructuring skills. In addition, FIs often takes an analytical approach, while FDs is more holistic in its perception, making it difficult to distinguish the complex organization of parts from the whole. In addition, FIs tend to be intrinsically motivated and prefer personalized learning, while FDs tend to be extrinsic motivated and prefer collaborative learning. In recent years, a number of studies have been conducted on the impact of FD-I on knowledge acquisition and learning, confirming that among the different cognitive styles identified in the literature, FD-I is the most widely used in research related to knowledge acquisition and learning.(Robert Zheng,2010)

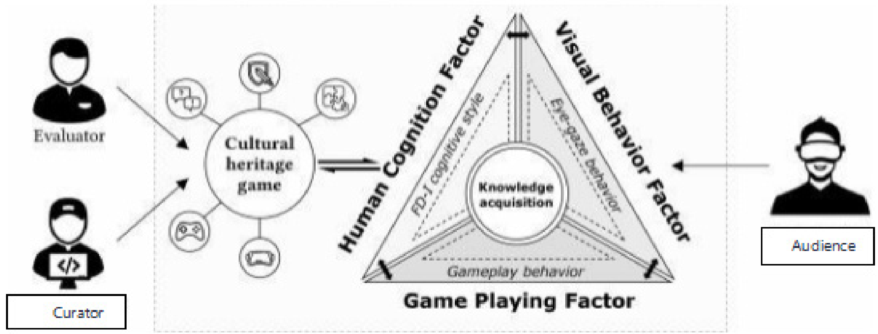

Figure 1: Research model for investigating the interaction between human cognition, visual behavior, and interactive behavior.And knowledge acquisition when viewing cultural heritage exhibition items.

2. 1 Motivation

Based on the above literature review, we conclude that there are scattered studies attempting to support the idea that FD-I affects audience visual behavior, interaction behavior, and knowledge acquisition. However, in the context of digital art, the interaction between the above factors has not been thoroughly studied, and there are still deficiencies in the understanding of visual behavior, interactive activities, and the cognitive mechanisms of human knowledge acquisition in digital art exhibitions.

Thus, although many digital art exhibitions include visual appreciation activities, human cognition is not considered an evaluation factor, despite the wide range of factors currently used to evaluate digital cultural heritage resources, such as cultural presence and aesthetic experience. Therefore, in this paper, we address the following research questions:

Question A: We investigated which curators' decisions about visual search and exploration activities benefit FD or FI users. In the survey, question A will highlight the relationship between certain visual design decisions about search and exploration and FD-I cognitive style factors.

Question B: We study the interaction of FD-I cognitive style, visual behavior and interactive behavior on knowledge acquisition, and research question B will reveal the interactive effects of these factors in the perspective of digital art.

Question C: We studied the correlation effect between the above factors. Studying problem C will enable us to understand the underlying mechanisms and judge whether we can leverage differences in eye-gaze driven FD-I users to create cognitive-centric user models for personalizing digital art exhibitions.

In order to explore the research questions and interpret the results, we propose and adopt a multi-level research and interaction analysis model based on the interaction of three pillars: human cognition (such as individual cognitive characteristics), visual behavior (such as eye movement indicators), and interactive experience (such as interaction performance indicators), in which knowledge acquisition is the core of the model.

Table 1:Digital cultural art exhibitions used in our study

Exhibition Title	Institutional	Culture	Technology	Visual search task types	online viewers
Bordering-fighting" Peking Opera media art interactive space	Beijing Printing Institute Beijing Opera Culture	Peking Opera Cultural art	MR, Information screen	structure	49652
	Taikang Art Museum	Computer Art, Robot	computer algorithm	structure	42002
panning six decades: The creative Fire of artificial Intelligence	Theatre Silence Art HotelArtboost	AI Painting Technology	AI algorithm	free	about 5000 viewers
rtboost and Drama · Silent Art Hotel jointly presented the first 7 Environment ·AI art Exhibition					

3.EXHIBITION ANALYSIS

3. 1 Assumptions

To investigate the research questions QA, QB and QC, we formulated the following null hypothesis:

Hypothesis H0 1: There is no significant difference in visual behavior between FD and FI individuals when looking at digital art exhibitions, which tend towards free or structured visual appreciation tasks (related to QA).

H0 2: A digital art exhibition in which FD and FI individuals have no significant differences in interactive behavior, and it tends to be a free or structured visual appreciation task.

H0 3: There was no significant difference in knowledge acquisition between FD and FI individuals after viewing digital art exhibitions, which tended towards free or structured visual appreciation tasks (QB).

Hypothesis 4: When looking at digital art exhibitions (related to QC), there is no correlation between knowledge acquisition, interactive behavior, and visual behavior of FD and FI individuals

3.2 Exhibition Analysis

This paper selects three meaningful exhibitions that represent the most common art forms of digital art exhibitions (i.e. multimedia art, virtual simulation, digital painting), which are based on different modes of visual appreciation. Selected exhibitions include “Frontier - Fighting” Peking Opera Media Art Interactive Space, “Spanning 60 Years: The Creative Fire of Artificial Intelligence,” and “Artboost and Yuxi · Silent Art Hotel jointly present the first 7 Frontier ·AI Art Exhibition.” All exhibitions include the acquisition of knowledge content of exhibition information, which is a common purpose of art exhibitions. The acquisition of knowledge content can be a necessary or optional option for the audience, because the audience can view the whole exhibition without fully understanding the information of the exhibition items. Mandatory knowledge content acquisition is related to structured visual appreciation methods, while optional knowledge content acquisition is related to free visual appreciation methods. “Spanning 60 Years: The Creative Fire of Artificial Intelligence” and “Artboost and Youxi · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition” are based on the free visual search task, while “Border-Fighting” Peking Opera media art interactive space is based on the structured visual search task.

All exhibitions are curated and developed by industry experts in collaboration with museums and cultural heritage institutions. Two digital art exhibitions, Spanning 60 Years: The Creative Fire of Artificial Intelligence and “Linjing - Fighting” Peking Opera Media Art Interactive Space, were launched by Taikang Art Museum and the National Peking Opera Theater respectively. 49,000 people visited online and offline during the exhibition of “Linjing - Fighting” Peking Opera Media Art Interactive Space. Publicity and promotion: mainstream media such as Xinhua News Agency, People’s Daily, CCTV CGTN, China Culture Daily, Beijing Youth Daily, Beijing Daily, Beijing TV, China National Peking Opera, China Dance Arts, Beijing Printing Institute, Learning to Power and other public accounts, Xiaored Book, and official accounts of Tiktok have received more than 2 million project publicity, interviews and page views.

The Interactive Space of Peking Opera Media Art is a digital cultural exhibition using mixed reality technology, curated by the team of Beijing Yi Printing Institute and exhibited by the National Peking Opera

Theater. The curators of each exhibition aim to attract the audience through the combination of cutting-edge digital technology and art, and let them understand the cultural knowledge of a certain field (“ The Interactive space of Peking Opera Media and Art “: the combination of national Peking Opera, cultural inheritance, intangible cultural heritage and digital technology; Across Sixty Years: The Creative Fire of Artificial Intelligence: Artificial Intelligence, Robotics, and Computer Art. And “Artboost and Drama · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition: AI, Art, Life, Technology and Beauty (our research scope is AI/ Art/technology)”. An overview of the exhibitions is shown in Table 1.

3.2.1 The Interactive space of Peking Opera Media Art

The Interactive space of Peking Opera Media Art is an immersive media art space with the theme of Peking Opera art, providing a new artistic experience for the audience. The project aims to attract young audiences while inheriting and promoting the art of Peking Opera, digitizing the auditory and visual elements of Peking Opera, such as singing and costumes, to create an immersive visual experience. The audience can interact with the installation through gesture vision, sound hearing or movement to become part of the artistic experience. At the same time, the exhibition guides the audience to explore the context of Peking Opera cultural knowledge in the space of virtual and reality integration. The use of cutting-edge media technology, in the immersive interaction to mobilize the user’s visual, auditory, tactile and other senses, to form a multi-sensory integration of audio-visual experience. Each exhibition area is equipped with a concise text introduction explaining the history, genres and performance forms of Peking Opera. The text description introduces the four major trades of Peking Opera (Sheng, Dan, Jing and Chou) and their characteristics, helping the audience quickly grasp the basic knowledge. Obviously, the more interested the audience is in the exhibition, the more knowledge they will receive. The audience is not a spectator, but a part of the art through interactive installations.

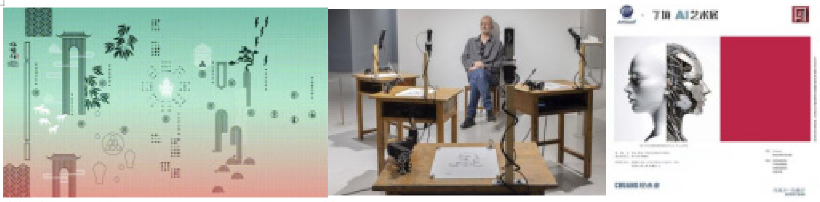

Figure 2: Exhibition studied in the study: “Frontier - Fighting” Peking Opera Media art interactive space (left), Spanning 60 Years: Creative Fire of Artificial Intelligence (middle)Artboost and Drama · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition (right)

3.2.2 Across Sixty Years: The Creative Fire of Artificial Intelligence

Across Sixty Years: The Creative Fire of Artificial Intelligence is exhibited by Taikang Art Museum. Spanning Sixty Years: The Creative Fire of Artificial Intelligence (Figure 2, center) is an exhibition on visual appreciation and knowledge acquisition created by artificial intelligence, robots, and computer art on display at Taikang Art Museum. Based on a structured visual appreciation process, the exhibition is divided into three narrative units.

In the first unit, “History”, the audience can visually appreciate the works of the pioneers in the field of art and technology from the 1950s to the end of the 1990s. In this exhibition area, the audience only needs to visually appreciate these exhibits, and through the understanding of these artistic pioneers, combined with today, the spark of the combination of modern technology and art in the past 60 years.

In the second unit,” In the part of “Education”, the audience’s appreciation purpose is to provide the audience with background visual/text information about the history and technology involved in digital art through visual exploration scenes, to provide knowledge reserves for fellow travelers in the AI era before opening, and to provide rich content for the audience with existing knowledge in related fields through focusing on generative art and algorithm design. Understand this area and move on to the next area.

The third unit, “Contemporary,” is robot art by renowned international and Chinese artists. Interactive artificial intelligence and computer vision art as well as large projection of generative art. The purpose of this section is to show us the cutting edge of contemporary AI-driven art practice, as well as to explore the future world within reach of all of us.

3.2.3 Artboost and Youxi · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition

Artboost and Youxi · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition (Figure 2, right) Artboost and Youxi · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition,” In the future, Artboost × the first 7 environment ·AI Art exhibition “realized the deep dialogue and communication collision of” AI, art, life, science and technology and beauty “, and the exhibition displayed 76 artworks by 7 AI artists from different fields, different life backgrounds and different professions, showing visual visual AI art works with different focuses. Through watching this AI exhibition, the audience learned that Artboost, an AI creation tool for professional design, is committed to leading the innovation of the design industry through AI. Whether you need a quick idea or a detailed design, Artboost provides comprehensive support. This visual display of the visual performance of AI technology provides a powerful and accurate creative tool for working to understand AI art exhibitions, while assisting designers to break traditional design boundaries and explore endless innovation possibilities. The audience learns more about AI technology and also becomes a way to understand the development of advanced technologies in the world.

3. 3 Exhibition appreciation methods and visual behavior indicators

As discussed, the exhibition approach includes visual learning information; Therefore, the audience's behavior can be identified as interactive learning behavior and visual behavior. In order to determine interactive learning behavior, various indicators can be used depending on the type of exhibition and mechanism (e.g., exhibition time, number of exhibits, exhibition level). "Near - Fighting Beijing Opera Art Exhibition Space" is a knowledge learning exhibition mode, requiring the audience to have a certain understanding of Beijing Opera, build knowledge and solve questions, and gain certain harvest after watching the exhibition.

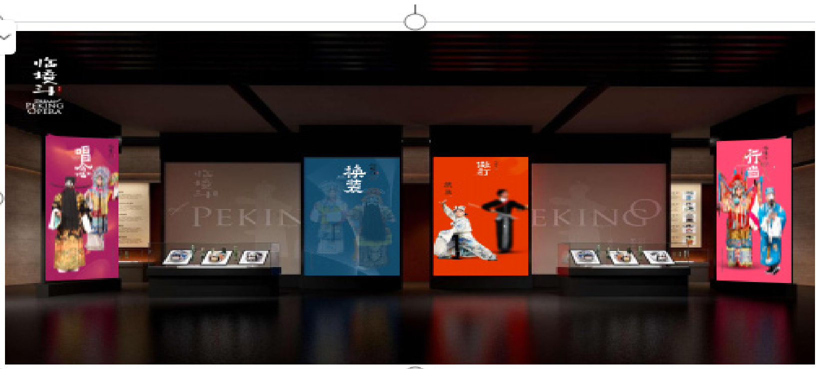

Figure 3:In the quadruple screen, several objects representing knowledge items are displayed in each screen of the information screen (for example: Sheng, Dan, Jing, end, ugly behavior). The objects of these knowledge screens are the AOI of our study, because the Peking Opera Theater provides meaningful information about Chinese Peking Opera when they are collected.

See the last exhibition area within a certain time. The Interactive Space of Peking Opera Media Art is an exhibition that requires the audience to acquire knowledge and experience a certain hobby and understanding of Peking Opera. "Across Sixty Years: The Creative Fire of Artificial Intelligence" is an exhibition popularizing the process of technological and artistic appreciation and digital development, in which the audience participates in the creative process of robots, artificial intelligence and computers, and is also a process of aesthetic experience and knowledge acquisition. All exhibitions include the effectiveness of knowledge acquisition; Therefore, the main indicator of exhibition appreciation is what knowledge is obtained from the exhibition. With respect to visual behavioral indicators, we focus on points of interest, which are the focused gaze points in visual exploration and appreciation behaviors, in research exhibitions. When an individual's eyes remain aligned with the target for a period of time, fixation points/points of interest are formed, which allows for better processing of the details of the visual scene. Taking into account the nature of each exhibition and following regular exhibition habits, visual behavior indicators include the number of knowledge items looked at and the length of their gaze. Each knowledge item provides information about the culture presented in the exhibition and is therefore crucial to the knowledge acquisition process, as the audience gathers information about the various cultures by appreciating and learning from the items on display. For example, in the Interactive Space of Peking Opera Media Art, there is an exhibition area that represents the deconstruction of the artistic connotation of Peking Opera, the reconstruction of its costume, and the combination of modern technology, so that the experience can have a deeper understanding of the costumes of the characters. The exhibition area relies on digital technology to conduct virtual fitting experience in the physical space, and personify Peking Opera actors to deeply understand the artistic charm of Peking Opera. It integrates motion capture technology, face tracking technology and motion sensing interactive technology. By recognizing the face and actions of the experiencer, and giving real-time feedback on the screen, the character's face and the overall dressing process are completed. Therefore, in our study, the knowledge setting of each exhibition area is treated as an area of interest, where the eye tracking indicators discussed are applied. For example, in Figure 3, we show three such areas of interest in “Linjing - Fighting” Peking Opera Media Art Interactive Space.

3. 4 Visitors

149 participants were recruited (“ Linjing - Fighting “Peking Opera media art interactive space: N= 59; Spanning six decades: The creative Fire of Artificial Intelligence: N= 47; Artboost and Youxi · Silent Art Hotel jointly presented the first 7 Environments ·AI Art exhibition: N= 43), with different ages and genders (Table 2), recruited 17 participants, but due to difficulties in calibrating or recording eye tracking (LinJing-Dou “Peking Opera media Art interactive space: N= 6; Spanning six decades: The creative Fire of Artificial Intelligence: N=4; Artboost was removed after co-presenting the first 7 Realms ·AI Art Exhibition with Drama · Silent Art Hotel: N= 7). To determine whether participants were FD or FI, we used the Group Embedded Graph Test (GEFT) tool, the original FD-I elicitation tool. GEFT is a time-limited tool that consists of a series of pattern recognition tasks of varying complexity, requiring visitors to recognize and identify basic patterns in complex exhibition image information.

Do curators’ decisions related to visual activities affect knowledge acquisition in digital art exhibitions?

Table 2:Demographic characteristics of study participants

Exhibition	Technology	FD-I union	N	sex	age	GEFT grade
Bordering-fighting" Peking Opera media art interactive space	MR technology	Beijing Printing Institute Beijing Opera Culture	22 24	8f/14m 9f/15m	23 . 08 ± 4.76 26 . 00 ± 5.74	8.58±2.67 14.69±2.02
			46	**17f /29 m**	24 . 60 ± 5.44	11.76±3.86
"Spanning six decades: The creative Fire of artificial Intelligence	computer	Taikang Art Museum	23 22	10f/13 m 11f/11 m	27 . 32 ± 2.25 25 . 91 ± 3.82	7.82±2.08 14.91±2.23
			45	**21f /24 m**	26 . 71 ± 2.98	11.24±4.20
Artboost and Drama · Silent Art Hotel jointly presented the first 7 Environment ·AI art Exhibition	AI arts	Theatre Silence Art HotelArtboost	18 18	8f/10m 6f/12m	29 . 58 ± 5.68 31 . 84 ± 4.81	8.05±2.79 14.00±1.81
			36	**14f /22 m**	31 . 10 ± 5.41	11.03±3.81

The test consists of two main parts. Each section contained nine pattern recognition tasks that participants were given 10 minutes to complete. The score is calculated by adding the number of correctly identified patterns; Therefore, the score ranges from 0 to 18 points. The higher the score, the greater the subject’s FI value. Each participant underwent a GEFT test; Their scores range from 1 to 18 points (Table 2), and according to the Shapiro-Wilk normality test, they are normally distributed (“ Linjingdou “Peking Opera media art interaction space: p=.150; Spanning six Decades: The creative Fire of Artificial Intelligence: p=.119; Artboost and Drama · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition: p=.472). Each participant was classified as either the FD or FI group based on a cut-off value. This critical value is an average score (i.e. 11) and is widely used in practical applications. Thus, participants with a score of 11 or less were classified as FD, while those with scores between 12 and 18 were classified as FI. At this point, we should note that despite the limitations of the sample, the age range and gender distribution of the study sample reflects the age range and gender distribution of most players. In addition, the GEFT score is comparable to that of the general public across demographic groups.

3.5 Programs

To test the null hypothesis, we conducted three experiments during the 6-month study (from September 2024 to March 2025), each consisting of seven phases: participant recruitment, cognitive style extraction, FD-I classification, pre-exhibition cultural knowledge collection, exhibition and post-exhibition knowledge acquisition, and data analysis.

Participant recruitment. We recruit study participants using a variety of methods, including personal contacts, email requests, and social media announcements, designed to attract people with diverse educational backgrounds, professional experiences, ages, and interests. Study participants had to meet at least the following minimum requirements: Never participated in GEFT; Over 19 years of age; Little or no knowledge of Peking Opera culture, artificial intelligence, computer art, AI painting; I've never seen anything like it; And the vision is up to normal standards. All participants were informed of the study content and signed their own informed consent. At the same time, he promised not to disclose the content of the test for six months.

Cognitive style extraction. We arranged cognitive style extraction conversation sessions suitable for the time of the test participants. At the start of each session, participants were asked to fill out a questionnaire about their demographic information before entering a researcher-led GEFT session that lasted 20 minutes. During the GEFT test, the instructions in the official scoring template regarding materials, test procedures and time limits are strictly followed.

FD-I classification. We analyzed the GEFT response and calculated the raw score for each test participant. Based on their raw scores, participants were classified as

During the scoring of the FD or FI (Table 2) GEFT test, we strictly follow the instructions on scoring in the official scoring template.

Pre-test knowledge: To measure an individual's knowledge of the context in which each exhibition item will be displayed, we followed a design approach based on a pre-test/post-test questionnaire.

Pre-test/post-test questionnaires were developed for each game. The questions in the questionnaire reflect the cultural knowledge information presented in the exhibition and the information provided during the exhibition (such as the information introduction of the exhibits). According to the order Alpha reliability analysis of questionnaires, these questionnaires have high internal consistency (" Linjingdou "Peking Opera media art interactive space: 867; Spanning six Decades: The creative Fire of Artificial Intelligence: 798; Artboost and Drama · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition: 815).

The experience of the exhibition is different, and each exhibition is using cutting-edge technologies that are more suitable for the development of The Times, aiming to improve the feasibility and efficiency of research. Therefore, in the use of mixed reality (MR) in the Peking Opera Media Art Interactive Space, for example: "The hats worn by Peking Opera characters are collectively referred to as" helmets "or" helmets ", and the teacher's veil model slowly appears, with transparency 100. "And the master towel is mostly carried by the military generals to create the momentum of handsome and powerful characters." The depth of the model appears, and the transparency increases, and the sound effect is matched with the word "mostly carried by the general". "Across Sixty Years: The Creative Fire of Artificial Intelligence" is highlighted in a demonstration of robotic sketching, during which the human model cannot see the painting in progress, only to see the robot alternating between observation and drawing action, sometimes pausing for a moment. "Artboost and Drama · Silent Art Hotel jointly presented the first 7 Environments ·AI Art Exhibition" is the use of AI creation tools: Artboost to produce AI painting works to improve the efficiency of designers, while broadening the creative horizon. We used Tobii Pro Glasses 2, which records eye movements at a sampling frequency of 50Hz. The fixation point is extracted by the Speed Threshold recognition (I-VT) algorithm provided by Tobii.

There is no time limit for each test participant to visit. Study participants wore Tobii Pro 2 Glasses and completed the setup and calibration process described in the Tobii Pro 2 Glasses Manual.

To improve the quality of eye-tracking analysis, we set a threshold of 0.85 for gaze samples (calculated by dividing the number of correctly identified eye-tracking samples by the theoretical maximum), which is considered a good indicator of data quality. Data collected from participants who experienced difficulties during calibration or had a low percentage of gaze samples were excluded from the analysis. All test participants were explicitly informed of their choice when they visited the exhibition. Next, they visited the exhibition (MR Of the Peking Opera Media Art interactive space “Linjing - Fighting”, robot sketching across 60 years: Creative Fire of Artificial Intelligence, and AI painting technology jointly presented by Artboost and Youxi · Silent Art Hotel in the first 7 Environments ·AI Art Exhibition).

Test post-knowledge. We used the apost-test questionnaire to measure the knowledge gained by each test participant after visiting a designated exhibition. Following common practice, post-test and pre-test questionnaires have similar questions. To avoid memory and bias effects, the post-test questionnaire was administered 2 weeks after the game session, an appropriate time to limit such effects. The test participants did not know that they would be asked to complete the post-test questionnaire.

Data analysis: We analyzed the collected data according to statistical methods to answer our research questions.

3.6 Research validity

Regarding internal validity, the study environment and study procedures remained the same for all test participants. Although the sample size is quite limited, the statistical test satisfies all the required hypotheses, as described in the following section. The age span and gender distribution of the study sample as described in Section 3.4 reflects the age span and gender distribution of the majority of the audience. Regarding the research tool, we used the GEFT test to classify individuals as FD or FI based on critical values. Considering that the GEFT test emphasizes cognitive differences on a continuous scale, it may not be possible to correctly classify individuals between the two endpoints using a threshold value;

Therefore, multiple studies use a third dimension called field mixing to characterize individuals with GEFT scores that are close to the average score of the study sample. However, in this literature, the dichotomy that takes the average score as the critical value is widely adopted. With regard to external effectiveness, it is worth mentioning that many cultural heritage exhibition activities are based on visual appreciation and project collection tasks.

Therefore, we expect that similar findings will be replicated in the context of different activities. Regarding the ecological validity of this study, the exhibition test session was rationalized with a time and date convenient for each participant. The laboratory was converted into an exhibition room, equipped with all the necessary technical resources (MR Mixed reality technology, robotic art, AI painting design technology, stable and high-speed Internet connection).

These devices are powerful enough to support the study without affecting the participants’ experience, even if they perform poorly. Regarding mixed reality technology, none of the participants had ever used it before, so they had a quick demonstration of how to use the new technology. With regard to eye tracking devices, participants usually do not use such devices while watching the exhibition,

Do designers’ decisions related to visual activities affect knowledge acquisition in digital art exhibitions?

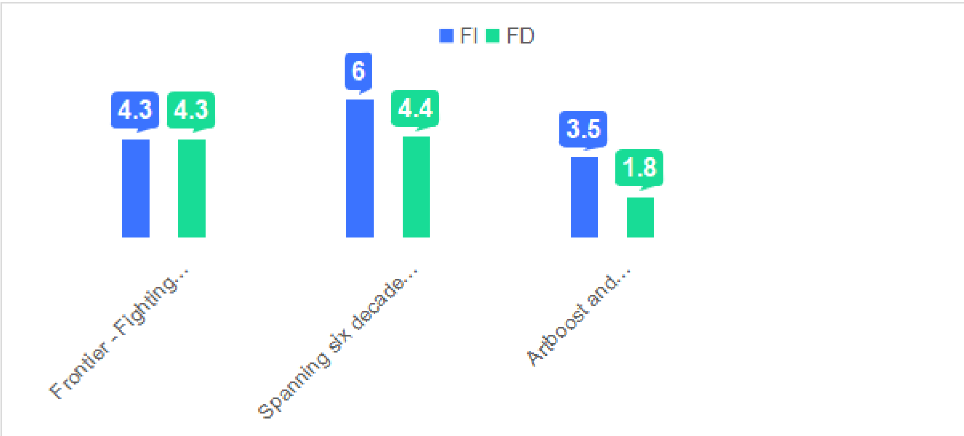

Figure 4: When the exhibition includes free visual appreciation tasks, FI field is dependent on more items than FD field is independent. When the exhibition is based on For structured visual appreciation tasks, we did not find any differences.

But the fact that the device is wearable glasses makes them feel more comfortable after a while because they can interact with the system as usual. At this point, we should mention that due to calibration difficulties or the poor quality of the gaze samples collected, we removed some participants from the analysis, which is discussed in Section 3.5. The research team conducted the study in accordance with the ACM Code of Ethics.

4.RESULTS ON THE EFFECTS OF FD-I

4.1 Effects of FD-I on visual behavior

To investigate H01, we performed statistical tests on indicators of visual behavior: the number and duration of gaze at exhibition objects. With regard to the number of gaze exhibits (Figure 4), we conducted an aMann-Whitney U test for each exhibition experiment. As assessed by visual inspection, the number of exhibition items viewed by FDs and FIs was similarly distributed. The results showed that in the Interactive space of Peking Opera Media Art, the median number of exhibits focused by FIs was significantly higher than FDs (10 vs. 8), (U = 178.400, z= -2.588, p =.008, r =.393). FIs looked at 9.637 ± 2.669 exhibits, while FDs looked at 7.664 ± 2.749 exhibits. For Across Sixty Years: The Creative Fire of Artificial Intelligence, the median number of items viewed by FIs was significantly higher than that of FDs (38 vs. 33), (U = 43.005, z= -3.783, p <.004, r=.628). FIs looked at 38.829 ± 3.444 items, while FDs looked at 33.447 ± 3.124 items. For "Artboost and Drama · Silent Art Hotel jointly present the first 7 environments ·AI Art Exhibition", the audience needs to learn 9 AI painting production projects, so they are watching all the exhibition projects. Taking into account the fixed time of each exhibition item (Figure 5), we conducted an independent sample test for each competition. According to the procedure provided by Templeton, the fixed time values were standardized and each test satisfied the required assumptions. The analysis showed that when visiting the Interactive space of Peking Opera Media Art, FIs focused on game items significantly longer than FDs (FIs: 4.289 ± 1.671 minutes, FDs: 2.870 ± 2.033 minutes, t= 3.017, p=0.027, d=0.768), and also when visiting Across Sixty Years: The Creative Fire of Artificial Intelligence (FIs: 8.038 ± 2.022 minutes, FDs: 6.634 ± 1.049 minutes, t= 2.873, p=0.006, d=0.869), as well as when visiting Artboost and Drama · Silent Art Hotel to present the first 7 Environments ·AI Art Exhibition (FIs: 27.214 ± 4.149 min, fd: 23.615 ± 4.006 min, t = 2.628, p=0.017, d=886).

4.2 Influence of FD-I on interaction behavior

To investigate H02, we performed the Mann-Whitney U test (Figure 6) for each match, satisfying all the necessary assumptions. Analysis of the results showed that for Across Sixty Years: The Creative Fire of Artificial Intelligence, the median number of FI (8 items) was significantly higher than FD (7 items) (FI: 7.961±3.035 items, FD: 6.291± 2.597 items, $U = 210.005$, $z = -2.004$, $p=.034$, $r=.294$). For "Artboost and Drama · Silent Art Hotel jointly present the first 7 Realms ·AI Art Exhibition", the median number of FI is significantly higher than FD (36 items), while FD's median is 30 items.

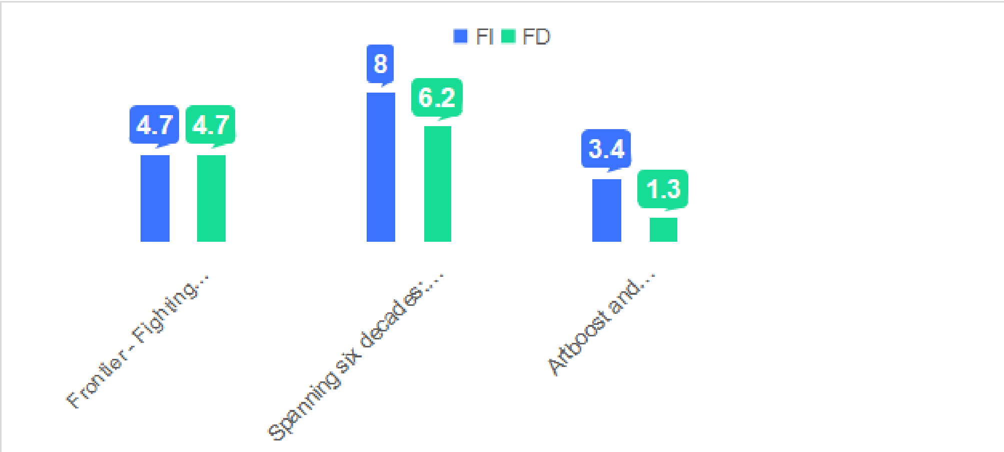

Figure 5: In the free and structured visual appreciation task, FIs focused on game items longer than FDs.

Indicates deeper visual information processing.

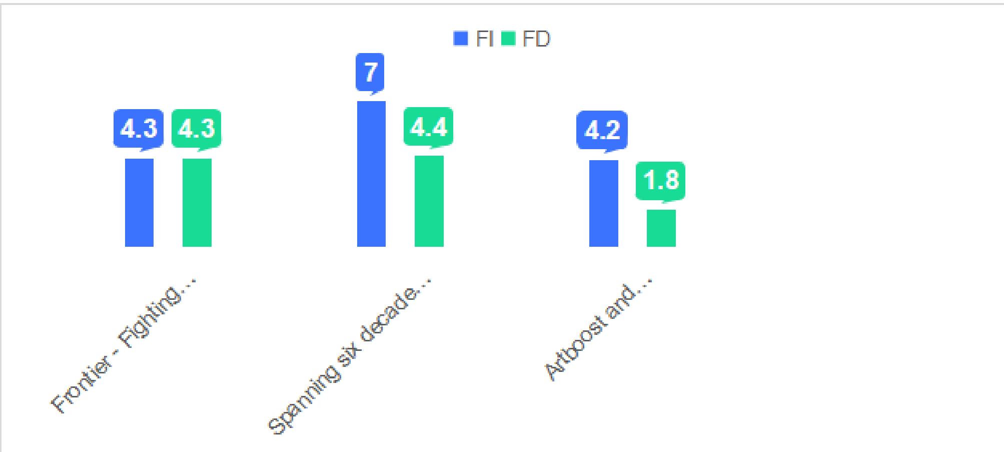

Figure 6:FI collects more items than FD when collecting items is not a mandatory requirement for the visiting method.

4.3 Influence of FD-I on knowledge acquisition

To investigate H003, we performed the Mann-Whitney U test (Figure 7) for each match, satisfying all the necessary assumptions. The analysis revealed that FI(7) had significantly higher median correct answers than FD(5) in Time Over Sixty Years: The Creative Fire of AI (FD: 5.582± 1.246 correct answers, FI: 6.434± 1.298 Correct answer, U= 209.499, z= -2.047, p=.038, r=.300). There was no significant difference in median correct answers between FI(5) and FD(5) for Artboost and Drama · Silent Art Hotel presenting the first 7 Environment ·AI Art Exhibition (FD: 5.164±1.089 correct answers, FI; 5.335± 1.068 Correct answer, U = 234.008, z=-4.48, p=.678). For The Holographic Journey, the median number of correct answers in FI(7) was significantly higher than that in FD(6) (FD: 5.732±0.896 correct answers, FI: 6.829± 1.228, U= 78.499, z= -2.710, p=.009, r=.457). Therefore, FI performs better than FD in the knowledge posttest of exhibitions based on the free visual search task, while there is no significant difference in the performance of exhibitions based on the structured visual appreciation task.

It is worth mentioning that as for each test participant's knowledge of the cultural background of the exhibition they are pointing to, according to the analysis of the answers to the pre-test questionnaire, both FDs and FIs showed low prior knowledge, which is expected. There were no significant differences between FDs and FIs in all the exhibition cases evaluated by the Mann-Whitney U test, which satisfied all the necessary assumptions (across six decades: The Creative Fire of AI: FIs: 401±.315, FDs: 538±.500, U= 297.008, z=.379, p=.708; Artboost and Drama · Silent Art Hotel jointly present the first 7 Environment ·AI Art Exhibition: FIS: 765±.620, FDs: 749 ±.726, U= 297.010, z=.174, p=.859; Beijing Opera media art interactive space: FIS: 1.0075 ±.856, FDs: 587±.466, U = 55.010, z= 1.341, p=.226).

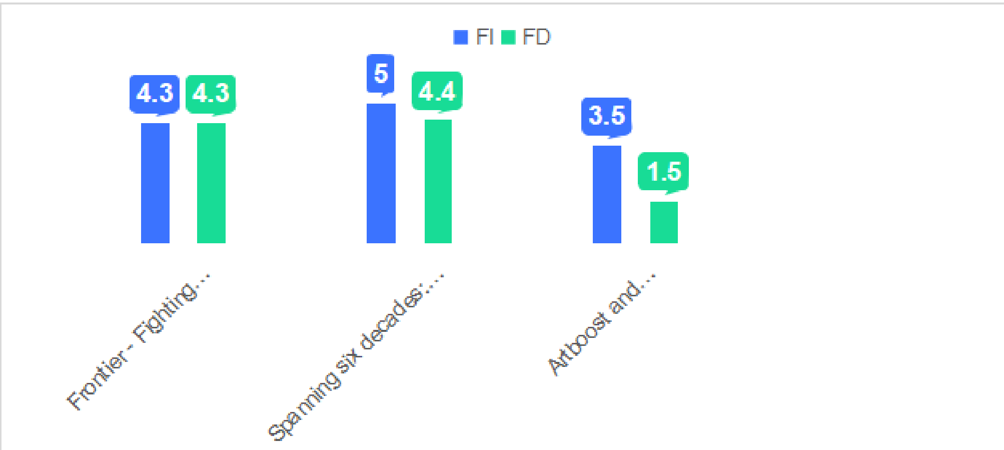

Figure 7:Pre-test and post-test knowledge acquisition (expressed in milliseconds of correct answers) for each exhibition. Before the test it was shown that individuals had the least background and cultural knowledge of each culture, while after the test it was shown that FI performed better than FD.

4.4 Correlation between visual behavior, interactive behavior and knowledge acquisition

To investigate H04, we performed a Pearson correlation test for each match, which satisfied all the required hypotheses. The results of each test (Table 3) are discussed below.

As for the Interactive Space of Peking Opera media art, there is a strong correlation between interactive behavior and knowledge acquisition (r=.571, p=.006). This means that the longer the audience stays with certain exhibits, the more correct answers they get on the post-test questionnaire. Knowledge acquisition is also related to the visual behavior of the audience, as there is a moderate correlation between the number of fixations and the number of correct answers (r=.326, p=.025), and between the time of fixations and the number of correct answers (r=.305, p=.033). In addition, the more times and the longer the audience looked at the exhibition item, the more correct answers they got on the post-test questionnaire. In addition, visual behavior is closely related to interactive behavior, because the more times the audience looks at the exhibit, the more knowledge and information they acquire (r =.755, p =.006).

For Time Spans Sixty Years: The Creative Fire of Artificial Intelligence, there was a moderate correlation between viewer gaze time on robotics and computer art and knowledge acquisition (r=.329, p=.025). This means that the longer the audience looks at computer art, the more likely they are to answer correctly after the test, and the more they learn about artificial intelligence, generative art, robotics, and virtual reality.

With regard to Artboost and Drama · Silent Art Hotel presenting the first 7 Environment ·AI Art Exhibition, there is a moderate correlation between the information acquired knowledge and the number of exhibits watched (r =.338, p =.036), which means that the more exhibits viewed by the audience, the more knowledge acquired. In addition, there is a strong correlation between the amount of knowledge acquired and the number of correct answers after the test (r=.506, p=.001), which means that the more relevant information players acquire, the more likely they are to answer the correct answers to the questions after the test, and thus the more they understand the culture of AI painting technology.

5.INTERPRETATION OF RESULTS

The results discussed below correspond to the research model shown in Figure 1. Thus, they are presented through the interaction of human cognition and visual behavior, human cognition and interactive play, visual behavior and interactive play, and all factors on knowledge acquisition, as shown in Figure 8.

- Curators' decisions about visual appreciation tasks influence the visual behavior of FDs and FIs. FDs and FIs employ different visual strategies in playing free visual appreciation exhibitions (i.e. situations where users are expected to visually appreciate scenes and identify cultural assets but are not forced to). FIs is more focused on cultural game projects (Figure 4), and over a longer period of time (Figure 5) than FD;

Our findings reinforce and validate the results of other studies, as well as our research on the art of digital cultural exhibitions. This behavior is due to the analytical nature of FIs and their ability to visually identify details from the surrounding environment, as they tend to adopt a deeper visual appreciation, scanning the large layout of the exhibition environment. More prolonged gaze means better memory, greater amount of information extracted and accumulated, and attention in visual appreciation tasks. Given that FI is more efficient at retrieving items from memory) than FDs, the fact that they generate more and longer fixations on key display items helps them pay more attention and better understand the information provided for each culture.

Game designers' decisions about visual search tasks affect the game behavior of FDs and Fls. FDs and Fls follow different gameplay (Figure 6)

When exhibiting free visual appreciation tasks, FIs gather more information than FDS because they follow an analytical approach. Fis have an inherent skill in recognizing key visual information because they tend to focus on detail and can easily distinguish it from their surroundings. When looking at the free visual appreciation exhibition, FI is interested in discovering the curatorial scheme, which is the result of their tendency to develop self-deconstructing goals and execute independently outside of the given rules. However, FDs does not interact with many exhibition items when access to knowledge information is not necessary to complete viewing the exhibition. This may be because FDs tends to adhere strictly to the guiding principles and objectives of the exhibition (e.g., entering the last section to receive the seal); As a result, FDs collect fewer items than FIs because this is not your main goal in the exhibition, and they take a holistic information search approach.

The visual behavior of FDs and FIsi influenced their interactive behavior, and in the free visual appreciation task, the user's visual behavior influenced their interactive behavior (Table 3).

The more knowledge items they focus on, the more project information they gain as they interact with the items that capture their attention. In addition, the longer the audience looks at an exhibition item, the more likely they are to interact with it and acquire its cultural information, as increased gaze time indicates greater concentration and attention. Therefore, the curators decided to include knowledge items that would attract the audience's visual attention for a long period of time, influencing their interactive behavior and helping them gain access to a wider range of knowledge information, resulting in increased access to cultural knowledge and implying better learning outcomes.

Both visual and interactive behavior had an impact on knowledge acquisition in the cognitive style group, but Fls inadvertently favored knowledge acquisition in the free visual appreciation and immersion exhibitions. In the free visual appreciation game, F learned significantly more about ancient civilizations than FDs, because they answered more post-test questions correctly (Figure 7).

Users' performance in the post-test was affected by interactive and visual behaviors (Table 3). The inclusion of free visual appreciation tasks in design decisions, and the inherent difficulty of FDS in recognizing simple details in complex visual environments, lead FDS to focus on collecting fewer critical knowledge items, which hinders their acquisition of knowledge and ultimately affects learning benefits.

6.DISCUSSION AND REVELATION

Our findings suggest that specific design decisions associated with digital visual activities inadvertently influence interactive behavior and thus knowledge acquisition for individuals with different cognitive characteristics. Considering that the increasing use of digital technologies in the field of art and culture exhibitions makes the evaluation process necessary, such evaluation studies, such as the one described here, take into account the multidimensional nature of the field of art and culture and the cognitive characteristics of its users (such as visitors) to guide the research to explore undiscovered paths. Taking human cognition as an evaluation factor reveals the root cause of unbalanced knowledge acquisition when performing cultural and art exhibition activities involving information processing tasks. Therefore, evaluators should consider the individual cognitive characteristics of visitors when conducting cognitive-centered assessment, which can help them better evaluate the objectives of cultural and art exhibition activities.

Returning to the assessment studies discussed in this article, if our party had used FD-cognitive style as an assessment factor, we might have observed average knowledge acquisition in free visual viewing tasks, but could not understand the root cause of the observed results. This can lead not only to inaccurate interpretations of research findings, but also to faulty design recommendations and guidelines (for example, avoiding free visual appreciation tasks). By using cognitive characteristics as assessment factors, we reveal new dimensions of individual diversity through factor analysis and gain a deeper understanding of why activities meet (or fail to meet) their goals.

A "one size fits all" approach is not the best way to deliver meaningful cultural experiences to the end audience. Through cognitive-centered assessment, cultural heritage stakeholders will not only be able to identify differences in knowledge acquisition among users with different cognitive characteristics when interacting with cultural heritage resources, but also understand the reasons behind these differences and better interpret them. Cognitive-centered assessments therefore point to the importance of considering how the type of task (e.g., free or structured modes of visual appreciation) better fits each exhibition environment and user cognitive characteristics, especially within the field of cultural exhibitions. However, in some cases, an imbalance in knowledge acquisition may be related not only to the visualization of the content or the type of task, but also to other factors, such as the content itself. For example, for those who process visual information more effectively than verbal information (such as visual-linguistic cognitive styles), content should be provided in graphical form; For those who process verbal information more effectively than visual information, of course, the content should be provided in text form. Activity types should also be considered as evaluation parameters because different types of activities benefit individuals with different cognitive characteristics. It is worth mentioning that the effects discussed apply not only to digital art cultural exhibitions, but also to cultural heritage activities that include information processing tasks, such as virtual Tours and guided Tours, which have also been shown to be influenced by cognitive characteristics. In addition, in our study, we only focused on visual interaction; However, cultural heritage activities can also include audio - and space-based interactions, such as storytelling and location-aware applications. Therefore, it is necessary to investigate whether other cognitive characteristics, such as auditory cognitive style, affect the audience's behavior and experience in such situations. The lessons learned from our research are as follows:

Cognitive-centered digital culture exhibition activities and resource evaluation help us better understand the underlying causes of different behavior patterns among individuals with different cognitive characteristics.

Cognitive-centered evaluation connects information processing methods (e.g., visual information seeking, information understanding) with different aspects of human cognition (e.g., style, skills) to help us effectively evaluate the final audience experience and suggest ways to improve it based on the audience's cognitive preferences and needs.

The evaluation of the Cognitive Center points out the importance of considering the type of task (e.g. free or structured visual search) that is more appropriate to the context of each exhibition project and the cognitive characteristics of the audience in the field of cultural heritage.

The cognitive-centered evaluation takes into account all aspects of digital cultural heritage resources, as it is closely related not only to the types of tasks, but also to the mechanisms of visualization, types of high-level activities, modes of interaction, etc.

Cognitive-centered assessment contributes to a deeper understanding of the importance of the assessment process and its necessity, aiming to have a better impact on the short - and long-term experience of the end audience. This is especially important given that cognitive traits, such as cognitive styles, rarely change over a person's lifetime.

In human-centered curatorial design, evaluation is used to drive the optimization of design or information systems. Therefore, we assess that the interpretation of research results can lead to the formation or optimization of specific recommendations and rules for designing and adapting cultural heritage activities to support the diverse information processing needs of audiences with different cognitive characteristics and to best serve their information understanding and knowledge acquisition. Focusing on the FD-I cognitive style, FDs has difficulty recognizing details in complex visual environments and therefore may miss valuable information when performing free visual appreciation tasks. Therefore, in activities based on free visual appreciation tasks, the system should be designed to help FDs acquire such information. This can be achieved by employing a variety of techniques: a focus on a specific area of interest, which can be applied when the FD user approaches a knowledge item within a predetermined distance.

Considering that FDs benefits or has a significant effect when information is provided in light color recolor, such alternative visualizations can be provided for event items/areas that provide critical information about the civilization/culture that the event is showcases.

In order to increase gaze time and focus the viewer's attention on key areas of interest, the entire scene can be blurred, except for known knowledge items. Blurring effects is a sufficient technique to keep the audience

The system can support a sequential dual-track approach for supporting both structured search and free appreciation tasks. In this approach, all tasks are initially based on structured viewing until a certain threshold is reached. This threshold can be a collection of specific items, a collection of a predefined number of items, and so on. Once the threshold is exceeded, the task transforms into a visual free-viewing task designed to stimulate the user's sense of self-efficacy and autonomy, thereby facilitating the knowledge acquisition process.

- In project collection activities, some items are important for users to build knowledge, while others are complementary. Therefore, the collection of important items can be based on structured search, while the collection of complementary items can be based on free search.

Thus, the evaluation studies reported in this paper provide insights into which mechanisms enable users with different cognitive characteristics to better meet activity goals. Considering that certain types of tasks may not benefit users with specific cognitive characteristics, appropriate assistance mechanisms can be introduced to ensure that the audience finds the intended content. In order to support these diverse mechanisms, cultural and art exhibitions should provide adaptive interventions aimed at specific cognitive characteristics to enable personalized access to cultural information. Cultural heritage activities should be adapted to the cognitive characteristics of each user. This adaptation can be achieved through the use of different technical means. Following a rule-based adaptation approach, rules implement visual information functions and content presentation mechanisms, tailored to the cognitive characteristics of the audience. These rules are derived from studies like the one reported here. For example, in a free visual appreciation task, recolor or highlight effects can be applied to knowledge items while the FD user performs the activity. Cognitive-centered assessments thus construct rule-sets that can be used to accommodate the unique cognitive preferences and needs of cultural activities.

Given the nature of the field of cultural and art exhibitions, many visitors are considered first-time visitors because they are interacting with digital cultural heritage resources for the first time (and possibly the only time in their lives). We note the importance of runtime and dynamic adaptation of cognitive-focused interventions in digital cultural heritage activities. In order to provide this run-time cognitive center personalization activity, it not only ADAPTS to the cultural heritage activity at run time (which has been adequately addressed in other works in the field of cultural heritage), but also acquies the user's cognitive characteristics (e.g. cognitive style) in real time at the initial stage of the activity, when the audience experience is not yet fully formed. To adapt the content and seamlessly, ensuring that the adaptation mechanism does not affect the established user experience. Given that current extraction tools (such as GEFT) are not suitable for runtime adaptation because they are based on explicit and time-consuming processes that require manual work, we can use eye tracking methods to implicitly reveal the cognitive characteristics of the audience in the early stages of the exhibition, as our research shows that there is a correlation between visual behavior and cognitive characteristics. This revelation can be done at the tutorial level before the audience begins to play the cultural heritage game, so as not to affect the viewing experience.

Finally, the high-level implication of our study is that a cognitive-centered framework must be adopted for design and evaluation purposes. The framework inspires, stores and maintains cognitive-centered user models through implicit extraction and cultural activities based on the output of recommendations and rules from evaluation studies, as described here, with the aim of providing each visitor with an optimized personalized cultural heritage experience. A cognitive-centred framework will help evaluators effectively evaluate digital cultural heritage exhibition activities, resulting in a better understanding of end-user interactions and highlighting differences in information-seeking approaches that can lead to imbalances with the objectives of the activities; Designers are able to create personalized cultural heritage activities that meet the unique cognitive characteristics of end users; As a result, the audience will have a better experience, a deeper understanding of the information presented, increased knowledge acquisition and, ultimately, improved learning benefits. Taking into account the involvement of multiple stakeholders in the field of cultural heritage (e.g., visitors, evaluators, designers, curators, institutions), the Cognitive Centre framework is expected to be able to identify the needs and interests of each stakeholder in the ecosystem, as well as the interdependencies, and to provide the most appropriate and impactive cultural heritage activities.

Do curators' decisions about visual activities affect knowledge acquisition in digital art exhibitions

Table 3:Correlation matrix

"Bordering-fighting" Peking Opera media art interactive space					
Measurement Type	Indicators	(1)	(2)	(3)	(4)
1 Visual behavior	fixed number of exhibitions	1			
2	Fixed time	r= .182 p= .212			
3 Interactive behavior	acquisition knowledge evaluation	r= .753 p= .002**	r= .132 p= .360		
4 Knowledge to obtain	the correct answer numbe	r = .324 p = .022*	r = .301 p = .034*	r = .571 p = .006**	1

Spanning six decades: The creative Fire of artificial Intelligence				
Measurement Type	Indicators	(1)	(2)	(3) (4)
1 Visual behavior	fixed number of exhibitions	1		
2	Fixed time	n/a 1		
3 Interactive behavior	acquisition knowledge evaluation	n/a	n/a 1	
4 Knowledge to obtain	the correct answer numbe	n/a r=.331n/a	1 p=.028*	

Artboost and Youxi Mo Art Hotel jointly presented the first 7 environment AI art exhibition				
Measurement Type	Indicators	(1)	(2)	(3) (4)
1 Visual behavior	fixed number of exhibitions	1		
2	Fixed time	r= .1353		
3 Interactive behavior	acquisition knowledge evaluation	r= .344 r= .147 p= .028* p= .392	1	
4 Knowledge to obtain	the correct answer numbe	r= .294 r= .179 p= .080 p= .297	r= .505 p= .002** 1	

The correlation was significant at the 0.05 level (two-tailed).

The correlation is significant at the 0.01 level (2-tailed).

n/a. Since at least one variable is a constant, it cannot be calculated.

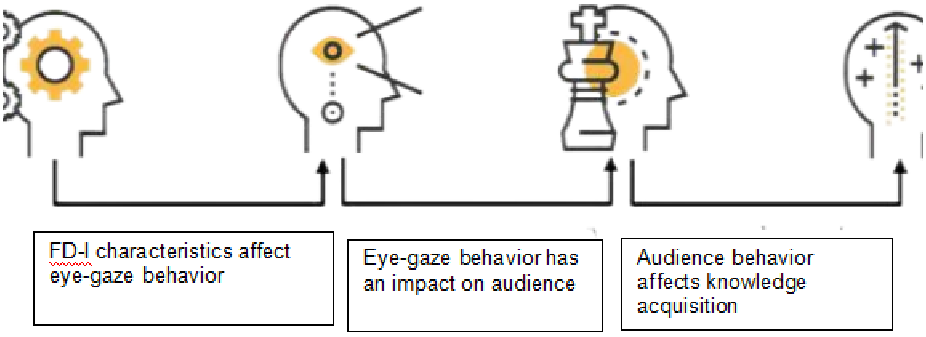

Figure 8: Players' perception of FD-I characteristics influenced their visual and game behavior, and thus had an impact on the knowledge acquisition process.

7.CONCLUSIONS

In this paper, we assess whether and how the decisions of different curators regarding visual appreciation activities affect the acquisition of knowledge in digital art exhibitions, adopting a human cognitive perspective. We conducted three intersubject eye tracking user studies. A total of 149 participants were classified as either FD or FI based on their performance on the GEFT. For each study, participants were divided into two groups according to their cognitive style and visited several popular digital art exhibitions (" Linjing - Fighting "Peking Opera Media Art Interactive Space" : N= 59; Across Sixty Years: The Creative Fire of Artificial Intelligence: N=47; "Artboost and Drama · Silent Art Hotel jointly present the first 7 Environments ·AI Art Exhibition" N=43).

Quantitative analysis shows that curators' decisions about visual search favor FI, while hindering FD's knowledge acquisition. In particular, in free visual viewing tasks (that is, tasks in which the audience visually explores the scene and interacts with the item without being forced by activity rules), FD and FI take different approaches to processing visual information, leading to unintentional knowledge acquisition imbalances.

However, in a structured visual search task (where the rules of the event force players to visually search and collect a specific number of items), there is no understanding of the knowledge imbalance between FD and FI, as all viewers are required to view the same display items and thus access the same level of critical information.

The findings highlight the impact of human cognition on viewing visual information in the context of digital culture and art, and the need to support individuals with specific cognitive characteristics, such as FDs, to engage in interactive activities including information search and understanding tasks. Stakeholders of cultural heritage should consider the cognitive characteristics of individuals during the design and evaluation phase, aiming to provide audiences with personalized access to cultural information and help them enhance learning benefits and experiences. We envision that cognitive-centered personalization mechanisms can be used by stakeholders of digital cultural arts to adapt to cultural experiences.

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Cognitive characteristics of the audience (e.g., museum visitors). This personalization mechanism will alleviate the observed imbalance and help audiences improve knowledge acquisition when participating in digital cultural and art exhibitions. Given that we are moving toward more immersive technologies (e.g., mixed reality), we expect this cognitive-focused personalized experience to further help users, as these technologies have been found to amplify the effects of cognitive differences.

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Exploring New Media Art Exhibition Aesthetic Preferences Through the Unified Model of Aesthetics

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Abstract
Based on the Unified Model of Aesthetics (UMA), this study investigates the impact of opposing factors on aesthetic preferences in new media art exhibitions across three dimensions: perceptual, cognitive, and social. Using the Linjing·Dou Peking Opera Media Art Interactive Space as a case study, 203 Chinese audiences were surveyed via a 7-point Likert scale. Results indicate that: 1) Perceptual unity, cognitive cultural typicality, and social interactive connectedness positively influence aesthetic preferences; 2) When measuring opposing factors through the UMA model, the cognitive dimension exerts the strongest impact on aesthetic judgment, followed by the social dimension, with the perceptual dimension showing the weakest effect. This research provides interdisciplinary theoretical support for new media art curation.

Keywords
Aesthetic preferences; Unified Model of Aesthetics (UMA); New media art; Cultural dissemination

1.INTRODUCTION

New media art exhibitions are increasingly becoming central to contemporary cultural experiences. Their aesthetic value extends beyond visual presentation to profoundly influence cognitive engagement and social interaction efficacy. Market data reveals that the global immersive art exhibition market reached $12.7 billion in 2023, with audience retention rates 43% higher than traditional exhibitions (Arts Economics, 2023). This appeal originates from the neural reward mechanisms of multisensory aesthetic experiences—when audiovisual and tactile stimuli achieve cross-modal synergy, activation intensity in the prefrontal multisensory integration zone increases by 2.8-fold (Stein et al., 2020), triggering stronger emotional resonance. However, current curatorial practices face a critical paradox: 62% of attendees report cognitive fatigue due to sensory overload (Chen et al., 2022), exposing fundamental flaws in purely technology-driven aesthetic strategies.

The theory of aesthetic preferences has undergone three paradigm shifts, gradually revealing multidimensional decision-making mechanisms. Early Gestalt theory (Wertheimer, 1923) emphasized perceptual organization principles but struggled to explain dynamic interactions in new media art. Berlyne's (1971) novelty-complexity model introduced arousal concepts but neglected cultural context's regulatory role in cognitive evaluation. The Unified Model of Aesthetics (UMA) (Hekkert, 2014) broke new ground by integrating perceptual (unity/variety), cognitive (typicality/novelty), and social (connectedness/autonomy) dimensions into a cohesive framework for analyzing complex aesthetic phenomena. However, its validation has predominantly focused on industrial design, revealing limitations in cultural product applications—particularly in addressing high-autonomy creations that disrupt traditional typicality (e.g., user-generated content deconstructing prototype features).

Three theoretical gaps persist: First, perceptual diversity measurements still rely on static visual elements (e.g., color contrast, geometric complexity), failing to capture cross-modal gain effects in dynamic interactions (Knoop et al., 2021). Second, cognitive novelty assessments continue to use the MAYA threshold for closed-category products (Hekkert et al., 2003), lacking dynamic models for cultural prototypes' elastic recognizability. Third, social autonomy research predominantly employs unidirectional individual decision-making metrics (e.g., autonomy satisfaction scales) (Blijlevens & Hekkert, 2015), inadequately revealing the dynamic balance between autonomy and connectedness. While UMA demonstrates robust explanatory power in industrial design (Hekkert, 2014), its applicability to new media art interactive spaces remains fundamentally questionable due to media ontology differences: Traditional product aesthetics rely on static gestalt perception (e.g., furniture symmetry), whereas new media art prioritizes emergent aesthetics from dynamic interactions (Kwastek, 2013). When users transition from passive observers to co-creators, UMA's dimensional relationships may undergo structural reorganization.

2.THEORETICAL BACKGROUND

2.1Development of Aesthetic Preferences

The study of aesthetic preferences is one of the oldest topics in psychology, tracing its origins to ancient Greek philosophy. Early explorations in this field were grounded in the works of Plato and Aristotle (Phillips et al., 2011; Whitfield & de Destefani, 2011). Prior to the 19th century, aesthetic research primarily relied on philosophical deduction. A pivotal shift occurred in 1876 when Gustav Fechner pioneered experimental aesthetics, introducing systematic scientific methodologies to aesthetic inquiry. The emergence of experimental aesthetics marked the transition of aesthetic studies from purely philosophical speculation to empirical science, gradually establishing itself as the dominant research paradigm in modern psychology (Suhaimi et al., 2023). Fechner's early work focused on traditional «highbrow» arts such as painting, sculpture, and architecture. Over time, the scope of aesthetic research expanded to encompass «lowbrow» domains with utilitarian aesthetic features, such as product design (Suhaimi et al., 2023).

Following Fechner, experimental aesthetics underwent continuous theoretical refinement, with researchers striving to identify core factors linked to aesthetic pleasure. Against this backdrop, the Unified Model of Aesthetics (UMA) emerged, integrating multiple critical aesthetic elements in product design to establish a comprehensive theoretical framework (Yahaya, 2017). Rooted in Darwin's theory of evolution (Darwin, 1859), UMA reinterprets its core principles through a modern lens, framing human aesthetic instincts as evolutionary adaptations. According to this model, humans assess environmental cues to determine whether they signal safety or danger, with higher processing fluency of information eliciting stronger positive aesthetic responses (Reber et al., 2004). This perception-based aesthetic pleasure functions as an evolutionarily-driven mechanism, reflecting humanity's equilibrium between safety and achievement needs. Numerous studies highlight that individuals perpetually seek this balance across perceptual, cognitive, and social dimensions to attain optimal aesthetic experiences (Blijlevens & Hekkert, 2015; Hekkert et al., 2003; Post et al., 2013).

2.2Perception dimension: unity and Variety

Aesthetic preferences at the perceptual level are shaped by the interplay of unity and variety. Unity provides coherence and consistency to aesthetic experiences, while variety enriches objects with complexity and allure. According to UMA, perceptual unity forms the foundation of aesthetic preferences, enabling individuals to rapidly comprehend and accept aesthetic objects (Zhang et al., 2023). Neurologically, unity correlates with efficient information processing by the brain; unified structures are more easily recognized and processed by the visual system, eliciting positive aesthetic responses (Gruen, 2015). However, variety remains indispensable, satisfying the need for novelty and stimulation. Studies show that aesthetic appreciation peaks when unity and variety achieve optimal balance (Rodway et al., 2016). This equilibrium manifests across domains: In product design, adjusting elements of unity and variety enhances attractiveness (Kiiski et al., 2016); in web design, symmetry (unity) and color richness (variety) jointly improve aesthetic judgment (Aleemi et al., 2020). This balance extends beyond visual art to music (melodic unity vs. rhythmic variety) and environmental design (natural unity vs. artificial variety), demonstrating that optimized information processing and perceptual experiences universally elevate aesthetic appeal.

2.3Cognitive dimension: Typicality and Novelty

Typicality and novelty at the cognitive level critically determine aesthetic preferences. Typicality offers familiarity and acceptability, while novelty stimulates cognitive interest and exploration. The MAYA principle ("Most Advanced Yet Acceptable") posits that the balance between typicality and novelty drives aesthetic preferences (Xue, 2018). Neurologically, typicality aligns with the brain's rapid recognition of familiar information, evoking positive emotional responses (Jiang et al., 2023). Novelty, conversely, activates the brain's sensitivity to new stimuli, triggering deeper cognitive engagement (Santosa et al., 2018). Domain-specific variations exist: In ceramic design, typicality dominates (Post et al., 2016), while industrial products show smaller typicality effects for high-functionality items (Post et al., 2017). Clothing design requires balancing both factors—typicality predicts preferences for pants and jackets, whereas shirts demand novelty-typicality equilibrium (Berghman et al., 2017). Perceived novelty also correlates with complexity and mystery, amplifying aesthetic appeal (Loos et al., 2022). Contextual factors like visual complexity, viewer expertise, and environmental settings further modulate these effects (Ma et al., 2025; Makin et al., 2018). Thus, typicality and novelty balance familiarity and innovation, fulfilling cognitive and emotional needs to enhance aesthetic value.

2.4 Social Dimension: Social Connectedness and Autonomy

Social connectedness and autonomy constitute critical social dimensions of aesthetic preferences. Social connectedness emphasizes the influence of sociocultural environments on aesthetic judgments, while autonomy reflects individual independence in aesthetic decision-making. According to the Unified Aesthetic

Model (UMA), social connectedness significantly enhances aesthetic preferences (Che et al., 2018). Neurocognitive studies reveal that social connectedness correlates with the brain's sensitivity to communal signals, where social rewards (e.g., cultural belonging) modulate aesthetic experiences (Huang et al., 2020). For instance, individuals' aesthetic evaluations of artworks are profoundly shaped by art critics' evaluations or perceptions of the artist's warmth (Gauvrit et al., 2017). Cultural contexts further sculpt aesthetic preferences, as distinct sensory inputs and social reinforcement mechanisms foster divergent aesthetic values across populations (Watts, 2019).

However, autonomy remains equally vital. Personality traits—particularly openness to experience—significantly predict aesthetic preferences, with higher openness linked to preferences for complex and novel art forms (Qi, 2022). Socioeconomic status also modulates preferences: individuals with lower status often favor intricate designs perceived as embodying greater effort and value (Lee, 2017).

In new media art exhibitions, balancing connectedness and autonomy is paramount. On one hand, exhibitions must leverage social interaction and cultural contextual guidance to amplify collective aesthetic engagement. On the other hand, they must preserve individual autonomy by offering diverse aesthetic choices. This equilibrium not only satisfies social needs but also stimulates creative aesthetic exploration. Ultimately, the interplay between social connectedness and autonomy reflects the dual forces of cultural influence and personal agency, co-shaping rich aesthetic experiences.

Current studies frame aesthetic preferences as outcomes of multidimensional interactions, yet their paradigms remain constrained by binary opposition variables (e.g., unity/diversity) applied to closed-category artifacts. Research on open-category artifacts (e.g., digital art) lacks systematic deconstruction and comprehensive analytical models. This theoretical impasse is acutely evident in UMA, which attempts to integrate perceptual (unity/diversity), cognitive (typicality/novelty), and social (connectedness/autonomy) dimensions. However, its binary framework struggles to explain multidimensional conflicts in highly open cultural products like new media art. Openness-closure exists on a continuum: closed themes align with safety needs, while open themes prioritize achievement needs. Consequently, reducing variables to binary oppositions oversimplifies complex dynamics.This study selects the Peking Opera New Media Art Exhibition as its experimental locus—a "hyperliminal negotiation field" where cultural archetypes collide with digital mediation. The exhibition's three openness properties provide ideal conditions for theoretical validation: 1) Each openness property corresponds to a specific UMA dimension (perceptual/cognitive/social), preventing cross-contamination. 2)Triangulated Verification: Combines objective behavioral data (e.g., narrative path selection logs) with subjective Likert-scale responses. 3)Transforms cultural openness into quantifiable experimental variables, extending UMA's empirical scope.This design enables independent manipulation and cross-validation of tri-level variables. Grounded in evolutionary aesthetics and neural plasticity theory, three competing hypotheses are proposed:

H1: At the perceptual level, new media art installations with the strongest multisensory impact will be prioritized.

H2: At the cognitive level, higher novelty will correlate with greater preference for installations.

H3: At the social level, installations balancing autonomy and connectedness will dominate user choices.

3. METHOD

3.1Stimuli.

The study focuses on the «Immersion·Fight·—Peking Opera Media Art Interactive Space» as its primary research object. This exhibition employs new media technologies such as digital projection, motion-sensing interactive installations, and immersive theater systems to reimagine the artistic experience of Peking Opera. Guided by the tripartite theoretical framework of the Unified Aesthetic Model (UMA), the research team selected 10 representative exhibition units as experimental stimuli, categorized across three dimensions: the perceptual layer (unity and diversity), the cognitive layer (typicality and novelty), and the social layer (connectedness and autonomy). To minimize confounding variables, all exhibition units underwent standardized processing. First, video parameters were uniformly adjusted using Adobe Premiere Pro to ensure consistency in luminance (150 cd/m²), color temperature (6500K), and resolution (4K UHD). Second, interaction logic was reconstructed in the Unity engine, with motion-response latency calibrated to a range of 80–120 milliseconds. Finally, spatial installations were topologically optimized in Cinema 4D to eliminate material discrepancies. To address potential cultural cognitive biases, pre-experimental screening identified universally recognizable visual symbols (e.g., facial mask patterns, water-sleeve movements) while excluding region-specific stylized elements. This systematic design of multimodal stimuli preserves the technological essence of new media art while ensuring measurable experimental variables aligned with UMA's dimensions.

Figure1:Eight exhibition area designs

3.2Participants.

The study recruited 203 naturally visiting local audience members in Beijing, with 197 valid samples retained after on-site convenience sampling and occupational screening. Participants were exclusively from Beijing, encompassing diverse groups such as university students, faculty, local residents, and educational tour members. University participants were recruited through non-targeted channels at institutions like the Beijing Institute of Graphic Communication, while residents and tour members voluntarily enrolled at the exhibition site. The sample spanned ages 7–65, with occupational backgrounds including education, technology, and service industries, demonstrating significant heterogeneity.

To ensure data objectivity, professionals such as theater practitioners and digital artists were excluded, as their expertise might predispose judgments about interactive design, aesthetic expression, or cultural interpretation, thereby skewing perceptions of immersive Peking Opera experiences among general audiences. All participants had no systematic training in Peking Opera, ensuring their feedback authentically reflected non-specialists' receptiveness to innovative cultural dissemination models.

3.3Procedures

The study employed on-site convenience sampling to evaluate the exhibition experience of "Immersion·-Fight·—Peking Opera Media Art Interactive Space." Data collection was conducted within the exhibition's physical environment through collaboration between the research team from the Beijing Institute of Graphic Communication and venue staff. Prior to implementation, ethical review materials were submitted to the exhibition partner, the National Peking Opera Company, via the university's administrative channels. Formal authorization was obtained before trained research assistants distributed paper-based informed consent forms and questionnaires on-site.

The questionnaire adopted a dual-module structure designed to integrate participant screening with core variable measurement. The first module collected demographic data, including age and occupation, and incorporated a two-stage screening mechanism to exclude individuals engaged in theater, art, or cultural research through the question "Are you professionally involved in drama/arts/cultural studies?" Additionally, the "visit motivation" section included an "academic research/industry evaluation" option to filter out participants with potential expert perspectives, ensuring the final sample focused on non-specialist audiences.

The second module focused on multidimensional perceptual evaluation of the exhibition, comprising 24 core measurement items. Participants evaluated eight key interactive zones—such as the "Eternal Heritage" projection curtain, "Essence of National Treasure" thematic display, and "Stellar Constellation" digital screen—based on real-time experiences. Each zone was assessed through three 7-point Likert scale statements measuring perceptual, cognitive, and social dimensions. The scale development drew from Blijlevens et al.'s (2014, 2017) experiential aesthetics framework. To ensure cross-cultural measurement precision, the questionnaire underwent rigorous bilingual adaptation: the original Chinese (Simplified) version was designed by two drama studies PhD candidates, followed by professional translation into English. Key terms such as "stylized movements" and "vocal systems" were standardized according to the Dictionary of Chinese Opera and Quyi to mitigate cultural interpretation biases.

4.RESULTS

The study ultimately collected 197 valid questionnaires. All participants were non-design and non-operatic professionals, with a balanced gender distribution: 96 males (48.7%) and 101 females (51.2%). Participants ranged in age from 7 years and older, distributed as follows: 52 individuals under 18 (26.39%), 24 aged 18–26 (12.18%), 68 aged 27–44 (34.51%), 30 aged 45–60 (15.22%), and 23 over 61 (11.67%).

As a digital cultural innovation project, "Immersion·Fight·—Peking Opera Media Art Interactive Space" targets audiences that bridge intergenerational cultural transmission and age-specific adaptability of digital media. The data reveals a multi-generational composition: the largest proportion (34.51%) represents the core 27–44 age group, which aligns with the primary users of digital interactive technologies. Simultaneously, the inclusion of culturally curious adolescents (26.39%) and culturally engaged seniors (26.89% combined for 45+ age groups) addresses the imperative for intergenerational dialogue in innovative cultural dissemination. This age distribution demonstrates the exhibition's successful adaptation to diverse demographic needs, balancing technological accessibility with heritage preservation objectives.

Table 1:Analysis of Variance (ANOVA)

	dfNUM	dfDEM	Epsilon	F	p	ηp^2
Pleasing to see	7	1372	1.000	45.23	<0.001	0.15
Unity	7	1372	1.000	8.17	<0.001	0.04
Variety	7	1372	1.000	35.29	<0.001	0.18
Typicality	7	1372	1.000	10.08	<0.001	0.05
Novelty	7	1372	1.000	25.64	<0.001	0.12
Connectedness	7	1372	1.000	18.71	<0.001	0.09
Autonomy	7	1372	1.000	17.89	<0.001	0.08

Repeated-measures analysis of variance (ANOVA) was conducted to examine response differences across the eight exhibition zones of "Immersion·Fight·—Peking Opera Media Art Interactive Space" on each 7-point Likert scale. Table 1 presents the ANOVA results for all scales, revealing statistically significant differences ($p < 0.001$) across all stimulus scales.

Additionally, ANOVA was employed to analyze the relationships between age, gender, and aesthetic pleasure, testing whether participant responses varied by demographic factors. Results indicated negligible interaction effects between age, gender, and aesthetic pleasure, as evidenced by extremely low partial eta-squared values ($\eta^2\_p < 0.01$). Given the trivial effect sizes, these variables were excluded from subsequent repeated-measures ANOVA and generalized estimating equations (GEE) analyses. Table 2 summarizes the ANOVA results for the aesthetic pleasure scale.

Table 2:Analysis of Variance (ANOVA)

	Sum of Squares	dfNUM	dfDEM	Mean Square	F	p	ηp^2
Pleasing to see	1124.73	7	1372	160.68	45.23	<0.001	0.150
Pleasing to see x Age Range	52.18	28	1372	1.86	0.52	0.975	0.009
Pleasing to see x Gender	16.34	7	1372	2.33	0.66	0.705	0.003
Pleasing to see×Age Range×Gender	43.72	28	1372	1.56	0.44	0.991	0.008

Additionally, estimated marginal means were derived for each scale through repeated-measures ANOVA. Figures 2, 3, and 4 display the estimated marginal means and corresponding exhibition zones for the Aesthetic Pleasure, Unity-Diversity and Typicality, and Novelty-Connectedness scales, respectively. For the Aesthetic Pleasure scale, the Splendid Attire MR Interactive Zone received the highest score (6.83), while the Stellar Constellation Digital Screen Zone scored the lowest (3.19). Other zones' ratings fell between these extremes. In the Unity-Diversity scale, the Splendid Attire MR Interactive Zone and Havoc in Heaven Immersive Experience Zone ranked highest (6.43 and 6.24, respectively), whereas the Stellar Constellation Digital Screen Zone remained the lowest (3.48).The estimated marginal means were further calculated for six predictors (unity, diversity, typicality, novelty, connectedness, autonomy). Results demonstrate that the Splendid Attire MR Interactive Zone achieved the highest scores in diversity, novelty, connectedness, and autonomy, but lower scores in unity and typicality. For example, Figures 3 to 5 illustrate the estimated marginal means across the six predictor scales.

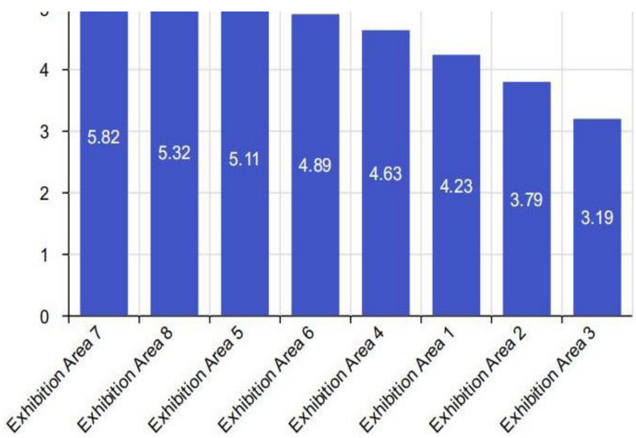

Figure 2:This figure shows the estimated marginal means for the 'pleasing to see' scale with the attached eight exhibition areas designs.

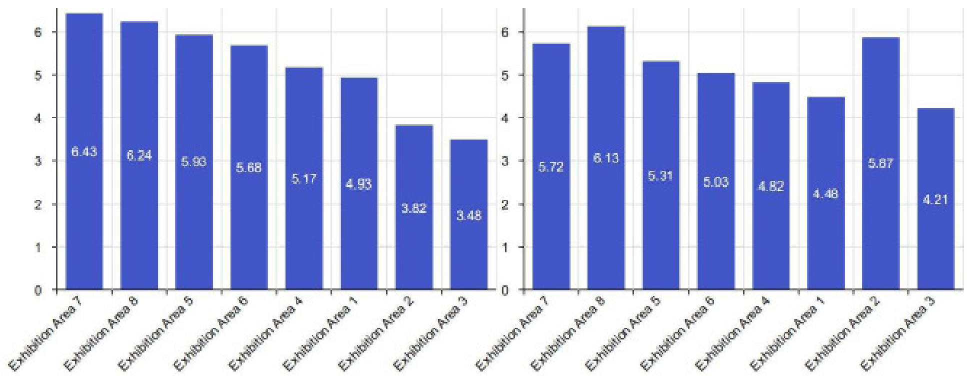

Figure 3:This figure shows the estimated marginal means of the unity and variety scale across eight exhibition areas designs.

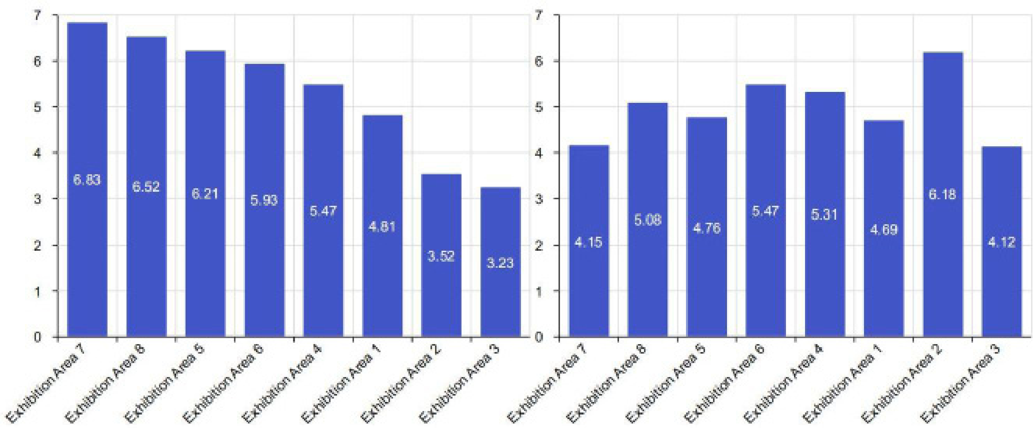

Figure 4:This figure shows the Estimated Marginal Means of the typicality and novelty scale across eight exhibition areas designs.

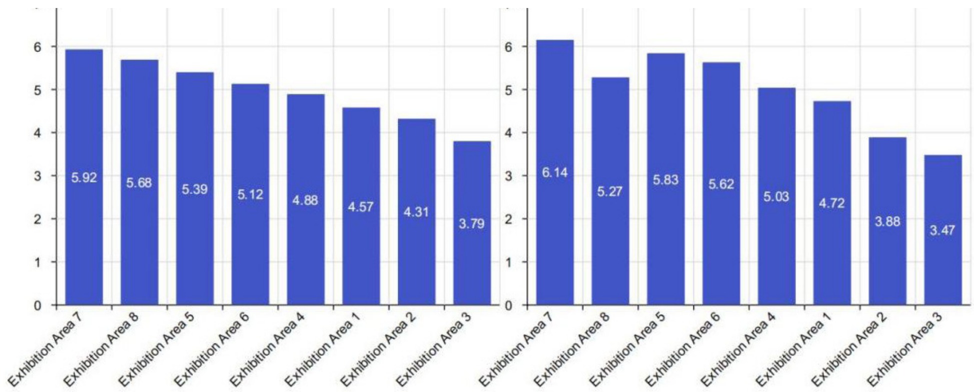

Figure 5:This figure shows the estimated marginal means of the connectedness and autonomy scale across eight exhibition areas designs.

Generalized estimating equations (GEE) were calculated to determine the predictive strength of each independent variable in explaining the dependent variable. The dependent variable in this study was aesthetic pleasure, with all other scales serving as predictors. The obtained beta coefficients confirmed the effect sizes derived from partial eta-squared (η^2_p) results. Diversity ($\beta = 0.42$) and novelty ($\beta = 0.38$) exhibited the strongest predictive effects on aesthetic pleasure, followed by unity ($\beta = 0.35$) and connectedness ($\beta = 0.21$). Typicality and autonomy demonstrated the weakest effects. These findings suggest that, when accounting for the combined influence of factors at the same analytical level, perceptual-level variables (unity, diversity) exert greater influence than cognitive (novelty, typicality) and social (connectedness, autonomy) variables. Detailed results are presented in Table 3.Complementing these findings, Pearson correlation coefficients (Table 4) revealed significant positive relationships between aesthetic pleasure and diversity (r = 0.62***), novelty (r = 0.58***), unity (r = 0.41***), connectedness (r = 0.36***), and autonomy (r = 0.39***), further validating the conclusions.

in summary, in Immersion·Fight·—Peking Opera Media Art Interactive Space, distinct exhibition zones excel across different measurement scales. Factors such as diversity, novelty, and unity emerge as dominant drivers of audience aesthetic pleasure, collectively highlighting the multidimensional nature of aesthetic engagement in new media art contexts.

Table 3:Summary of Generalized Estimating Equation Analysis for Variables Predicting Pleasing to See for eight exhibition areas Designs.

Variable	β	SE β	95%CI for β	p
Unity	0.35	0.08	[0.19, 0.51	<0.001
Variety	0.42	0.06	[0.30, 0.54]	<0.001
Typicality	0.12	0.08	[-0.04, 0.28	0.14
Novelty	0.38	0.07	[0.24, 0.52]	<0.001
Connectedness	0.21	0.05	[0.11, 0.31]	<0.001
Autonomy	0.19	0.05	[0.09, 0.29	<0.001

Table 4:Pearson’s Correlation Coefficient Analysis Results.

Variable	Unity	Variety	Typicality	Novelty	Connectedness	Autonomy	Pleasing to see
Unity	1						
Variety	-0.35**	1					
Typicality	0.12	-0.08	1				
Novelty	-0.25**	0.45***	-0.15*	1			
Connectedness	0.18*	0.22**	0.1	0.30***	1		
Autonomy	0.14	0.27**	0.05	0.33***	0.28**	1	
Pleasing to see	0.41***	0.62***	0.09	0.58***	0.36***	0.39***	1

5.DISSCUSSION

The core objective of this study’s statistical analysis was to validate the applicability of the Unified Aesthetic Model (UMA) in explaining aesthetic preferences within media art cultural experience spaces through multidimensional analysis. Key findings reveal that at the cognitive level, diversity ($F = 35.29$, $\eta^2\_p = 0.18$) and novelty ($F = 25.64$, $\eta^2\_p = 0.12$) significantly contribute to aesthetic pleasure. Notably, typicality failed to reach statistical significance in regression models ($\beta = 0.12$, $p = 0.14$), creating theoretical tension with its significant ANOVA results ($F = 10.08$, $p < 0.001$). This discrepancy suggests that typicality may indirectly influence aesthetic experience through mediating variables rather than direct pathways.

At the perceptual level, unity ($\beta = 0.35$, $p < 0.001$) and diversity ($\beta = 0.42$, $p < 0.001$) exhibited synergistic effects, indicating that interactive spaces require both cohesive stylistic frameworks to establish ambiance and diverse elements to enhance engagement. This validates the established conclusion that “optimal balance between unity and diversity yields peak aesthetic appreciation” (Post, R. A. G. et al., 2016; Post, R. et al., 2017; Berghman, M. et al., 2017; Loos, S., 2022) within immersive art contexts. Social-level data demonstrated the positive predictive roles of connectedness ($\beta = 0.21$, $p < 0.001$) and autonomy ($\beta = 0.19$, $p < 0.001$), challenging the traditional binary opposition hypothesis of “autonomy vs. connectedness.” These results refine theoretical assumptions by revealing their complementary rather than antagonistic relationship in shaping aesthetic preferences.

Analysis using generalized estimating equations (GEE) revealed that while diversity, unity, novelty, connectedness, and autonomy all significantly influenced aesthetic pleasure, diversity exhibited the strongest relative impact among these factors. Across the eight exhibition zones, distinct zones excelled in specific dimensions. For instance, the Splendid Attire MR Interactive Zone achieved the highest ratings on the aesthetic preference scale, likely due to its exceptional performance in novelty (e.g., cutting-edge mixed-reality interfaces) and connectedness (e.g., culturally resonant interactive narratives). This contrast underscores how varying combinations of UMA dimensions shape audience responses to new media art installations.

This study marks the inaugural application of the Unified Aesthetic Model (UMA) to the digital preservation of cultural heritage, empirically validating a tripartite regulatory mechanism governing aesthetic engagement in new media art spaces. At the cognitive level, the efficiency of decoding cultural symbols—such as interpreting stylized Peking Opera gestures through augmented reality interfaces—emerges as a critical mediator. The perceptual level prioritizes the construction of visual order through modular systems that balance rhythmic repetition and dynamic variation, while the social level accommodates audiences’ elastic expectations for interactive autonomy, allowing nonlinear participation without compromising cultural authenticity.

These insights directly inform the optimization of Immersion·Fight·—Peking Opera Media Art Interactive Space through a proposed “3-5-2 Design Principle”: 30% of design resources should target cognitive dimensions by revitalizing traditional Peking Opera conventions through contemporary digital metaphors, 50% should focus on perceptual dimensions to establish cohesive yet adaptable visual frameworks, and 20% should address social dimensions through strategically placed interactive nodes that empower audience agency. A paradigmatic example is the Splendid Attire MR Interactive Zone, where the optimal integration of traditional facial mask motifs with parametric variations yielded exceptional diversity (EMMs = 6.43) and novelty (EMMs = 6.89) scores. Designers can amplify these effects by enhancing novelty elements—such as generative algorithms that reinterpret Peking Opera movements in real time—while fostering connectedness through collaborative interfaces and balancing unity with diversity in spatial compositions. Despite its contributions, this study carries inherent limitations. The exclusive recruitment of non-specialist participants, while ensuring ecological validity for general audience studies, risks oversimplifying evaluations of culturally embedded interactive mechanisms. For instance, lay audiences might overlook nuanced references to Peking Opera's koujue (oral performance formulas) embedded in sound installations. Additionally, the moderate sample size (197 valid responses) constrains the generalizability of findings across diverse cultural contexts, particularly regarding cross-generational differences in digital literacy. Future research should incorporate mixed-method approaches—combining psychophysiological measures with qualitative interviews—to triangulate these pioneering insights.

Three critical limitations warrant attention in this study. First, the stimulus materials were confined to a single cultural category (Peking Opera), limiting cross-comparative insights into other intangible heritage forms like shadow puppetry or Kunqu Opera. Future research should incorporate diverse cultural prototypes to test the generalizability of UMA's regulatory mechanisms. Second, the absence of physiological measurements (e.g., galvanic skin response, heart rate variability) restricted granular analysis of emotional engagement dynamics. Third, the moderating role of cultural background—particularly audience expertise in traditional opera—remained unquantified, potentially skewing evaluations of symbolic fidelity.

To address these gaps, three strategic recommendations emerge. 1) Subsequent studies should prioritize developing a Digital Heritage Aesthetic Diagnostic Matrix to assess cross-cultural validity across media art interventions. 2) Simultaneously, constructing a multimodal evaluation system integrating eye-tracking, EEG, and behavioral metrics could unlock deeper insights into neuroaesthetic processing. Furthermore, experimental exploration of AI-generated content (AIGC)'s dynamic impact on aesthetic thresholds—such as how algorithmic style transfers reshape cultural archetypes—is imperative.3) Theoretically, establishing a dedicated aesthetic framework for Culture-Tech products has become urgent. Such a framework must reconcile the dialectical tensions between heritage preservation and technological innovation, particularly as metaverse-driven cultural dissemination redefines audience expectations in the Web3 era.

6.CONCLUSION

This study employs the UMA model to dissect the aesthetic mechanisms of enclosed cultural experience spaces, achieving the first systematic deconstruction of aesthetic elements in digital cultural heritage environments through a hybrid experimental design. Breaking from traditional unidimensional evaluation systems for art exhibitions, we established a tripartite "perception-cognition-society" analytical framework, validating cross-level interaction patterns in aesthetic preferences within media art interactive spaces. The explanatory power of the cognitive dimension surpassed that of perceptual and social dimensions, revealing a "decoding-priority effect" in cultural experience spaces: when the congruence between exhibition symbols and audience cognitive schemas increases, aesthetic pleasure significantly intensifies.

The study confirmed partial hypotheses. For instance, higher cognitive diversity strongly enhanced aesthetic pleasure, while unity also exerted significant influence. However, typicality showed no statistically meaningful impact on aesthetic pleasure, and variable correlations diverged from prior studies—potentially attributable to the uniqueness of Peking Opera art and the distinct characteristics of the study population. These findings not only validate the applicability of existing theories to cultural display spaces but also refine and expand current research paradigms.

By integrating repeated-measures ANOVA, generalized estimating equations, and Pearson correlation coefficients, this research comprehensively analyzed factors shaping aesthetic preferences, offering methodological references for similar studies. It provides scientific guidance for optimizing Immersion·-Fight·—Peking Opera Media Art Interactive Space, enhancing visitor experiences, driving digital innovation in cultural transmission, and enriching the application of aesthetic psychology in heritage contexts. Subsequent research should expand sample sizes, incorporate professional cohorts, and conduct comparative studies across expertise levels to elucidate differences in aesthetic preferences. Exploring emerging technologies like virtual reality (VR) and augmented reality (AR) could deepen immersive engagement in interactive spaces. Interdisciplinary collaborations integrating psychology, communication studies, and computer science are critical for unraveling the formation mechanisms and dissemination efficacy of aesthetic experiences, ultimately advancing holistic cultural preservation and innovation.

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The Paradigm Shift of Spatial Research: The Triadic Construction of New Media Exhibition Space

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Abstract

"Space" and "time" are the basic forms of material existence, but for a long time, people tend to prefer the study of time, and ignore the significance of space in people's social life. Until the emergence of the "space turn" in the 70s of the 20th century, Lefebvre called for the humanities and social sciences to shift the perspective of research to the spatial level, arguing that the academic community has seriously underestimated the function of space for centuries, and the traditional idea of seeing space as rigid and static should be criticized. As a result, space is no longer just a noun concept, but a product of nature, social development and various events, and people's definition of space has undergone a fundamental change.While the importance of space and space in understanding and interpreting cultural and social phenomena has gradually become prominent, the exhibition space as a social and cultural window has also undergone a transformation of space construction, and many exhibition activities have begun to use new technologies and new media to expand and package the original exhibition space, and have begun to pursue the experience and immersion of space, enriching cultural expressions and disseminating social values through space. Compared with the traditional exhibition space, the contemporary exhibition space environment with the intervention of new media technology pays more attention to the collection and mobilization of visitors' senses in the exhibition space environment. Breaking the traditional linear time clues, it guides visitors to form their own display content architecture with dynamic streamlines to obtain a unique spatial experience, and space and experience have begun to become the theme of contemporary exhibition space. Therefore, the study of the social attributes of space provides a dynamic analytical framework for the new media exhibition space, which is different from the "instrumental" construction logic of the traditional exhibition space, and introduces the three-dimensional structure of material exhibition space, symbolic narrative space and daily social space, so that the exhibition space is no longer a static and passive container in the traditional sense, but is endowed with dynamic and multi-dimensional meaning, and becomes the intersection of society, culture, and practice.

Keywords

Spatial steering; triadic dialectics; new media exhibition space; The return of technical rationality

1. THE "INSTRUMENTAL" LOGIC OF TRADITIONAL EXHIBITION SPACES

1.1 Linear spatial logic

The traditional exhibition space is a typical hierarchical space in terms of spatial layout and presentation of works: different exhibition halls have obvious spatial divisions: the exhibition hall layout is carried out according to the category of exhibits, such as painting gallery, bronze gallery, calligraphy gallery, etc.; The artworks in each exhibition hall are displayed linearly according to the time of creation, and each exhibition hall has an exit and entrance. In terms of spatial nature, it is a neutral and homogeneous exhibition environment. Therefore, the spatial layout of the traditional exhibition space is mainly based on geometric spatial patterns, and the sense of order is emphasized by "linearity" to guide the visitors' viewing order.

In the previous exhibition hall, we can see that the two-dimensional plane display method is the most common, the designer through the interface of the exhibition board, the exhibition wall and the booth as the medium of information bearing, to display the theme of the development of the timeline to the display content and the division of the exhibition space to form a two-dimensional plane linear display mode, this display mode makes the use of space to achieve a perfect balance, will not cause a sense of visual "crowding". For example, the Hongyan Revolution Memorial Hall (Fig 1), built in 1999, is located in Chongqing, and this memorial hall belongs to the "Red Culture" memorial hall built earlier, and the exhibition hall tells the story of the Hongyan spirit formed by the Communist Party of China in the struggle for national liberation and people's democracy in the practice of struggle for national liberation and people's democracy under the leadership of the Southern Bureau of the Communist Party of China during the War of Resistance Against Japanese Aggression and the early stage of the Liberation War.

Figure 1:Hongyan Revolutionary Memorial

At the same time, due to the constraints of traditional display forms, the display space of traditional artworks is often presented as a simple rectangular structure, and the internal space is not obstructed, but has the same entrance, resulting in a single route for visitors and an obvious linearized route. The display units also present a deterministic and linear superposition structure in the plane form of the space, and the continuity of the space can be determined by the opening and closing of the whole space. The flow of visitors in the traditional exhibition space is roughly divided into straight lines and circular lines. (Fig 2) the linear tour route sets the entrance and exit opposites, and visitors pass through the exhibition hall in a straight line according to the order of the exhibits to complete the visit. In the loop route, visitors need to complete a "turnback", and the entrance is the exit, resulting in a circular viewing mode.

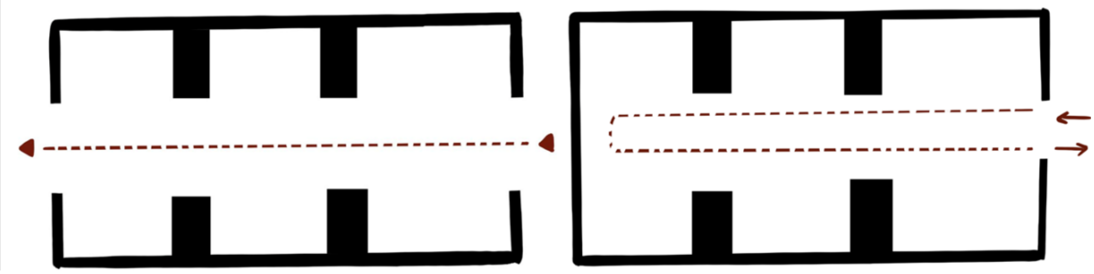

Figure 2:Left: straight line;Right: Ring line

1.2 Static perceptual environment

Vision is the sensory channel through which human beings receive the most symbolic information and obtain information the fastest. When we open our eyes to see the world, vision is a basic means for human beings to perceive the world, and the relationship between people, people and society, and people and culture is constantly constructed through the act of "seeing". This view has been confirmed in psychology: "Vision is the main way for people to understand the world, and human beings form visual representations in their minds through the practical activity of seeing, and then construct memories and develop cognition". (Liu X H,2020)

Static perception refers to people's behaviors such as stopping and resting in the exhibition space, and the overall perception of environmental elements through sensory organs dominated by vision. In the article "Visual Field", Zhao Junxiang divides the macro visual information in the exhibition space into three types: the first is based on the visual perception obtained in the real space, including the material, color and form of the exhibits themselves. The second is the spiritual value contained in the exhibits, that is, the inner expression of the exhibits. The third is text and visual information that is indirectly transmitted through the media, such as display boards, information screens, etc. When the exhibits are framed and hung on the wall or placed in isolation in a certain position, the frame can be regarded as another space that is different from the original space of the artwork, but the mosaic relationship between this space and the overall space also creates a neutral, sacred, and static space style. Vision has become the only way to observe the work and the space. In this static visual perception, space is also stationary, becoming a container of knowledge. In the exhibition hall of the Legacy of the China Arts and Crafts Museum, the overall spatial background is shown as a dark gray, so as to focus the visitors' attention on the utensils and words, and introduce the production process of the guqin with words. (Fig 3)

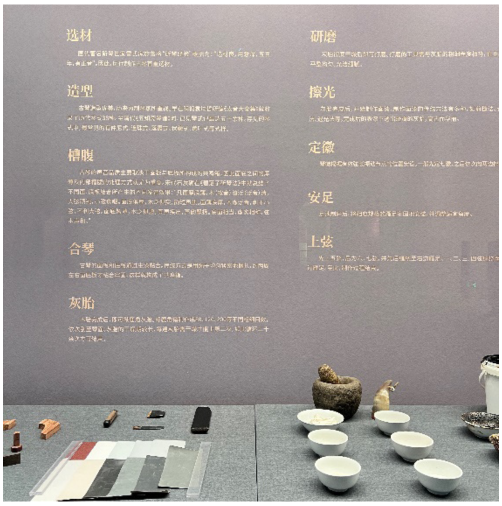

Figure 3:Exhibition Hall of China Arts and Crafts Museum

1.3 One-way information reading

In McLuhan's theory: the medium is the environment. He believed that every medium is an extension of the human body, and that each extension changes the equilibrium of the five senses and creates a new environment. When a medium is used universally for a long time, it shapes a social culture. Exhibition activity is a social activity for the purpose of disseminating information, when the exhibition designer uses various spatial modeling factors and means to block or enclose the space, and uses various media to create a specific atmosphere, the purpose is to enable the audience to obtain display information through this spatial environment. Traditional exhibition activities are limited by fixed time and space, and the dissemination of information is singular.

For example, in a 19th-century art salon, space and painting were separate from each other (Fig 4). The walls are only used as supports, and they are covered with paintings from top to bottom, leaving no gaps like wallpaper. "Each painting is seen as a self-contained whole, completely isolated from the neighboring paintings by the heavy borders and the complete perspective system within the painting." (Li H;Shen K，2009) The relationship between the visitor and the exhibit is that of two independent individuals with a sense of space and distance, and the visitor receives information in the exhibition space by "seeing".

Figure 4:19th century art salon

Therefore, the dissemination of information can only form a passive single mode in the traditional exhibition space, and the visitor is a passive visual experience mode based on the physical exhibits. "Seeing, which precedes words, is not only an individual experience, but also an essential historical experience of the audience's relationship with the past, that is to say, the search for the experience that gives meaning to life, and the experience of trying to understand history so that we can become creators in it". (John B;Dai X Y,2005) Its experience mode is to form a retrospective spiritual resonance of visual experience to stimulate historical experience from the perspective of the reader's "seeing".

2. A CONTEMPORARY TWIST ON TRADITIONAL EXHIBITION SPACES

As a place for human survival and development, space is also the carrier of human daily activities and artistic creation, the creativity of space is enhanced, and its form is constantly changing, which in the exhibition space has also begun to focus on "space" to "tell stories", through the shaping of the exhibition space environment to guide visitors to participate in the exhibition experience, and to construct their own spiritual perception. At the same time, new technologies and new media are constantly integrated in the construction of exhibition space, as a means to assist exhibition activities and the shaping of exhibition space, which also requires the collaboration of multiple disciplines to create a space that conforms to people's life experience.

Therefore, the current new media exhibition space has gradually become a common space shaping mode for various theme exhibition activities, and the combination of materialized content and non-material means maximizes the carrying capacity of display information and the interest of display activities. As an "upgrade" of the traditional exhibition space, the new media exhibition space first intervenes in the environmental construction of the exhibition space from multiple sensory levels such as vision, hearing, and touch by means of digital technology. Secondly, it provides an interactive display medium or carrier as a work of art, expands the interactive relationship between people and works, and creates a new reading code for display activities. However, the application of new media and new technologies has also promoted the core of display to gradually shift like the pursuit of novelty experience mode, and the "landscape" of display form and the "shallowness" of display content have begun to become problems faced by the construction of contemporary new media exhibition space. A beautiful and interesting space began to outweigh the content with depth of thought, and the form of the space began to become the standard for measuring an exhibition activity, so there was a retrospective of the "instrumental" cognition of space. It's just that in the contemporary new media exhibition space, the "instrumentalization" of the space is wrapped by a large number of visual illusions created by technology, and people's experience in the new media exhibition space also stems from the shallow cognition of the content in the exhibition space.

3. A CONTEMPORARY TRANSLATION OF LEFEBVRE'S TERNARY DIALECTIC

Lefebvre's spatial triadism divides space into three dimensions: natural space, spiritual space and social space, and also corresponds to three structures of space production: "spatial practice", "spatial representation" and "representational space", which are perceptible, conceivable and experiential. Therefore, the division of spatial ternary exists in any space type, and at the same time provides a framework for us to understand and analyze different spatial structures.

3.1. Spatial practice of new media exhibition space

The spatial practice of the new media exhibition space combines the real space with the material attributes and the virtual space with the technical attributes, which can also be expressed as the new media exhibition space is the exhibition space entity with media attributes.

The production of new media exhibition space needs to occupy a certain physical space, so the new media exhibition space has material attributes, and at the same time, it is also a physical space that can be perceived.

The “objects” in the new media exhibition space include exhibits and display props, and visitors can perceive the exhibits and display props as “things” through sensory experiences such as sight, hearing, touch, and smell, so as to gain cognitive experience. Therefore, “things”, as the core experience of perception, are existing things and are intuitively perceived. According to the previous research, the traditional exhibition space embodies a kind of instrumental attribute, which uses the space as the background of the physical exhibits to form a sacred space, which isolates the interconnection between the exhibits and the space, and the mechanical relationship between the two is simply the container and the content. As new media art and technology began to intervene in exhibition activities, image-based digital screens and interactive control devices began to enter the exhibition space, the traditional physical display began to turn to a variety of media information display, and the space and exhibits were no longer limited to the traditional physical means of insertion, and developed in the direction of mutual integration and mutual shaping.

In the new media exhibition space, the exhibits are not arranged in the space or hung on the wall according to the traditional display method, but by embedding digital intelligence means, covering every physical interface of the physical space, “reducing” the overall perception space with the same function and concept as the display device. For example, in 2019, the “Immersive Van Gogh Exhibition” (Fig 5), which toured in China, pasted LED screens on the square space interface to show the display content, taking into account the ground effect in the form of ceiling projection, and the ground projection and the film content cooperated with each other, occasionally showing special effects scenes such as lightning, smoke, and falling chrysanthemum petals.In the perception and interpretation, the construction of the transformation of space like exhibits is realized.

Figure 5:Van Gogh: The Immersive Experience

3.2. The spatial representation of the new media exhibition space

In Lefebvre’s The Production of Space, the representation of space is interpreted as the projection of physical space, the projection of the mind on the basis of physical space as an event, which is expressed in the language of knowledge or symbols. Therefore, it is a symbolic narrative space based on the materialized exhibition space. According to the cultural philosopher Ernst Cassirer, “all forms of culture are forms of symbols”.(Cassirer,2013)The perception of symbols, on the other hand, is based on associations with past experiences, and “when we move from the impression of one object to the idea or belief of another, we are not determined by reason, but by the principle of habit or association.”(Hume;Guan W Y,1997)Just as when we see blue we think of the sky and the sea, when we see fire, we think of burns and pain. Therefore, the use of symbols is a kind of construction of artistic conception, the new media exhibition space as a kind of display activity space that reflects social and cultural phenomena, its spatial artistic conception itself is intangible, so it can only be expressed with the help of concrete and perceptible material forms, which is the construction stage of perceptual space, and the conceived space is the stage of recognizing and thinking about these material symbols, and visitors can experience the cultural spirit contained in it through the realization of the spirit of the perception place and the dialogue of the space. Zhu Legeng’s Art Exhibition (Fig 6) held at the China Arts and Crafts

Museum in 2023 extracts Chinese cultural symbols and constructs an aesthetic image with the characteristics of the ancient Chinese image of "the unity of heaven and man". He also wrote: "This concept of spatial structure comes from the concept of the unity of heaven and man in Chinese culture, and the concept of 'viewing the world under heaven'." The new media exhibition space embodies the theme of the exhibition in the form of symbols, so that visitors can associate the visual symbols with the theme of the exhibition, and finally realize the production of the conceived space through the interpretation of the spiritual level.

Figure 6 :Scene of Zhu Legeng's Art Exhibition

3.3. Symbolic new media exhibition space

The symbolic new media exhibition space is a space directly owned by visitors, a real experience space, a space that truly reflects people's daily life, integrates and transcends space practice and spatial appearance, that is, people's daily social space, but also the use of material space and symbolic space. The symbolic new media space accommodates various factors such as space and society, culture, etc., and the use of new technologies and new media also makes the spatial relationship between people and people and objects in the space more complex.

As a kind of cultural entity space that deeply participates in the life of the public, the exhibition space is also the "material public sphere" (Habermas,J;Cao W D,1999) in the mouth of Jürgen Habermas, and is a social space integrating social communication activities such as information transmission, public performances, public communication, and leisure and entertainment. However, the traditional exhibition space is often regarded as a container for placing exhibits or a background for display, and its socio-cultural and cultural exchange attributes have not attracted widespread attention. However, with the increasing development of media technology, "physical places are no longer necessary elements of communication". (Meyrowitz Joshua， 2002)With the increasing development of digitalization and globalization, the physical space of the exhibition is unprecedentedly constructed with the network virtual space to form a more complex cultural landscape, when the public through mobile phones, computers, tablets and other network intelligent terminals wander through the website, social media and related short video platforms and other online virtual spaces to obtain the "grass" of a certain display activity, and with a variety of forms such as "punching in", "learning", "nostalgia" and other forms into the physical space to watch the exhibition offline, display every exhibit in the space, Every space, even the little-known "corner", has the potential to be disseminated across fields and groups with the public's digital practices, and eventually become a social topic or Internet celebrity "check-in place" (Fang L L;2023)that everyone can participate in.

The exhibition space is not only a place for production, but also a tool and purpose for production. As a constructive force, new media technology not only connects the physical exhibition space with the virtual cultural space, but also enables the often neglected visitors to actively participate in and transform the structural relationship between the exhibition space and themselves. The new media exhibition space is used as a creative platform for social communication, and visitors no longer engage in their own "knowledge production" all the time. Therefore, space transcends the attributes of ordinary production sites, and shifts from "the production of things in space to the production of space itself."(Henri Lefebvre ;Liu H Y,2022)As a new "Internet celebrity check-in place" in 2023, "Creating in Inheritance: Modeling, Performance, and Art Scenes--Zhu Legeng Art Exhibition" is just as the famous art theorist Professor Li Xinfeng said: "This is a "phenomenal" exhibition, and there has never been an art exhibition so close to the audience and let the audience join in so deeply." In the two groups of works, "The Triple Realm of Flowers" and "The Spirit of Flowers" (Fig 7), the behavior of the visitors has become an important part of the expression of the works, and visitors who come every day with the purpose of "checking in" have flocked to the "mirror space" plastered with mirrors around them, and played various poses with their bodies. Zhu Legeng's art exhibition does not adopt the traditional way of publicity and promotion, but the spontaneous sharing of visitors on social platforms has formed a huge flow, and more and more visitors have entered it and participated in the creation.

Figure 7:Scene of Zhu Legeng's Art Exhibition

4. THE RETURN OF RATIONALITY UNDER THE CARNIVAL OF TECHNOLOGY

In contemporary society, the real space is almost entirely dyed with technological factors. In the relationship between space and technology, first of all, any technology is developed in a given space, and different technologies also need to be expressed through different spatial forms. Secondly, space is also modified and shaped by technology, and different technologies can shape different forms of space. Therefore, the increasing maturity of technical means provides a form of "reproducing reality" for the new media exhibition space. Here, art installations such as exhibits, sounds, and multimedia attract the attention of visitors in their own ways, which not only pull visitors into a new representational world composed of space, technical objects, and visual symbols, but also form a "panoramic intellectual illusion". paralyzing the thoughts and actions of visitors. The intervention of technology has accelerated the virtualization of the world, and at the same time raised people's expectations for visual sensory capture. Bella Dicks argues that "a model that simply provides a sensory experience cannot demonstrate knowledge or principles that the subject can use elsewhere if the content of the exhibition itself is underinvested." (Bella Dicks, 2004)That is to say, if we rely solely on the external form of technology to shape and ignore the support of the display connotation, it is difficult to produce concrete perception of the illusion experience created by technology alone, and it is impossible to link emotions with the real world, so it is impossible to escape the "dilemma" dominated by appearances. In the final analysis, technology is only a means of spatial production, and it cannot become a "dominant force". As a social subsystem that includes politics, economy, culture, education and other categories, the real core of the exhibition should be: "To use the ideological conflict and collision of an exhibition to leverage the social exchanges of a wider range and more people, and to allow the audience to participate in a deeper cultural struggle." (Zhuang Y N,2021)Therefore, it is the future development direction of the new media exhibition space to resist the domination of science and technology with the core of culture, to take the exhibition itself as a cultural practice activity, to dominate the core of the display with the core of culture, and to connect the spatial level and the audience experience with technology.

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Research on the Development and Implementation of Image Processing Design Software Based on Dynamic Pixelation and Texture Replacement Technologies

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Abstract

This research designs and develops a web-based interactive image processing design software, focusing on the application of dynamic rasterization and material map replacement technologies for real-time image effect generation and visual reconstruction. The system is implemented using pure front-end technologies, allowing users to adjust parameters for image rasterization, dynamic animation generation, and material map replacement. With the introduction of the "image dark area filling" mechanism and dynamic raster generation algorithm, the system significantly enhances the visual expressiveness of images in art reconstruction, providing an innovative approach for lightweight generative art and web interaction design.The system features real-time preview, dynamic animation rendering, and export capabilities, running entirely on the browser without the need for additional software installation and supporting multiple platforms. Through the "Letter A" dynamic raster art case, the system demonstrates its application in creative expression, image stylization, and interactive design, confirming its value in digital art creation, interactive art, and digital media education. This research offers new forms of visual expression for artistic creation and provides efficient, flexible technical support for interactive art and digital media education, advancing the innovative application of image processing in the field of digital art and interaction design.

Keywords

Dynamic Pixelation;Texture Replacement;Front-End Image Processing;Real-Time Interaction;Generative Art;Image Reconstruction

INTRODUCTION

With the development of digital art and interactive design, the limitations of traditional image processing tools in artistic creation have gradually become apparent. Over the years of artistic practice, the author has extensively used Adobe Photoshop, experimenting with its “Filter → Pixelate → Color Halftone” function to reconstruct images and create stylistic expressions. (Color halftone is an image processing technique that simulates traditional printing technology by breaking an image into a visual structure composed of colored dots, creating unique retro and abstract/halftone art effects.) While the color halftone function can generate effects such as mosaics, dotted textures, and other unique artistic and visual effects, there are a series of limitations in its practical use, especially in terms of artistic creation.

Firstly, the colored dots in Photoshop are automatically generated by the system and cannot be replaced with user-defined shapes or images, severely limiting the creator’s visual control over the dot elements. Secondly, Photoshop does not allow dynamic parameter control for these dot elements. Creators cannot achieve animations, or adjust the density, size, or shape variations of the dots in real time, lacking interactivity and real-time feedback.

Based on these issues, the author conceived the idea of developing a simple-to-use, web-based image generator that requires no installation and offers interactivity and real-time feedback. This software would focus on the real-time generation and visual operation of halftone image effects. Users would not only be able to freely upload images and generate halftone effects, but also customize each dot with a substitute graphic (such as patterns, symbols, or custom material images). Additionally, users could control dynamic attributes such as motion, size, density, and deformation of these elements through parameters. The software would also support material texture mapping and visual parameter animation, expanding the expressive potential of images in the direction of “dynamic halftoning.” By integrating image processing techniques with interactive artistic expression, the aim is to explore new possibilities for visual image reconstruction, bringing richer and more dynamic forms of expression to digital art and design, and showcasing great innovative potential in the field of visual arts.

1.DESIGN CONCEPT

The author aims to create an image generation and creative platform that offers a highly personalized experience by integrating image processing with user customization and interactivity. Users can upload their own images, converting them into pixelated dot matrix images, and further customize each pixel with substitute graphics. This allows users to imbue the image with greater individuality and artistic expression while providing the freedom to adjust the effects based on personal preferences.

The goal is to break free from the limitations of traditional image editing tools, giving users more creative freedom. Through built-in dynamic effects, such as amplitude, pixel size, shape, density, and other parameters, users can not only adjust the appearance of the image but also control its dynamic evolution, exploring different visual rhythms and variations. This design, based on algorithms and user interaction, not only produces novel artistic effects but also allows each user to enjoy the fun of interacting with the image during the creative process.

The author also pays particular attention to a pain point in traditional image processing workflows: the inability to preview filter effects in real time. In traditional image software like Adobe Photoshop, users typically have to wait for the filter to finish processing before seeing the final result. This “what you see is not what you get” interaction model severely impacts creation efficiency and the overall editing experience. To address this, the author envisions introducing a real-time preview mechanism in the software system. After uploading an image, any changes—whether they involve substituting materials, switching geometric shapes, or adjusting parameters like amplitude or density—will be immediately reflected on the canvas, greatly enhancing interactivity and intuitiveness during the creative process. This design not only lowers the usage threshold but also allows users to experiment and adjust image styles efficiently, achieving more precise artistic control.

Furthermore, considering that traditional image editing software like Adobe Photoshop typically requires users to download and install the program, resulting in a high usage barrier, the author proposes developing the software as a fully HTML5- and JavaScript-based front-end image art generation tool. As a web application, it requires no installation, and users can simply open a webpage to start using it. All operations are executed locally in the browser, with no need for backend support. This ensures fast loading times and enables cross-platform compatibility with Windows, Mac, Linux, and mobile devices, greatly enhancing the convenience and accessibility of the creative process.

To bring this design concept and interactive experience to life in the software system, the author has carefully planned the implementation, covering aspects such as interface design, image processing workflows, core technology selection, effect realization, and material texture replacement technology.

1.1. Interface Design

The author first conceptualized the overall layout of the software's interface. The interface adopts a split-screen structure, with the control panel on the left and the image display canvas on the right. The control panel, arranged from top to bottom, includes the following elements: a "Upload Image" button, an "Upload Material Replacement Image" button, and various parameter adjustment sliders, covering amplitude, shape type (such as rectangle, circle, square), shape size, density, jitter, line style, and more. This sequence of elements is designed to guide users through the operation flow of "Upload → Replace Material → Adjust Parameters → Export," which enhances the intuitiveness and coherence of the user experience.

A zoom control slider is placed at the bottom-right corner of the canvas, allowing users to flexibly adjust the canvas proportion according to their needs, achieving both an overall structure preview and the ability to zoom in on pixel-level details. Given the rich detail of images after the pixelation process, this design significantly enhances user flexibility and precise control during the operation. At the bottom of the control panel, there is an "Export Image" button for users to easily save their final creations. Overall, the interface design emphasizes a clear and straightforward operational path to enhance system usability and interactivity.

1.2. Image Processing Workflow and Technology Selection

After completing the interface design, the author further planned the complete image processing workflow, covering key steps such as image upload and loading, pixel sampling, halftone decomposition, graphic dot replacement, dynamic bouncing control, and animation rendering and export. To achieve efficient and user-friendly functionality, the system is developed using front-end technologies. The page structure is built with HTML5, the layout and styling are handled by CSS, and image-level processing and dynamic effect rendering are implemented using JavaScript and the HTML5 Canvas API.

HTML is responsible for constructing the basic page structure, CSS handles the visual style and layout beautification, and JavaScript implements the core functionality and interaction logic. These three technologies work together to form a complete and efficient front-end framework, providing users with a stable, responsive, and feature-rich image processing experience.

1.3. Pixelation and Dynamic Effects Implementation

The core function of the software design is to automatically pixelate the uploaded image and activate dynamic bouncing effects. In terms of implementation, the software uses a "skip sampling" strategy, where it samples every certain number of pixels (the default interval is 2 pixels, controlled by the skip variable). This approach avoids pixel-by-pixel processing of the entire image, significantly reducing the computational load and improving performance. For example, for a 10×10 pixel image, the program samples pixels from columns and rows 1, 3, 5, 7, and 9, skipping the rest, thereby creating a sparse, regular sampling dot matrix.

After sampling, the system evaluates pixel color based on brightness and transparency. Only pixels that are darker or have higher transparency are converted into bouncing geometric shapes for rendering, while brighter and opaque areas are ignored to avoid visual clutter and emphasize the focal points of the image. The density and size of the shapes are adjustable by the user through sliders, with the default setting placing one shape every 10 pixels. The size, shape (circle, rectangle, etc.), and position of each shape are determined by the sampling results.

To create a natural and rhythmic dynamic visual effect, the system assigns different bouncing parameters (amplitude, frequency, phase) to each shape, making their movements inconsistent and giving the overall scene a breathing-like dynamic. This halftone bouncing mechanism is implemented using JavaScript and the Canvas API, with requestAnimationFrame used to continuously refresh the canvas and dynamically update the position or scale of the shapes. Users can adjust all parameters in real-time via the sliders on the left panel, catering to their personalized needs.

1.4. Material Texture Replacement Technology Design

Building upon the basic pixel dot matrix processing, the author further introduces the material texture replacement feature to enhance the image's expressiveness and visual depth. Using the Canvas API to retrieve image pixel data (via getImageData), the system selects dark pixels based on their brightness levels, and replaces them with user-uploaded texture tiles at these key positions.

Additionally, users can adjust the size, position, bouncing amplitude, and density of the texture tiles using sliders. The system employs sine and cosine functions to apply subtle bouncing offsets and scaling variations to the texture tiles, creating dynamic effects that are both lively and rhythmic. This technology not only enhances the visual quality and detail of the dot matrix image but also significantly improves the overall artistic expression and dynamic aesthetics, offering users a more expansive creative space.

2. TECHNICAL SOLUTION

Based on the detailed design concepts for the system interface layout, image processing workflow, and functional modules, this section further elaborates on the software's specific development and implementation. To efficiently execute image sampling, halftone reconstruction, and dynamic animation rendering on the browser side, the software is built entirely with a front-end architecture. The following will explain the technical implementation, presenting the software's architecture design and implementation path through a system module function comparison table, an image processing flowchart, and a front-end technology stack diagram.

This software is developed using front-end technologies and employs HTML5, CSS3, and JavaScript for image pixel sampling, graphic reconstruction, and dynamic effect presentation. Core image processing relies on the Canvas 2D rendering engine, which uses the getImageData() method to extract the image's pixel matrix. Based on user-defined geometric shapes (rectangles, circles, squares) or custom texture images, the system performs replacement drawing to create dynamic halftone effects.

The software's processing workflow includes modules for image loading, pixel sampling and processing, dynamic visualization, and user interaction control. Users can adjust parameters such as amplitude, shape ratio, and density to generate and modify image effects in real time. The dynamic effects are updated through the requestAnimationFrame() loop, ensuring smooth image rendering.

In terms of system design, users first upload the original image and optional texture images. The image is then loaded and sampled into pixel data. The software system generates a dynamic representation of the image through reconstruction and halftone replacement. During each frame render, the software calculates the dynamic generation of geometric shapes or texture patterns based on user-set parameters (such as amplitude, frequency, shape ratio) and the pixel data.

The software system also supports exporting the current image as a JPEG file and recording the dynamic effects as an MP4 video. All image processing is completed entirely on the client-side within the browser, avoiding complex server-side calculations and enhancing the user interaction experience. This software is suitable for interactive art creation, image style experiments, and teaching demonstrations, offering high real-time responsiveness and interactivity.

2.1 System Module Function Comparison Table

The system module function comparison table details the core modules of the entire application and their responsibilities, including the user interface control module, image import module, image processing module, animation rendering module, and image and video export module. Each module is assigned a specific function: the user interface module handles input control and parameter adjustments; the image import module facilitates local file loading and preprocessing; the image processing module performs pixel sampling and dynamic halftone generation; the animation rendering module is responsible for real-time drawing and frame animation updates; and the export module supports saving static images and video formats. The modules collaborate through data transfer and event-driven mechanisms, achieving high cohesion and low coupling, ensuring the system's flexibility and maintainability. (Figure 1)

Module Name	Function Description	Key Code Location or Critical Functions
User Interface Control Module	Manages various UI controls (sliders, buttons, file inputs) and their event bindings	`.controls` section in HTML, event listeners like `addEventListener`
Image Import Module	Handles the import of raw images and texture materials, loading them onto the Canvas	Functions `handleImage()` and `handleMaterial()`
Image Processing Module	Reads pixel data of the image, generates pixelated graphics based on parameters, dynamically calculates shape and position	Pixel sampling and drawing logic in the `draw()` function based on `imageData`
Animation Rendering Module	Implements time-frame based dynamic updates, integrating jitter, amplitude, and shape changes	`frame` variable controlling dynamic effects inside the `draw()` function
Image and Video Export Module	Supports saving the current canvas as an image and recording/exporting dynamic videos	Functions `saveImage()` and `exportVideo()`
Zoom Control Module	Allows users to dynamically adjust the zoom ratio of the Canvas display	Event listeners on `zoomSlider`, modifying `canvas.style.transform`

Figure 1: System Module Function Mapping Table

2.2 Image Processing Flowchart (Image → Halftone → Replacement → Animation)

The image processing flowchart clearly demonstrates the complete process from image input to dynamic presentation. The flow begins with the user uploading the original image and optional material images. After pixel data sampling, the image is divided into halftone units. Based on user-defined parameters (such as amplitude, shape ratio, density, jitter, etc.), the software system calculates the geometric form and dynamic offset for each halftone, and, combined with color information, determines the drawing style for each shape. The animation is achieved by updating the "frame" variable on a per-frame basis to create periodic dynamic changes. The system also supports the mixed drawing of lines and shapes to present rich visual effects. This flow ensures the real-time and interactive nature of image processing, effectively supporting immediate feedback based on user-defined parameters. (Figure 2)

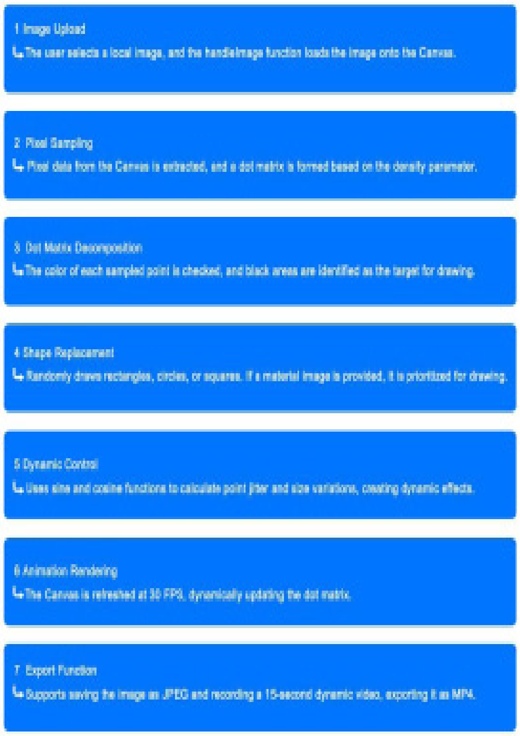
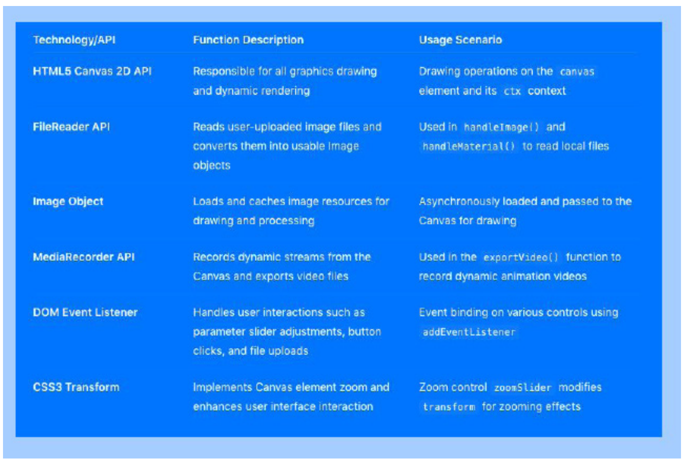


Figure 2: Image Processing Flowchart

2.3 Front-End Technology Stack Selection

The front-end technology stack selection diagram illustrates the technical path used by the system to implement complex image processing and animation rendering within a browser environment. The core technology is based on the HTML5 Canvas 2D API for graphic rendering, the FileReader API for local file reading, and the MediaRecorder API for recording dynamically generated video from the canvas. DOM manipulation handles user interaction control. The system adopts a pure front-end architecture, requiring no back-end support, which enhances the application's cross-platform compatibility and responsiveness. The technology selection focuses on standard web technologies and lightweight implementation, leaving room for future performance optimizations (such as WebGL acceleration or WebAssembly integration), ensuring the system has strong potential for technical evolution. (Figure 3)



Technology/API	Function Description	Usage Scenario
HTML5 Canvas 2D API	Responsible for all graphics drawing and dynamic rendering	Drawing operations on the `canvas` element and its `ctx` context
FileReader API	Reads user-uploaded image files and converts them into usable Image objects	Used in `handleImage()` and `handleMaterial()` to read local files
Image Object	Loads and caches image resources for drawing and processing	Asynchronously loaded and passed to the Canvas for drawing
MediaRecorder API	Records dynamic streams from the Canvas and exports video files	Used in the `exportVideo()` function to record dynamic animation videos
DOM Event Listener	Handles user interactions such as parameter slider adjustments, button clicks, and file uploads	Event binding on various controls using `addEventListener`
CSS3 Transform	Implements Canvas element zoom and enhances user interface interaction	Zoom control `zoomSlider` modifies `transform` for zooming effects

Figure 3: Frontend Technology Development and Technical Selection

3. SYSTEM IMPLEMENTATION AND INTERFACE DESIGN

This software system is built within a browser front-end environment, with no backend dependencies. It implements image pixel analysis, visual reconstruction, and dynamic rendering functionalities, primarily written using HTML5, CSS3, and native JavaScript, with the Canvas API serving as the core for graphic processing.

3.1 System Architecture

The architecture diagram illustrates how the front-end modules of the software system work together. The diagram clearly defines the relationships between different modules (such as image loading, pixel processing, dynamic rendering, and user interaction) and shows how the Canvas rendering engine generates the final visual effects through dynamic drawing and animation refresh. The responsibilities of each module and how they are interconnected help build the complete image processing workflow. (Figure 4)

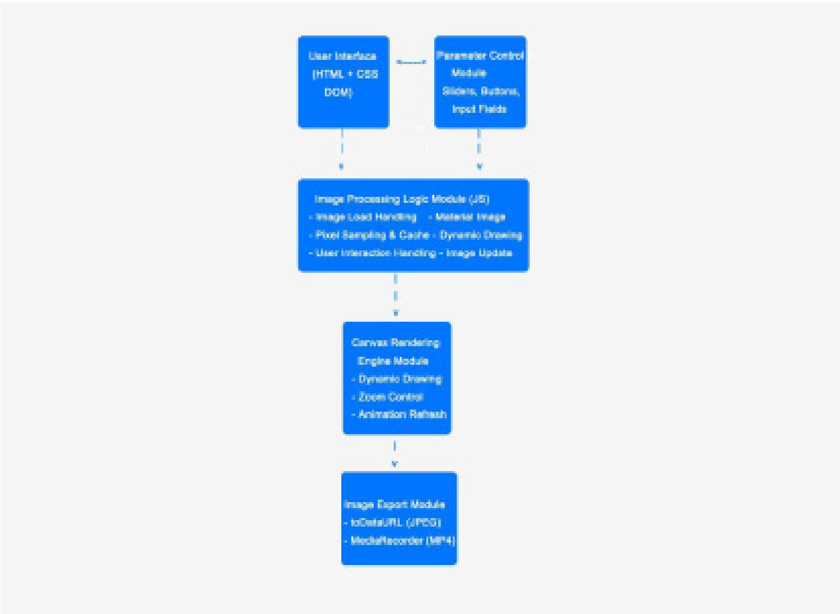


Figure 4: System Architecture Diagram

3.2 Interface Design

The software interface adopts a left-right split layout, with the left side serving as the control panel and the right side as the image display canvas. The control panel area is organized from top to bottom, starting with the “Import Image” and “Import Material Replacement Image” buttons, allowing users to import materials in sequence. Below these buttons are several parameter adjustment controls, including amplitude, shape type, shape size, density, jitter, and line style. Users can adjust the halftone effect and dynamic behavior flexibly using sliders and dropdown menus.

The right-side canvas area serves as the main space for image display and real-time preview, allowing users to visually check the halftone image effect based on the current settings. A zoom control is located at the bottom-right corner of the canvas, making it easy for users to zoom in on details or view the overall effect, enhancing the flexibility and accuracy of operations. At the bottom of the interface is the “Export Image” button, allowing users to save their creative results.

After development, the software interface is clean and intuitive, with a well-organized module layout and a clear, smooth operation flow, ensuring ease of use and an optimal interactive experience. Users can easily import images and texture images, adjust parameters such as amplitude, shape size, and density from the left control panel, and all changes will be reflected in real-time on the right canvas. The canvas supports zooming and dynamic preview, allowing users to closely observe every detail of the halftone image and its dynamic changes. Overall, the interface design emphasizes user experience, balancing aesthetics and practicality, and provides creators with an efficient and inspiring digital art platform.

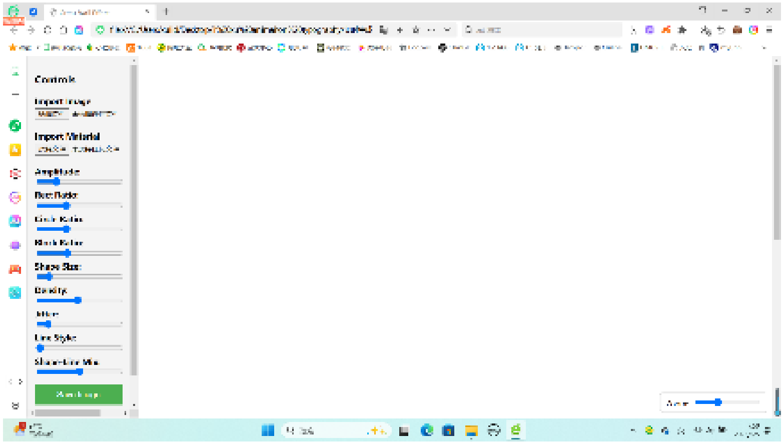


Figure 5: Interface Display Diagram

4. RUNNING TEST EXPERIMENTS AND VISUAL EFFECT GENERATION EXPERIMENTS

4.1 Software Running Test Experiment

After the software development is completed, it undergoes running tests to ensure its stability and reliability. Below is a textual table of the running test experiment for the image processing software, which primarily describes the software's performance in different environments, including functionality verification, performance testing, boundary condition testing, and exception handling. The goal is to comprehensively assess whether the software meets the expected functional requirements and provide a detailed analysis of its performance in real-world usage.

Based on the results of the test experiments, the image processing software performed well in all functionality, performance, and stability tests, meeting the expected requirements. It runs stably and adapts to various environments, demonstrating the software's practicality and reliability. (Figure 6)

Experiment No.	Experiment Item	Experiment Steps	Expected Result	Actual Result
1	Image Import and Display	Import an image and check if it displays on the canvas	The image is successfully imported and displayed	The image was successfully imported and displayed
2	Texture Replacement Import	Import a texture replacement image and check the effect	The replacement texture is successfully applied	The texture was applied correctly, and the image updated
3	Parameter Adjustment Test	Adjust parameters like amplitude, shape, and density, and check the image changes	Changes in parameters are reflected in real-time	The adjustments worked as expected, with real-time image changes
4	Dots Effect Test	Activate the dot effect and check how the image changes	The dot effect is successfully generated and shown	The dot effect was generated correctly, and the image matched the settings
5	Dynamic Effect and Jitter Test	Adjust dynamic effects and jitter, then check the image's response	The dynamic and jitter effects are applied smoothly	The dynamic and jitter effects responded well
6	Zoom Control Test	Use the zoom control to zoom in or out and observe the effect	The image can be zoomed in/out smoothly, with clear details	Zoom operation was smooth, and the image was clear
7	Image Export Function Test	Click "Export Image" and save the image to a specified path	The image is successfully exported, with correct format and location	The image was exported successfully, with the right format
8	Performance Test	Test processing time and performance for images of different sizes	The software processes different sizes efficiently	Fast processing with no lag or delays
9	System Stability Test	Run the software for an extended period, performing regular tasks	The software runs continuously without crashes or lag	The software ran smoothly and stably
10	Multi-Platform Compatibility Test	Run the software on different operating systems and test functionality compatibility	The software works normally on different platforms	The software runs smoothly across platforms with consistent functionality

Figure 6: Software Operation Testing Experiment Table

4.2 Visual Effect Generation Experiment

The author demonstrates the functionality and the rich variety of visual effects that this software system can generate through specific application scenarios, further showcasing its potential in art experimentation and visual expression. To present the software's functionality and artistic capabilities more intuitively, the following example illustrates how dynamic halftone and texture replacement techniques can transform a simple letter graphic into a completely new visual experience. The experiment focuses on the letter "A" and emphasizes the innovative effects of dynamic halftoning and texture replacement on visual expression. The following is a detailed operational process of the visual effect generation experiment:

4.2.1 Initial State: Static Letter "A"

Background color: Black

Initially, the letter "A" is in a static state with a black background. The letter itself is composed of a solid black area without any pixelated dots, giving it a complete, traditional letter appearance. (Figure 7)

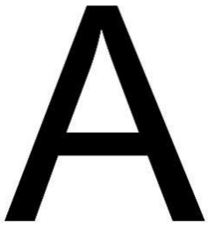


Figure 7: Letter A

4.2.2 Convert to Halftone Effect

After clicking the "Import Image" button at the top of the control panel on the left side and importing the letter "A" image, the right image display area shows the halftone effect of the letter "A" being generated. As the dynamic effect unfolds, the letter "A" gradually appears by displaying small particle points (pixels or particles) one by one. Each particle can be a small dot or a more creative shape, and they form the outline of the letter "A." These points can gradually appear, creating a dynamic effect of the letter being constructed over time. (Figure 8)

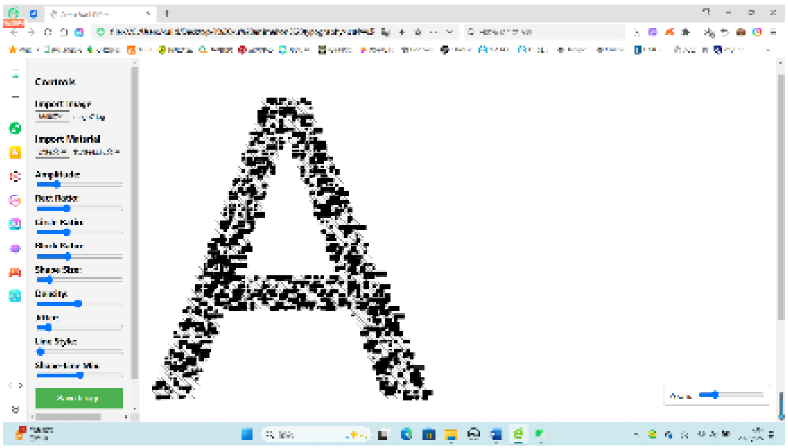


Figure 8: Dotted Grid Effect

4.2.3 Rich Visual Expression of the Halftone Image

To further enhance the visual effect, users can adjust all parameters in real-time through the sliders on the left panel. By assigning different bouncing parameters (amplitude, frequency, phase), they can create inconsistencies in the bouncing motion, which also leads to variations in the letter "A" effect. This allows for the display of diverse shapes or textures, generating unique and expressive visual effects that meet personalized needs. (Figures 9-11)

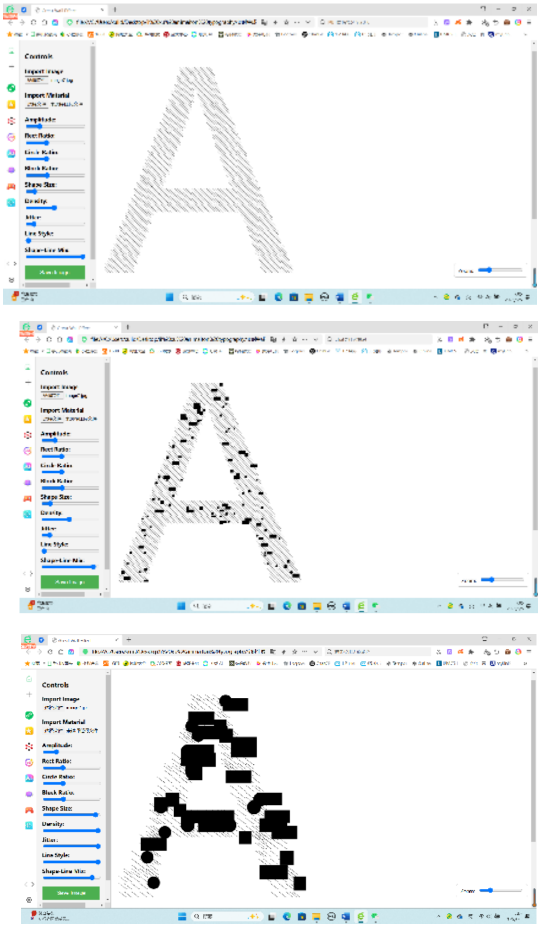


Figure 9-11: Diversified Texture Effects

4.2.4 Dynamic Texture Replacement

Loading the Texture Image:

Once the letter "A" is displayed in a halftone pattern, users can choose an image as a texture to replace these particle points. The system will automatically recognize the pixel information in the selected texture image and replace each point in the halftone grid with a corresponding pixel or texture from the chosen material.

Dynamic Texture Replacement in the Halftone Grid:

After clicking the "Import Texture Image" button at the top of the control panel on the left side, the original black halftone letter "A" will transform into an image composed of a new texture—such as a portrait image. (Figure 12) The entire letter "A" will be redrawn with the new texture, creating a fresh visual effect. This process can either be a smooth transition or a dynamic process where each point is gradually replaced.

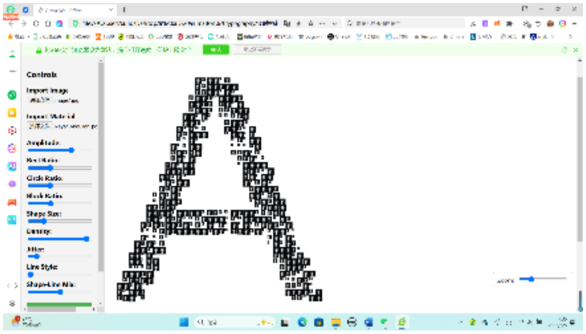


Figure 12: Portrait Replacement Effect

4.2.5 Interactivity of the Texture Image

If the user uploads different texture images, the appearance of the letter “A” can change instantly, producing entirely different visual effects. For example, replacing the texture with an image featuring floral patterns (Figure 13) or animal motifs like a cat (Figure 14) can create more complex visual layers and styles.

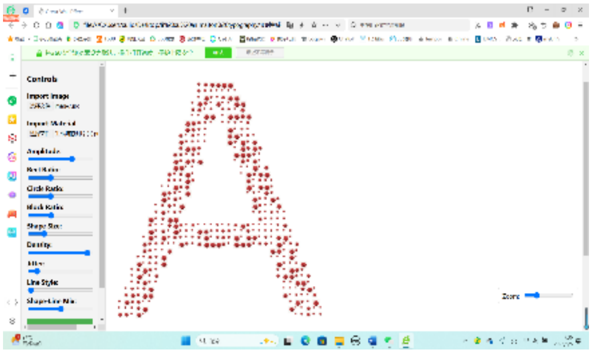


Figure 13: Floral Replacement Effect

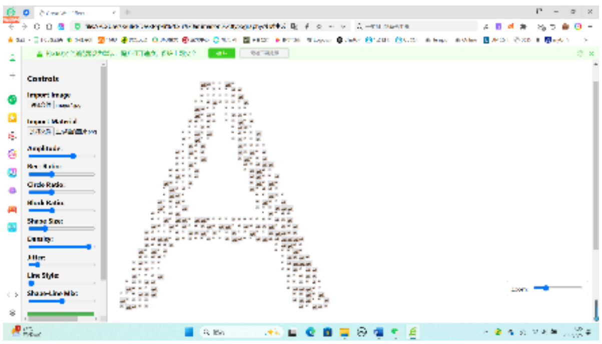


Figure 14: Animal Cat Replacement Effect

4.2.6 Save and Export

When the user clicks the save button on the left control panel, a dialog box will pop up, allowing them to enter a file name and specify the download location. After clicking the download button, the image will be saved in JPG format. (Figure 15)

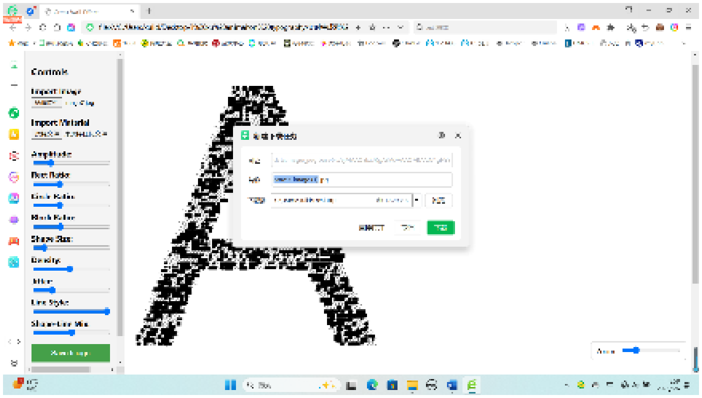


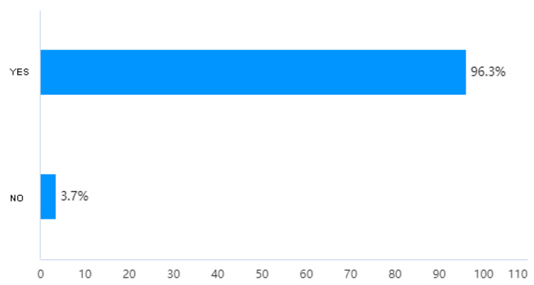
Figure 15: Save and Export

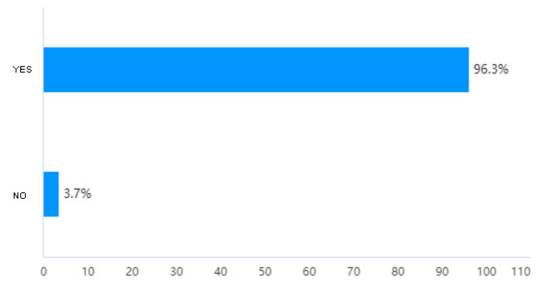
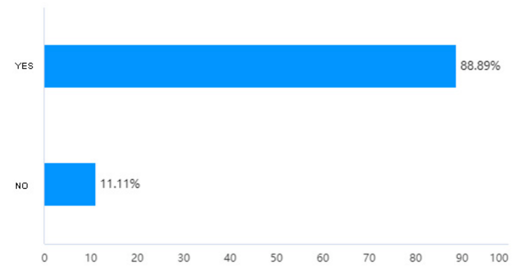
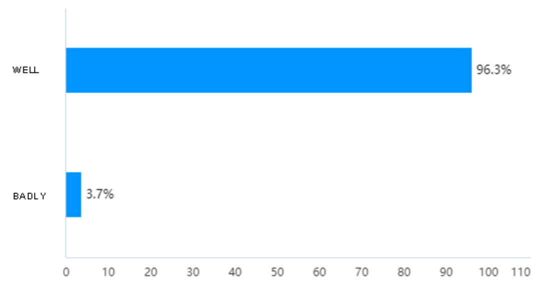
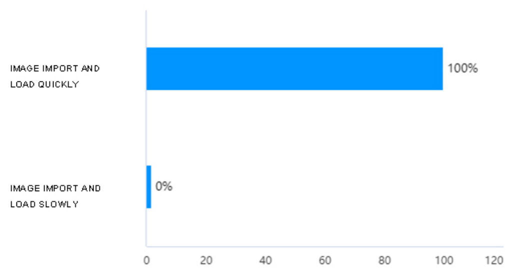
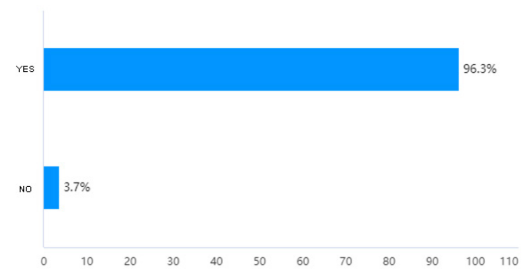
This experiment comprehensively validated the technical implementation of the system by demonstrating the gradual transition from a static letter "A" to dynamic halftone effects, real-time parameter adjustments, dynamic texture replacements, and the interactive display of texture images. It showcased the innovative expression of digital halftone images in visual arts. This process breaks through the limitations of traditional image processing, granting creators greater freedom and flexibility, and expanding the possibilities for digital art creation.

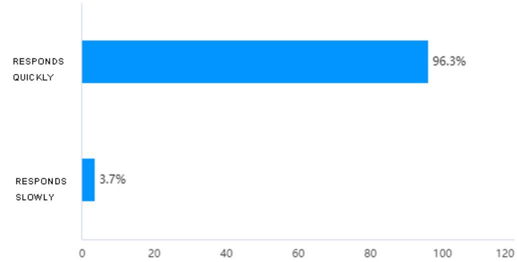
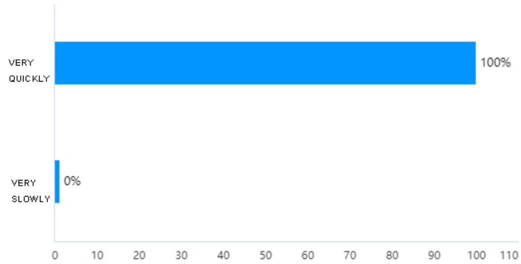
5. SURVEY AND SYSTEM PERFORMANCE EVALUATION

To further validate the system's operation, I designed and conducted a survey to gather feedback from participants regarding the system's performance in generating dynamic halftone effects, texture replacement functionality, and user experience aspects.

The purpose of this survey is to assess the performance and user experience of the image processing design software system, based on dynamic halftone and texture replacement technologies. The survey covers dimensions such as halftone dynamic effects, texture replacement, image visual effects comparison, performance testing, and overall user experience.

1	After importing the letter "A" image, did it transform into a pixelated effect?	

2	After importing the letter "A" image, did it start moving?	
3	After importing another material image, was the pixelated effect on the screen replaced by the corresponding material image?	
4	How is the overall experience of the process from importing the image, processing it, achieving the effect, to saving the image?	
5	How is the speed of the image display on the right side after clicking the "Import Image" button?	
6	After importing the image and sliding the left slider, does the image on the right side change?	

7	After importing the image and sliding the left slider, how is the visual effect change and the speed of the display on the right side?	
8	How many seconds does it take to save the image after clicking the export/save button?	

Through the analysis of the data, the performance of the image processing design software was evaluated across multiple dimensions. The survey results show:

In terms of basic image processing functionality, the survey indicated that the system's image import speed and save/export functions were highly praised by users. 100% of participants reported that image import was very fast, and the export/save operations were also very smooth, with short response times and almost no delays. This demonstrates that the system performs excellently and responds efficiently when handling large-scale image data.

In generating dynamic halftone effects, the vast majority of users (96.3%) felt that the system responded quickly during user interactions, and the dynamic effects on the screen were clearly noticeable. When adjusting the left-side slider, the right-side screen responded quickly and displayed significant visual effects. This highlights the system's real-time performance and smoothness in dynamic halftone processing. Although a small number of users (approximately 3.7%) reported slower responses in some cases, this did not affect the overall experience, and the efficiency of the system was acknowledged by most users.

Regarding the texture replacement function, the majority of participants (88.9%) indicated that the feature worked smoothly and quickly replaced the texture images, further confirming the system's high stability and excellent interactivity.

In terms of user experience, the overall feedback was very positive. Participants generally found the system's interface user-friendly, the operation simple, highly interactive, and capable of quickly responding to user needs, providing immediate feedback. This smooth interaction experience allowed users to efficiently complete image design tasks.

In summary, the survey confirmed the software's excellence in dynamic halftone effect generation, texture replacement technology, performance, and user experience. Most participants gave high ratings to the software's performance and interactive features, indicating that the image processing design software excels in meeting user needs, improving work efficiency, and providing a smooth operation experience.

6.Conclusion and Outlook

This study focuses on image halftoning and texture replacement techniques, designing and implementing a dynamic image processing tool based on a web platform. The system adopts a purely frontend architecture, leveraging HTML5, CSS3, and JavaScript technologies, combined with the Canvas API to achieve pixel-level image sampling, graphic reconstruction, and dynamic animation rendering. Users can interact with the graphical interface to customize halftone styles and substitute textures, adjusting animation parameters in real time to achieve dynamic visual reconstruction and artistic stylization of images. Experimental results show that the system offers advantages such as ease of use, efficient responsiveness, and rich visual effects, demonstrating broad application potential in fields like generative art, interactive design, and digital media creation.

In future development, the software will continue to be upgraded functionally, supporting the extension of various shapes and animation effects. Additionally, by incorporating features like the fusion and layering of multiple texture maps, and integrating deep learning techniques, the system aims to push image processing towards more intelligent, personalized, and artistically layered directions.

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