Designing Age-Friendly User Interfaces Based on Multimodal Sentiment Analysis: A Systematic Study on Bridging the Digital Divide and Improving Mental Healt

Abstract

The global aging population and the widespread use of digital technologies have exacerbated the digital divide among the elderly, affecting their mental health. This study utilizes multimodal sentiment analysis techniques to develop a theoretical framework for age-friendly user interface design, proposing optimization strategies. Through experimental and observational methods, the study validates the effectiveness of emotion-driven design in enhancing digital skills, improving mental health, and increasing user satisfaction among elderly users. The results indicate that multimodal sentiment analysis contributes to improving digital skills, operational efficiency, reducing loneliness and depression, enhancing cognitive abilities, and increasing willingness for digital engagement, thereby boosting user satisfaction and experience. This research provides a theoretical framework and optimization strategies for age-friendly user interface design, enriches relevant theories and practices, and offers guidance for improving digital experiences and promoting healthy aging for the elderly.

Keywords: Multimodal sentiment analysis; age-friendly user interface design; digital divide; mental health; emotion-driven design

1. Introduction

A. Research Background and Issues

With the increasing trend of global population aging, the elderly are gradually becoming an essential part of society. However, the rapid development of digital technologies has, while bringing convenience, widened the gap between the elderly and the digital society (Gómez, 2019). The digital divide is not only manifested in differences in access to devices and digital literacy but also directly impacts the elderly's social participation and mental health (Di Giacomo et al., 2019). Psychological issues such as loneliness, depression, and anxiety are prevalent in the elderly population, further exacerbating their marginalization in the digital society (Mannheim et al., 2019).

Multimodal sentiment analysis technology offers a significant opportunity to optimize age-friendly user interface design (Chan & Teh, 2020). By integrating multimodal sentiment data such as visual, voice, and textual information, it is possible to accurately capture the emotional needs and interaction behaviors of elderly users, providing technical support for personalized and emotionally resonant design of interfaces (Blazic & Blazic, 2020). However, current research in age-friendly design has primarily focused on functional optimization and interface simplification, lacking a systematic design framework based on emotional data (Ball et al., 2019). The challenge remains how to utilize sentiment analysis technology to bridge the digital divide and improve mental health (Van Dijk, 2020).

B. Research Objectives and Significance

This study focuses on the field of age-friendly user interface design, supporting multimodal sentiment analysis techniques to systematically explore their role in narrowing the digital divide and promoting the mental health of elderly users (Lu et al., 2024). By constructing a design theory framework centered on emotion-driven approaches and proposing corresponding practical strategies, this research aims to enhance elderly individuals' digital engagement and user experience, providing theoretical support and technical solutions for healthy aging (Quan et al., 2021; Figueiredo et al., 2023).

From an interdisciplinary perspective, the project deepens the application of multimodal sentiment analysis in the field of age-friendly design, proposing innovative emotional design pathways to effectively

address the current lack of focus on emotional needs in age-friendly interface design (Zhang et al., 2024; Jin et al., 2023). Through empirical research, the effectiveness of the design is validated, providing scientific evidence for the full integration of elderly groups into the digital society (Wang et al., 2023; Kim & Song, 2024).

C. *Research Innovation and Contribution*

This research integrates theory with practice, aiming to promote the in-depth development of age-friendly user interface design and provide feasible pathways and innovative ideas to address the challenges posed by aging in the digital society. The study constructs an emotion perception-driven design framework by integrating multimodal sentiment analysis techniques, proposing a systematic method covering emotional perception, user need modeling, and interface design optimization (Han et al., 2023; Liao et al., 2023). The research also introduces a multidimensional emotional design strategy focusing on three major dimensions: visual, interaction, and content, forming an emotion-driven age-friendly interface optimization strategy (Zeng et al., 2024). A comprehensive evaluation and empirical validation are conducted through experiments and field observations, thoroughly validating the design's effectiveness in bridging the digital divide and improving mental health (Wei et al., 2024; Xu et al., 2024).

2. Literature Review

A. *The Digital Divide and Digital Experience of the Elderly*

The digital divide is one of the primary challenges preventing the elderly from integrating into the digital society, encompassing disparities in device access, digital skills, and willingness to use technology (Llorente-Barroso et al., 2022). Specifically, issues such as complex device operation, high network costs, and lack of technical support limit the elderly's ability to access digital devices (Smith, 2021). These external barriers are compounded by intrinsic factors, such as inadequate digital skills training, memory decline, and cognitive deterioration, which make the use of digital technologies particularly challenging for the elderly (Zhou et al., 2024). Additionally, concerns regarding the safety and privacy risks of new technologies, along with traditional beliefs, further diminish the elderly's willingness to try and adopt digital technologies (Grigorovich et al., 2022).

Current research indicates that optimizing user interface design can effectively lower the barriers to digital technology usage for the elderly (Gao & Zhou, 2022). For example, interface simplification, intuitive operation processes, and navigation designs tailored to the elderly's characteristics all contribute to enhancing their user experience (Wang, 2023). In particular, the introduction of multimodal sentiment analysis techniques provides a new breakthrough in this field. This technology integrates multimodal data, such as voice, visual, and textual information, enabling the recognition and response to elderly users' emotional states, simplifying the interaction process, providing personalized guidance, and enhancing emotional interaction experiences (Ahn et al., 2020). This not only improves the digital experience of the elderly but also effectively mitigates the social exclusion caused by the digital divide, offering a more convenient and user-friendly digital environment for older adults (Vigouroux et al., 2021).

B. The Impact of Mental Health on Elderly Digital Interaction

Mental health is a key factor influencing the elderly's adoption of digital technologies and digital interaction. Research shows that psychological issues such as loneliness, depression, and anxiety directly reduce the elderly's motivation to learn new technologies and their willingness to engage with digital platforms (Wu et al., 2024). Moreover, cognitive changes, including inattention, memory decline, and decreased executive functioning, further weaken the elderly's operational efficiency and confidence (Ramanarayanan, 2024). These psychological and cognitive challenges not only affect the elderly's attitude toward digital technologies but also hinder the effectiveness of age-friendly designs (Baig & Kavakli, 2019).

In age-friendly design, multimodal sentiment analysis technology provides a proactive intervention for mental health issues by sensing elderly users' emotional states in real time. For example, systems can enhance the elderly's confidence in operating digital devices through voice prompts, friendly visual elements, or motivating feedback, reducing their resistance to digital technologies (Yang et al., 2020). Additionally, dynamic adjustment of emotional feedback improves the user's interaction experience, creating a more positive cycle of usage (Seng et al., 2020). This technological approach improves the elderly's digital interaction experience from both psychological and behavioral perspectives, helping them better integrate into the digital society

(Vigouroux et al., 2021).

C. The Application of Multimodal Sentiment Analysis in User Interface Design

Multimodal sentiment analysis technology combines various data forms such as visual, voice, and text to capture users' emotional characteristics and behavioral preferences. This technology has already demonstrated significant advantages in general user interface design, such as improving interaction quality and user satisfaction. However, its application in age-friendly design is still in its early stages, and existing research lacks depth in technology and scene adaptability.

The core advantage of multimodal sentiment analysis lies in its ability to accurately identify emotional fluctuations in users, providing strong support for emotion-driven interface design. For instance, this technology can dynamically optimize interface feedback mechanisms by gaining insights into the emotional needs of elderly users and designing interaction patterns that better align with their cognitive characteristics. Specific applications include real-time adjustments to font size, color contrast, interaction prompts, as well as the integration of more humanized emotional elements, such as voice prompts expressing care or emotionally soothing animations. Through these techniques, emotion-driven interface design not only enhances the elderly's operational satisfaction but also indirectly improves their mental health, thus increasing their acceptance of digital technologies.

D. Summary of Literature Review

In summary, the digital divide and mental health issues are the two major factors hindering the elderly's integration into the digital society. Multimodal sentiment analysis technology provides an innovative pathway to address these challenges by recognizing emotions and dynamically optimizing interface interactions, creating a more humanized digital experience for the elderly. However, current research still lacks sufficient exploration of technology implementation and the suitability of age-friendly application scenarios, and the relevant theoretical frameworks and practical models remain underdeveloped.

Future research should further combine elderly users' emotional needs with technological advantages to construct a more systematic theoretical framework for age-friendly user interface design. For example, more in-depth exploration of the adaptability of multimodal sentiment analysis in specific scenarios and its evaluation methods is

needed. Additionally, digital solutions should be developed with greater adaptability, catering to the personalized needs of different types of elderly users. This would not only help bridge the digital divide but also offer more possibilities for improving the mental health of the elderly, achieving both technological inclusivity and social equity.

3. Multimodal Sentiment Analysis–Driven Framework for Age–Friendly User Interface Design

A. Multimodal Emotion Perception and Feature Extraction

Multimodal emotion perception technology integrates multiple data sources, such as images, voice, and text, to accurately capture the emotional states of users. In age–friendly design, this technology achieves comprehensive emotion feature extraction from the following three dimensions:

1) *Visual Emotion Analysis*

Based on facial expression recognition technology, it extracts features like wrinkles and muscle movements to monitor emotional fluctuations in the elderly.

2) *Voice Emotion Recognition*

By analyzing pitch, speed, and tone variations, it identifies emotional information in elderly users' speech interactions.

3) *Text Emotion Analysis*

It analyzes user input or system interaction texts to detect subtle emotional changes in language usage. The fusion of these multimodal data enhances the accuracy and comprehensiveness of emotional feature extraction, providing a reliable foundation for designing personalized and emotionally engaging age–friendly interfaces.

B. Emotion–Based User Need Modeling

With the support of multimodal sentiment analysis, this study constructs a user need model for the elderly, encompassing functional needs, emotional needs, and cognitive ability characteristics:

1) *Functional Needs*

Includes key functions such as socializing, entertainment, and healthcare, with a focus on layered functionality and user preferences.

2) *Emotional Needs*

Focuses on the elderly's need for safety, accomplishment, and social connection, reflecting the intensity of their emotional and psychological needs.

3) *Cognitive Ability Characteristics*

Considers individual differences in attention, memory, and information processing speed, ensuring the design aligns with the cognitive load capacity of the elderly. This needs model effectively guides designers in meeting the psychological, physiological, and emotional needs of elderly users through interface design.

C. Emotion-Driven Interface Design Strategies

Based on emotion-based user need modeling, this study proposes three emotion-driven design strategies:

1) *Emotional Visual Design*

Color Design: Uses warm, soft tones and high contrast to enhance visibility.

Icon Design: Simple, intuitive, and semantically clear icons for quick recognition by elderly users.

Layout Optimization: Organizes the interface according to information hierarchy and visual focus principles to reduce visual burden and highlight key content.

2) *Emotional Interaction Design*

Interaction Methods: Utilizes multimodal interactions such as touch and voice, tailored to elderly users' physiological characteristics.

Immediate Feedback: Implements positive emotional feedback mechanisms like encouraging language or animations to boost users' confidence.

Gradual Guidance: Offers step-by-step instructions to help elderly users gradually master the interface operation.

3) *Emotional Content Design*

Information Density: Controls the complexity of information to ensure content is clear and understandable.

Multimedia Integration: Combines images, videos, and text to enhance content accessibility.

Language Style: Uses friendly and positive language to strengthen emotional resonance and improve user experience.

4) *Design Evaluation and Iterative Optimization Mechanism*

To ensure the practical effectiveness of the design, this study develops a multidimensional evaluation system that includes usability,

emotional experience, and long-term effect monitoring:

Usability Testing: Assesses the interface's ease of use by measuring task completion time, error rates, and other relevant indicators.

Emotional Experience Evaluation: Utilizes emotional surveys and physiological indicators to measure elderly users' emotional satisfaction.

Long-Term Monitoring: Analyzes the behavioral data and psychological trends of elderly users in real-world usage to assess the ongoing impact of the design. Based on the evaluation results, the interface design undergoes iterative optimization, following a "Evaluation – Optimization – Re-evaluation" loop, continuously improving the quality and user experience of age-friendly design.

4. Experimental Design and Methodology

D. Experimental Goals and Hypotheses

This experiment aims to verify whether multimodal sentiment analysis-driven age-friendly user interface design can:

Hypothesis H1: Effectively narrow the digital divide, significantly enhancing elderly users' device operation abilities and digital skills.

Hypothesis H2: Improve the psychological health of elderly users, including reducing loneliness and depression levels, and enhancing cognitive abilities.

Hypothesis H3: Drive design optimization through emotional feedback, increasing user satisfaction and engagement.

E. Experimental Group and Control Group Design

The experimental group uses the multimodal sentiment analysis-driven optimized age-friendly interface.

The control group uses traditional, non-emotion-driven interface design.

Both groups consist of 50 elderly participants, totaling 100 participants, who are balanced according to gender, age, and educational background.

F. Experimental Procedure

1) Preliminary Preparation

Equipment: Emotion data collection devices (facial expression camera, voice emotion analysis microphone), smart devices (tablet, smartphone).

Tools: Multimodal emotion analysis software, mental health

questionnaires, digital skill tests.

2) Experimental Tasks

Task 1: Register an account and complete personal information.

Task 2: Complete a simple social interaction (send messages, add friends).

Task 3: Complete a health record upload task (take a photo, edit, and submit).

3) Data Collection

Behavioral Data: Task completion time, error rates.

Emotion Data: Real-time facial expressions, voice emotion fluctuations.

Survey Data: Loneliness scale, depression and anxiety scale, cognitive ability tests.

Experimental Duration: Each participant will spend 2 hours on the experiment, completed in two sessions, with long-term behavior observed.

G. Data Analysis and Processing

1) Statistical Methods

Descriptive Statistics: Analyze the basic demographic characteristics of the experimental and control groups (average age, gender ratio, etc.), as well as the average and standard deviation of task completion time and error rates.

Hypothesis Testing

Significance Testing: Independent sample t-tests will compare differences in operational abilities and digital skills improvement between the experimental and control groups.

Correlation Analysis: Pearson correlation coefficients will be used to analyze the relationship between emotion data and user satisfaction, as well as improvements in psychological health.

Regression Analysis: A multiple regression model will quantify the impact of multimodal sentiment analysis on design optimization and bridging the digital divide.

2) Data Visualization

Task completion efficiency, emotion fluctuations, and psychological health improvements will be visualized using line charts, bar charts, and heat maps.

H. Data Processing Results

1) Bridging the Digital Divide

Device Operation Ability Improvement

Task Completion Time: The experimental group reduced time by an average of 40%, while the control group only reduced by 15%.

Error Rate: The experimental group decreased to 4%, while the control group remained at 12%.

Regression Analysis: A multiple regression model will quantify the impact of multimodal sentiment analysis on design optimization and bridging the digital divide.

This figure shows the differences in task completion time and error rates between the experimental and control groups, with the experimental group demonstrating better efficiency and accuracy.

Fig.1. Task Completion Time and Error Rate Comparison

2) Psychological Health Improvement

Loneliness and Depression Levels

The experimental group showed a decline in loneliness from 4.2 to 2.1, while the control group only declined from 4.3 to 3.8.

The experimental group experienced a 35% reduction in depression scores, while the control group showed only a 10% reduction.

This figure shows the changes in loneliness and depression levels before and after the intervention, with the experimental group showing more significant improvements.

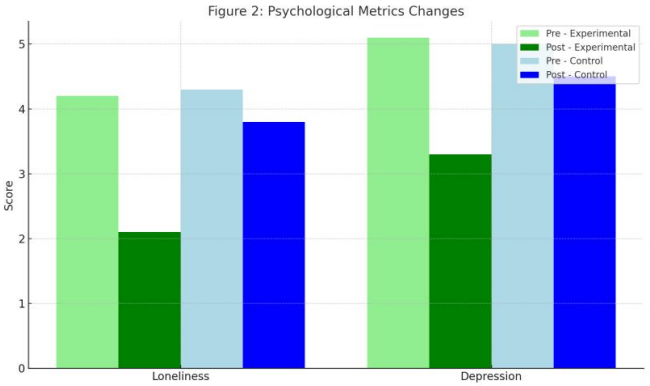

Fig.2. Psychological Health Indicators Change

3) Emotional Data Feedback for Design Optimization

Positive Emotion Peaks: These occurred after the successful completion of tasks, with the feedback mechanism significantly enhancing user satisfaction.

Frustration Emotion Points: These were observed at the initial stage of Task 2, where emotion analysis guided optimizations to the interaction path.

This figure shows the distribution of positive emotion peaks and frustration points during the task completion process, with the experimental group exhibiting prominent optimization effects.

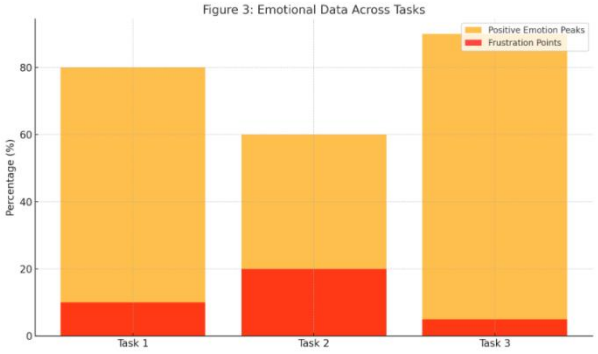

Fig.3. Emotion Data at Different Stages of Task Completion

I. Experimental Results and Analysis Summary

The experimental results indicate that:

The multimodal sentiment analysis–driven interface design significantly enhanced elderly users' digital skills and operational efficiency, effectively narrowing the digital divide (supporting H1).

The emotional design strategies improved elderly users' loneliness and psychological health, stimulating cognitive abilities (supporting H2).

The feedback from emotional data allowed for dynamic design optimizations, boosting user emotional experience and satisfaction (supporting H3).

This experiment provides systematic, quantitative evidence and practical guidance for age–friendly design.

5. Discussion and Analysis

J. The Mechanism of Multimodal Sentiment Analysis in Age–Friendly Design

The results of this study show that multimodal sentiment analysis plays a pivotal role in age–friendly user interface design. The mechanism of this technology manifests in several key areas:

1) Accurate Emotion Perception

By integrating multimodal signals, such as visual, voice, and textual data, sentiment analysis technology can detect the emotional state and interaction barriers of elderly users in real time. This provides crucial insights into the emotional needs of users, offering a clear guide for interface design.

2) Emotion–Driven Design Optimization

Emotional feedback plays a crucial role in guiding design improvements. For example, this feedback can simplify interaction processes, enhance emotional responses, and improve content presentation, ensuring that design modifications align with users' emotional states and needs.

3) Promoting Digital Integration and Psychological Health

optimizing digital interaction experiences, sentiment analysis technology boosts elderly users' engagement and confidence in using digital devices. This creates a positive cycle of "emotion perception → design optimization → increased participation → psychological improvement," which benefits both digital inclusion and mental well–being.

This mechanism offers a new technological pathway for addressing both the digital divide and psychological health challenges among the elderly, while also expanding the potential applications of sentiment analysis in age–friendly design.

K. Effectiveness of Design Strategies

The research proposes several strategies, such as emotional visual

design, emotional interaction design, and emotional content design. These strategies showed a synergistic effect in the experiment:

1) Visual Design

Warm color tones, high-contrast color schemes, and simplified, intuitive icons and layouts significantly improved the readability and comfort of the interface. This design effectively supported elderly users in navigating the interface and carrying out tasks.

2) Interaction Design

Simplified interaction processes, gradual guidance, and immediate emotional feedback significantly enhanced elderly users' learning efficiency and confidence in digital skills. The design enabled smoother transitions for users who were less familiar with digital interfaces.

3) Content Design

The integration of multimedia elements and emotionally resonant language enhanced the attractiveness and emotional affinity of digital content. This design strategy contributed to a more engaging and positive user experience.

The experimental results validate the effectiveness of these strategies in improving elderly users' digital interaction experiences and psychological health. The findings suggest that age-friendly user interface design should focus on a multidimensional and synergistic approach to optimization.

L. The Impact of Individual Differences on Design Effectiveness

While the overall experimental results demonstrate the effectiveness of the design, individual differences among elderly users play a crucial role in determining the outcome of the design:

1) Age and Health Status

Older individuals and those with poorer health conditions experienced more difficulty with digital interaction. For these users, the interface design needs to emphasize usability and accessibility features, such as voice navigation or larger font modes, to provide additional support.

2) Digital Experience

Digital novices tend to rely more heavily on guidance features and basic task prompts. In contrast, experienced users prioritize efficiency and advanced functionality. Therefore, the interface should offer customizable options that cater to both novice and experienced users.

3) Cultural Background and Preferences

Preferences for visual styles and interaction methods vary based on cultural and habitual differences. The design should strike a balance between personalization and universality, ensuring it can accommodate diverse user preferences while maintaining a consistent user experience.

Future research should focus on refining the stratified needs of elderly users, allowing for more personalized age-friendly design solutions.

M. Research Limitations and Future Directions

This study has certain limitations in sample size, experimental setting, and technological implementation, which suggest several directions for future research:

1) Sample Size and Diversity

The participants in this study were largely from a specific region and demographic group. Future studies should expand the sample size to include participants from diverse cultural backgrounds and socioeconomic levels to ensure the findings are generalizable.

2) Experimental Setting Limitations

Laboratory conditions may not fully replicate the complexity of real-world interaction scenarios. Future studies should focus more on observing and analyzing user behavior in long-term, natural settings to capture more authentic user experiences.

3) Technological Precision and Application Scope

While multimodal sentiment analysis technology is promising, there is still room for improvement in terms of real-time processing and accuracy. Furthermore, its application in emerging digital scenarios, such as virtual reality or the Internet of Things, requires further exploration.

Future research could leverage cutting-edge technologies like artificial intelligence and virtual reality, combining cross-disciplinary approaches to develop a more comprehensive theoretical and practical framework for age-friendly user interface design.

6. Conclusion and Future Outlook

A. Research Conclusions

This study explores the interactive mechanisms through which multimodal sentiment analysis technology contributes to age-friendly

user interface design, aiming to bridge the digital divide and enhance the mental health of elderly users. The primary research conclusions are as follows:

1) Theoretical Framework Construction and Validation

A theoretical framework for age-friendly user interface design based on multimodal sentiment analysis was constructed. This framework includes emotional perception, need modeling, emotion-driven design strategies, and an evaluation optimization mechanism. Empirical research confirmed its effectiveness in reducing the digital divide and improving psychological health.

2) Technological Application Value

Multimodal sentiment analysis technology can accurately capture the emotional needs of elderly users, optimizing design through emotional feedback. This significantly enhances user experience and operational confidence, fostering a positive cycle that boosts elderly users' willingness to engage with digital tools and their mental health.

3) Design Strategy Achievements

The collaborative optimization of emotional visual, interaction, and content design significantly improved elderly users' digital skills, emotional experience, and cognitive abilities. This highlights the positive role of age-friendly design in improving digital inclusivity and promoting healthy aging.

This research not only provides systematic theoretical support and practical pathways for age-friendly user interface design but also showcases the broad potential of multimodal sentiment analysis technology in digital design.

B. Future Outlook

Despite significant progress in age-friendly design, there is still vast space for exploration. Future research can further deepen and expand in the following areas to enhance elderly users' digital interaction experience:

1) Expanding the Scope of Research

a) Increasing Sample Size and Geographic Scope

The study's sample was concentrated in specific regions. Future research should expand the sample to include more regions, cultural backgrounds, and socioeconomic groups of elderly users. By comparing digital skills, emotional needs, and interface preferences across different regions, ethnicities, and cultures, designs can be tailored to be

more universal and targeted.

b) Focusing on Subgroup Needs

Beyond age and health status, deeper studies into the subgroups within the elderly population are needed. For example, elderly individuals living alone may prioritize social functions, while those with higher health management needs may require optimized health tracking and medical services interfaces. Additionally, developing personalized support features for those with cognitive impairments can help them adapt better to digital technology.

2) Integrating Cutting-edge Technologies

a) AI and Sentiment Analysis Fusion

Artificial intelligence (AI) can enhance the accuracy of multimodal sentiment analysis, recognizing emotional states and automatically adjusting interface designs according to different emotional patterns. AI can also push personalized digital content and services, further enhancing elderly users' experience.

b) Virtual Reality (VR) and Augmented Reality (AR) Applications

VR and AR technologies can offer more immersive and interactive digital experiences. For example, VR-based virtual social platforms can help alleviate loneliness among elderly users, while AR can provide real-time operational guidance, making interfaces more intuitive and user-friendly. Furthermore, VR and AR can be utilized for cognitive training and rehabilitation activities to improve elderly users' cognitive abilities.

c) Internet of Things (IoT) Potential

IoT technology can connect elderly users' digital devices with smart homes, providing an intelligent living environment. For instance, smart sensors can monitor health conditions in real time and adjust home settings based on the data, offering timely reminders and services.

C. Strengthening Long-term Effects Research

1) Long-term Natural Experiments

Future research should involve long-term tracking of elderly users' behavior and psychological state changes in everyday life. Compared to controlled laboratory settings, long-term natural experiments better reflect the actual use scenarios and allow for the evaluation of the long-term impact of age-friendly designs.

2) Comprehensive Evaluation of Quality of Life and Social Integration

In addition to digital skills and mental health, future studies should

examine how age-friendly designs affect elderly users' quality of life and social integration. By assessing elderly users' physical health, mental status, and social relationships, the impact of these designs on their social interactions and participation in society can be better understood, offering a more holistic view of age-friendly design's role in active aging.

D. Promoting Policy Support and Industry Practice

1) Policy Support and Guidance

Governments should introduce policies to support the development and application of age-friendly digital technologies. Providing research funding, tax incentives, and industry standards will facilitate the widespread implementation of age-friendly designs. Policy guidance can also increase societal awareness of elderly users' digital needs, further promoting digital inclusion for elderly populations.

2) Encouraging Industry Collaboration and Innovation

Collaboration between digital technology companies, elderly care institutions, and design firms should be strengthened to create an age-friendly digital ecosystem. Through partnerships with research institutions and businesses, technology innovation and product optimization can be accelerated, facilitating the adoption of age-friendly design principles.

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