Eye Tracking in Human-Computer Interaction Research: Themes, Roles, and Trends (Post-print)

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Abstract

[Purpose/Significance] Eye-tracking is widely applied in human-computer interaction research. Analyzing eye-tracking within this domain can deepen our understanding of the current state of eye-tracking applications in human-computer interaction, the role that eye-tracking plays in this process, and future research directions. [Method/Process] Using databases such as Web of Science and ACM as data sources, Python and VOSviewer were employed to cluster relevant research topics, and related article content was summarized to analyze eye-tracking-related content in human-computer interaction research from both "quantitative" and "qualitative" perspectives. [Results/Conclusion] Interaction input, output, and application directions constitute the main themes of interest in related research, while eye-tracking plays different roles across different research themes. The research trends summarized based on the "quantitative" and "qualitative" analyses can provide references for subsequent research on eye-tracking and human-computer interaction.

Full Text

Eye-Tracking in Human-Computer Interaction Research: Themes, Roles, and Trends

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Abstract:
[Purpose/Significance] Eye-tracking is widely used in human-computer interaction (HCI) research. Analyzing eye-tracking applications in HCI can deepen our understanding of the current state of research, the role of eye-tracking in this

process, and future research directions. [**Method/Process**] Using Web of Science and ACM as data sources, Python and VOSviewer were employed to cluster relevant research topics. The content of related articles was summarized to analyze eye-tracking in HCI research from both "quantitative" and "qualitative" perspectives. [**Result/Conclusion**] Interactive input, output, and application directions are the main topics of related research, with eye-tracking playing different roles across different research themes. Research trends summarized based on "quantitative" and "qualitative" analyses can provide reference for subsequent eye-tracking and HCI research.

Keywords: Human-Computer Interaction; HCI; Eye-Tracking; Research Trends
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Human-computer interaction is a discipline related to the design, evaluation, and implementation of interactive systems for human use. It primarily investigates the relationship between human cognition, information processing, and interactive behavior, focusing on how to design, implement, and evaluate interactive systems based on human activities, with particular emphasis on human-computer interaction relationships and implementations. Consequently, it has attracted attention from computer science, cognitive science, information science, and related disciplines. From the early stages of computer language command interaction and graphical user interface interaction to today's natural human-computer interaction era, HCI has increasingly emphasized human-centered natural interaction. To enable users to express interaction intentions more conveniently and effectively while allowing computers to accurately recognize these intentions, multi-channel interaction methods integrating visual, auditory, tactile, and other sensory modalities have become important approaches for achieving natural human-computer interaction.

Vision is a crucial pathway and sensory channel for humans to receive external information. By tracking and capturing human eye fixation points, we can obtain human visual information. To realize multi-channel human-computer interaction methods, eye-tracking has been widely applied in HCI research and has become an important method and technology. The increasing application of eye-tracking in HCI research makes reviewing its research status particularly necessary. This not only helps us understand the application of eye-tracking in HCI research and grasp macro-level development trends but also provides directional references for the organic integration of eye-tracking and HCI research in the future. Based on this, using Web of Science and ACM databases as literature sources, with search terms such as ("eye-tracking" or "gaze-tracking" or "eye detecting" or "gaze detecting" or "eye-tracking" or "gaze-tracking" or "eye movement") AND ("human-computer interaction" or "HCI" or "human-machine interaction" or "computer-human interaction" or "machine-human interaction" or "human-robot interaction"), we retrieved and screened relevant literature, obtaining 2,081 articles. This paper uses Python and VOSviewer

visualization tools to process and analyze the obtained literature, summarizing the current state of research, development trends, and the role of eye-tracking in HCI research, aiming to provide directional references for the future integration and development of eye-tracking and HCI research.

1. Analysis of HCI Research Themes Integrating Eye-Tracking

1.1 LDA-Based Research Theme Analysis

This paper applied Python to conduct LDA topic analysis on the abstracts of the obtained literature to identify current research themes in eye-tracking-based HCI. LDA can identify topic information in a corpus. Since the articles were retrieved using specific search terms, these terms became high-frequency vocabulary in the articles, making distinctions between different topics less obvious. Therefore, based on stop-word removal, we also removed words containing search terms from the abstracts, such as "eye-tracking" and "human-computer interaction." When attempting to divide topics into 3-10 categories, we found that classification worked best with 6 topics, as differences between themes could be clearly identified. Thus, we ultimately chose to divide the relevant research into 6 categories, with results shown in .

Table 1. LDA Topic Analysis Results for Eye-Tracking-Based HCI Research

Topic Category	Keywords	Theme Summary
Input	input, visual, mouse, touch, typing, dwell, gestures, keyboard, multimodal, interface	Interactive Input
Tracker	tracker, calibration, estimation, camera, 3d, position, pupil, accuracy, systems, model	Eye-Tracking Devices

Topic Category	Keywords	Theme Summary
Movement	movement, image, pupil, head, detection, accuracy, algorithm, features, estimation, techniques	Gaze Estimation
Data	data, visual, visualization, design, dynamic, quality, approach, content, real, time	Visualization
Cognitive	cognitive, search, reading, web, attention, behavior, interface, driving, patterns, usability	Behavior and Usability
Design	design, attention, visual, environment, virtual, VR, collaboration, mobile, devices, software	Virtual Reality

In Table 1, "Keywords" represent the terms from each LDA topic category. Based on these classification results, we summarized the keywords to derive theme names and further categorized them into "Topic Categories" according to each theme's content. The table reveals that input is a primary focus in HCI research using eye-tracking analysis. Among input methods, keyboard/mouse, gestures, and touch are common ways for users to input information to interactive devices. To enable more natural interaction, multimodal input methods have become a topic of interest. Regarding input devices, research on more lightweight, accurate, and simple eye-tracking devices constitutes an important topic in eye-tracking-based HCI. Compared to commercial eye-trackers, current eye-tracking algorithms emphasize detecting pupil positions, particularly in natural environments, making eye-based HCI more natural and providing assistance for daily eye movement analysis and context-aware research.

In gaze estimation, accurate eye movement capture forms the foundation of related research, while algorithms and techniques help improve gaze capture accuracy and identify head and pupil positions. In interactive output, LDA topic analysis shows that visualization is a current research focus. Related studies emphasize data visualization, referring to how computers process and output eye-tracking data—namely, how to reveal collected eye-tracking data more intuitively and vividly. LDA topic analysis also reveals that user behavior and usability evaluation constitute a research direction for eye-tracking in HCI. Capturing users' eye movements in specific contexts such as reading and driving can combine eye-tracking with cognition to improve learning efficiency and deeply investigate driving behaviors. Web or application development and evaluation are also research concerns. By analyzing user behavior through eye-tracking, usability evaluation of applications can be conducted to achieve specific functions or meet user needs in particular contexts, supporting richer human-computer interaction.

1.2 VOSviewer-Based Keyword Co-Occurrence Analysis

Keyword co-occurrence can reveal key content in related research from a terminological perspective. Therefore, we used the visualization tool VOSviewer to conduct co-occurrence and clustering analysis of article keywords to preliminarily explore research content from a keyword perspective. Unlike LDA topic analysis data, VOSviewer uses author-assigned keywords, while LDA uses article abstracts. VOSviewer is a knowledge mapping software that visualizes relationships in bibliographic data. For analysis type, we selected co-occurrence analysis with "keywords" as the unit of analysis. During keyword preprocessing, since articles were related to "eye-tracking" and "human-computer interaction," these terms were high-frequency and would affect keyword co-occurrence visualization. Therefore, we excluded keywords that were search terms when visualizing keyword co-occurrence relationships. The final keyword co-occurrence results are shown in [Figure 1: see original paper].

In the figure, larger circles indicate more frequent keywords. The co-occurrence results show that related research can be roughly divided into six categories related to virtual reality, visual attention, visualization, usability, visual search, and gaze estimation, which is largely consistent with LDA topic analysis results. Figure 1 shows that virtual reality frequently co-occurs with gaze input, eye input, accessibility, and assistive technology, reflecting that effective interactive input methods are a focus in virtual reality. Visual attention correlates with terms like virtual environment, design, and video games, showing that vision has been explored and applied in other areas. Visualization correlates with scan path, cognitive load, visual analysis, and gaze user interface, reflecting visualization's role in intuitively revealing eye-tracking data, paths, and user cognition. Regarding usability, terms like usability evaluation, user experience, and reading co-occur frequently, revealing the close relationship between usability and user experience/behavior. Visual search is one way users input information to

machines, with eye saccade information helping identify visual search paths. Additionally, in gaze estimation, machine learning methods are applied, with eye-trackers, gaze control, and gaze gestures also related, indicating that visual input receives significant attention and that machine learning methods are valued and applied by researchers.

In summary, eye-tracking-based HCI research features diverse and rich themes with close connections between them. For instance, virtual reality research is often related to user interactive input. In HCI research, input and output have always been two important components, with the ultimate goal of providing more natural interaction methods and promoting research applications in more areas.

2. The Role of Eye-Tracking in HCI Research

2.1 Fusion of Visual Channel in HCI Methods

In HCI processes, users interact with device interfaces to generate input and output for achieving their goals or completing tasks. Keyboard/mouse, voice, gestures, and touch are common input methods. Eye-tracking has long been an effective HCI method, proven to have potential for improving daily HCI interface quality. In this process, users can control computers using only eye movements, typing by looking at keys on a virtual keyboard without manual input. Additionally, in specific systems, users can control mouse pointers with their eyes to complete device interactions. Eye-tracking plays an important role in these HCI processes: since user eye movements can reveal fixation points and scan paths, researchers can intuitively understand what users primarily focus on, accelerating graphic selection speed in graphical user interfaces (GUIs) and providing assistance for object selection in virtual reality, improving VR application quality, and saving bandwidth and resources.

With multi-channel interaction technology development, multi-channel interaction methods including eye movement combined with language have proven effective in compensating for single-input method limitations and improving user-system interaction efficiency. Multi-channel interaction refers to systems integrating two or more input channels (such as gaze, voice, touch, gestures). In multi-channel interaction, users can engage visual, auditory, and haptic sensory channels through eye movements, hands (including gestures and touch), voice, or combined methods for full interaction with devices.

"Eye-tracking + keyboard/mouse" is a common user-device interaction method in HCI research, particularly in interactive information retrieval. Since information retrieval is a cognitive process of user psychology and behavior interaction, researchers use eye-tracking to record user behavior, psychological and cognitive characteristics, preferences, or differences when users complete specific tasks with keyboard and mouse, analyzing how different factors (such as task difficulty/type, interactive devices/software, and demographic variables like age) affect user behavior. Eye-tracking helps record eye movement trajectories, fa-

cial expressions, and emotions to identify eye movement patterns and establish relationships between eye movements, search behavior, and other factors like user emotion.

"Eye-tracking + hand" is another common interaction method. Users can interact deeply with different devices (e.g., computers and phones) through "eye-tracking + touch," "eye-tracking + gesture," or "eye-tracking + gesture + keyboard/mouse" methods. Multi-touch interfaces enable simultaneous multi-finger interaction, making "eye-tracking + touch" possible. In this method, the relationship between eye movement features (particularly fixation) and touch receives attention. Research shows users exhibit two fixation behaviors before touching screens, with fixation used for target selection. Combined with multi-touch, this enables faster and more natural HCI and context switching. Compared to touch, keyboard, and mouse input, gesture input better utilizes hand expressiveness for rich interaction (e.g., extensive gesture input in 3D operation tasks), making "eye-tracking + gesture" and "eye-tracking + gesture + keyboard/mouse" fast, accurate, and touch-free interaction methods important multi-channel approaches. In "eye-tracking + hand" methods, different input methods are highly complementary, reducing pure eye input errors while improving target selection speed compared to pure hand input. Eye-tracking helps improve interactive interface target selection accuracy and enhance user HCI experience.

"Eye-tracking + voice" is another user interaction method with speech recognition systems or applications. In command and control contexts, combining eye-tracking and voice can reduce speech command ambiguity and improve speech recognition system accuracy. However, this interaction method plays different roles in different contexts. For example, in collaborative interaction scenarios, it helps different users complete tasks more accurately, while in driving scenarios, since different interaction methods have various advantages and disadvantages, the interaction method between driver and device must be selected based on specific contextual needs to avoid accidents.

2.2 Fusion of Eye-Tracking in Interactive Output and Application Directions

HCI interfaces are the medium for user-device interaction and an indispensable part of HCI. User eye movements are often used to develop and evaluate different types of interactive interfaces, with gaze-controlled interfaces being one type. In gaze-controlled interfaces, text input is typically implemented through virtual keyboards. User eye movement conditions and features play a fundamental and important role in developing and evaluating gaze-controlled interfaces, forming the basis for this interface type. During development, researchers must capture real-time eye movement trajectories, perform system calibration, detect pupil center positions, match raw eye-tracking data with scene images, select target words and/or objects in scene images, and adopt specific measures to optimize algorithms and stabilize cursor positions on user screens.

When users first encounter an interface, the navigation experience directly affects their first impression and subsequent behavior and usage intentions. Therefore, user eye movement features can measure interaction experience, highlighting the importance of user experience in HCI research. As HCI environments evolve from desktop to mobile, mobile HCI interface development and evaluation have gradually attracted researcher attention, particularly mobile game interface development and evaluation. Players have different visual strategies in different interaction contexts (e.g., free browsing vs. task-oriented), leading to different metrics for predicting mobile game navigation interface interaction experience. Therefore, in mobile game navigation interface development, besides using different eye-tracking metrics, researchers should fully consider player motivation to provide better interaction experiences.

3D interaction interfaces are another common type in HCI. 3D technology is widely used in entertainment (e.g., games, movies) and work contexts (e.g., hospital surgical environments), making 3D interaction interface development and evaluation a research focus. However, due to the lack of a third physical dimension, using standard input methods like touchscreens for 3D user interface interaction is problematic. In such cases, user gaze can be incorporated as an auxiliary interactive input method in 3D interaction interface development.

Virtual Reality (VR), Augmented Reality (AR), and Augmented Virtuality (AV) technologies provide users with more interaction methods and deeper, more immersive experiences. Whether adding auxiliary virtual information to real environments (AR) or using real objects to assist interaction in virtual environments (AV), eye-tracking plays an indispensable role. Taking VR as an example, user eye-tracking data can improve navigation or interaction accuracy in VR. By tracking and collecting user eye-tracking data and using machine learning methods to train models and identify user eye movement patterns and fixation depth, researchers can analyze and predict whether users need help during VR device interaction (e.g., navigation services during roaming). Additionally, user eye-tracking data can aid VR platform development. For educational VR, researchers have proposed eight visual cues to restore attention, providing reminders when eye-tracking detects student attention shifting away from key objects, making educational VR more visually attractive, improving learning experiences, and developing VR services for education.

2.3 The Role of Eye-Tracking in HCI Research

The ACM SIGCHI Curriculum Development Group proposes that HCI research mainly relates to four components: users, computers, interactive system development, and interaction contexts. Eye-tracking plays different roles in each component. Based on the aforementioned "quantitative" (topic clustering) and "qualitative" (article content) analyses, we summarize eye-tracking's roles. Since user-machine interaction typically occurs in specific contexts or scenarios, interaction context represents the specific background or conditions of user interaction. Therefore, tracking and analyzing user eye movements in specific inter-

action contexts ultimately means tracking and analyzing user eye movements during HCI input and output processes.

In user-related research, eye-tracking primarily explores user input methods to interactive devices. In current HCI research, besides eye movement input, eye input methods are often studied with other input methods (e.g., keyboard/mouse, voice, touch, gestures) to explore multi-channel input approaches.

In computer-related research, eye-tracking plays two main roles: first, in developing and evaluating interactive interfaces—using eye-tracking to develop interfaces and evaluate how specific elements affect user visual attention, applying these to education, life, work, and other contexts; second, in processing and analyzing eye-tracking data, often related to computer algorithms for cleaning and processing tracked eye movement data to achieve research objectives.

In system development, eye-tracking's role manifests in two aspects: first, developing new eye-tracking devices by capturing user eye movement information to train models and develop new devices; second, evaluating interactive system technologies or functions by tracking user eye movement information to assess whether functions meet user expectations and needs, providing support for future system improvements.

3. Trends in Eye-Tracking-Based HCI Research

3.1 Increasingly Rich Interaction Contexts

Eye-tracking applications in HCI feature diverse contexts such as teaching, work, and entertainment, with eye-tracking playing different roles in different application contexts. Additionally, due to various interactive devices like mobile equipment, HCI scenario switching becomes more frequent. In teaching contexts, eye-tracking can help students improve visual attention; in entertainment contexts, it can provide more immersive and realistic experiences. In information-rich contexts, how to provide accurate information recommendations based on context or develop intelligent adaptive interfaces that combine context with eye-tracking input methods represents a future direction for HCI research.

3.2 Broader Interaction Subjects

HCI research has evolved from focusing on individual and general user interaction behaviors to emphasizing interaction accessibility for elderly people, disabled individuals, vulnerable groups, and all people, covering increasingly more interaction subjects. While previous research examined interaction behaviors, interface design, and experiences for cognitive inhibition or impairment groups and visually impaired groups, other vulnerable groups (e.g., children with autism, children with genetic diseases) have gradually received attention. Eye-tracking has become a powerful tool for studying cognition and visual attention development in groups with potential cognitive impairments.

Furthermore, user eye movement features correlate with emotions—for example, pupil dilation when users are surprised. Since emotions affect interaction experience and continued usage intention, identifying user facial expressions based on eye movement features to establish associations with user emotions represents an important development trend in current eye-tracking HCI research.

3.3 Increasingly Efficient System Support

Effective interactive system operation relies on underlying data and algorithm support. Using deep learning or other machine learning methods to process eye-tracking data, identify eye movement scan path patterns, cluster fixation data, handle large-scale eye-tracking data, and predict user fixation and other eye movement features are ongoing research concerns. Additionally, eye-tracking data visualization is key to analyzing and presenting eye-tracking data. Therefore, how to scientifically and intuitively visualize user fixation and other eye-tracking data, or how to organically combine visualization analysis with machine learning, are also important research trends in eye-tracking and HCI.

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Li Jiyuan: Data processing;
Wu Dan: Research proposition, writing-review and editing.

Note: Figure translations are in progress. See original paper for figures.