

Research on Human-Computer Interaction using Eye Movement Technology in Fighter Cockpit Design

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Abstract:

The transformation of modern air combat modes has intensified the cognitive load of pilots in combat. As the main place for pilots to obtain battlefield information, make decisions and carry out tasks, the fighter cockpit directly affects the combat efficiency of pilots. A good cockpit interaction system can reduce the cognitive load on pilots, assist in decision-making, and improve combat effectiveness. Eye movement technology is a widely used physiological measurement technique. By analyzing eye tracking data, the effectiveness of human-computer interaction can be evaluated and the cockpit interface of fighter jets can be optimized. It can also be used as an interaction mode (eye control) to improve interaction efficiency and flight safety. By reviewing the current research status of eye tracking technology in the field of aircraft cockpit interaction design, this paper explores the potential advantages of eye control in human-computer interaction and summarizes the difficulties and technical problems that current researchers urgently need to solve, hoping to provide new ideas for future fighter cockpit design.

Keywords:

Eye Movement Technology, Eye Control, Human-Computer Interaction, Fighter Cockpit, Human Factors and Efficacy

1. Introduction

In the field of military aviation, the level of automation of fighter jets is gradually increasing. Pilots can perceive the battlefield situation and make decisions by monitoring the information inside and outside the cabin through the cockpit human-computer interaction interface. However, the explosive information emerging on the modern fighter cockpit interface has increased the cognitive load of pilots and affected the combat efficiency. Eye movement technology has the advantages of being intuitive, natural, and having high spatiotemporal resolution, and is widely used in fields such as education, medicine, design, marketing, and psychology. In military applications, in addition to helping researchers measure the cognitive load of pilots, attention allocation strategies, and evaluate flight skills and fatigue states, eye

movement technology can also be used as a new human-computer interaction mode (eye control) to quickly understand the intentions of pilots, assist in decision-making, and improve combat efficiency. This article summarizes the research status of eye movement technology in the field of aircraft interaction design, and focuses on analyzing the advantages of eye control in the interaction design of fighter cockpits and various problems that need to be urgently resolved, hoping to provide reference for future fighter cockpit design.

2. Research Status of Eye Movement in Human-Computer Interaction in Fighter Cockpits

Human-Computer Interaction (HCI): Input devices and output devices use corresponding methods in the computer to achieve a purpose of communication between the computer and people [1]. It includes the interaction among the three elements of people, machines, and the environment.

In contemporary air combat, pilots need to quickly identify, process, and handle the information presented by the computer to understand the combat situation and make decisions. Therefore, the efficiency of human-computer interaction directly affects the ability and efficiency of pilots' command and decision-making. In the military, human-computer interaction technology has completed the iteration from single-point to multi-point touch and from single-channel to multi-channel human-computer interaction technology. Compared with single-point touch that can only recognize one touch point at the same time, multi-point touch technology collects signals through hardware, software detects, tracks, and recognizes gestures, and finally sends user commands. It can collect information from multiple contact points at the same time, making HCI more convenient. Through multi-point touch technology, military commanders can view real-time intelligence in different areas, quickly switch data interfaces, etc., which greatly improves the speed and accuracy of decision-making. Pilots can quickly select weapon systems, lock targets, adjust attack parameters, etc., enhancing the flexibility and response speed of combat. In addition, multi-point touch technology also helps simplify the layout of the fighter cockpit, reduce the number of mechanical keys and knobs, reduce the operational burden of pilots, and improve the HCI experience. Compared with a single-channel interaction mode, multi-channel interaction technology comprehensively uses multiple different interaction channels (tactile, auditory, visual, etc.) to allow users to interact with the computer system more naturally, efficiently, and flexibly, and has gradually become the mainstream of contemporary interaction system design. At present, the National University of Defense Technology has developed a multi-channel interaction prototype system based on multi-point touch of the two-handed channel and the voice channel to analyze intelligence and combat situations.

Eye movement technology, that is, gaze tracking technology, is to capture the gaze trajectory by recording the movement changes of the eyeball through instruments to study people's psychological activities. In the military, domestic and foreign research scholars mainly use eye movement technology to carry out the following research:

(1) Using eye movement technology to study the visual attention distribution of pilots on different instruments, display screens, and control devices in the cockpit, so as to optimize the cockpit interface layout and information presentation mode and improve the efficiency of pilots in capturing key information. Song Zhitong found through analyzing the total fixation time that under the character coding size of

6.5mm character height, 400WC3C stroke width and 100 character spacing, the pilot has the highest information recognition efficiency [2]. Zuo Jiangli confirmed the best effective boundary distance and the air traffic controller's color preference for HCI by analyzing the eye movement data of the air traffic controller trainee experiment [3].

(2) Study the information processing mode and cognitive load of pilots: Blinking and pupil-related indicators (saccade amplitude, blinking frequency, pupil size variability, etc.) can reflect the difficulty of information processing and the degree of fatigue of pilots. Pan Lingling analyzed the data of the reaction time, blinking rate, heart rate variability of the subjects under different lighting environments, and concluded that the visual load is the lowest when the cockpit illumination is 1500Lux [4]. Xu Hanyang verified the effectiveness of the eye movement parameters detection method for the fatigue state in the flight mission in view of the problems existing in the Head-Up Display (HUD) of the "Xiaolong" fighter. When the ground personnel detect that the pilot's fatigue risk index is high, the task adjustment can be made in time [5]. Wang Sirui proposed a pilot situation awareness state evaluation method based on visual fixation information based on eye movement data and the visual environment area of interest in the aircraft cockpit, and the accuracy of this method reaches 91.53% [6].

(3) Evaluate the usability and ease of use of the aircraft cockpit interface. Yang Kun evaluated the effectiveness of the flight instrument layout by building a simple simulation platform and collecting the eye movement data of the subjects driving different aircraft models to complete three simulated flight tasks of straight climb, straight flight, and horizontal turn [7]. Abroad, Li W C proved through experiments that the integrated digital display layout is more in line with humanized requirements than the decentralized pointer display layout [8].

(4) In flight simulation training, comparing the eye movement patterns of professional group and inexperienced group students and analyzing the differences in their attention characteristics can better provide personalized guidance for new students. Liu Zhifang found that the downward-looking and head-up display presentation systems are respectively suitable for the precise flight of the professional group and the learning and training of novice pilots [9]. Lu et al. found through simulated flight tasks that pilots have more out-of-cabin fixation times and fixation durations during circling tasks. When the attention characteristics of pilots conform to this distribution pattern, good situation awareness (SA) level and flight efficiency can be achieved [10]. The experimental results provide guidance for the practice of flight students' attention.

The above research shows that by processing the eye movement data collected at each stage of HCI, many flight problems such as information acquisition and reception efficiency, attention stability and allocation strategy, evaluation of pilots' cognitive load and fatigue state, and task difficulty can be analyzed. This part of the research is already very mature at home and abroad, but the application of eye movement technology in evaluating the effectiveness of the cockpit still faces the following problems: (1) The selected eye movement indicators are single and the evaluation system is not perfect; (2) When there are many eye movement indicators, the credibility of the qualitative analysis results will be reduced, and it is urgent to establish a mathematical model for quantitative analysis; (3) The single eye movement technology evaluation method has limitations; (4) The test accuracy

depends on the calculation method of eye movement data, and the error accuracy under different test methods varies greatly [11].

3. New Development of Eye Movement Technology - Eye Control

With the development of eye movement technology, researchers are no longer limited to using it as a means of measuring and evaluating human-machine ergonomics, but also study it as an interaction mode (eye control). Eye control, that is, by presetting a reasonable eye movement human-computer interaction mode, allowing the machine to receive the user's line of sight with trigger intention to perform operation tasks [12]. Compared with traditional touch control and voice control, eye control has the characteristics of flexibility, convenience, naturalness and intuitiveness. Its advantage lies in being able to increase the information flux transmitted in HCI [13], and it is especially suitable for scenarios such as military operations that require rapid response and processing of a large amount of information. At present, eye control has been applied in the fields of assistive devices for the disabled, medical diagnosis, virtual reality, and so on.

There are generally four modes of eye control: fixation control, blink control, smooth pursuit, and eye gesture control. In the first two modes, the unconscious fixation of the human eye is prone to cause misoperation, and closing the eyes for a long time will lose the fixation point and reduce the interaction efficiency and accuracy. It is generally suitable for static operations such as key triggering. Smooth pursuit is a low-speed saccadic movement and is suitable for dynamic actions such as sliding up and down and rotating left and right. Eye gesture is an active, purposeful, and conscious line-of-sight movement path, also called fixation posture. It can meet more interaction needs than the first three types. It has the advantages of low interface requirements, low misoperation, fast interaction efficiency, and not easy to cause eye fatigue. In aircraft design, using eye control technology and combining other physiological sensors (such as EEG, heart rate, etc.) or behavior data for multimodal interaction research can track the state of pilots, reduce cognitive load, and assist their decision-making. This is also the direction that researchers are vigorously developing in fighter cockpit design at present.

3.1. Research Status of Eye Control in Human-Computer Interaction

In 1986, Mikaelian et al. developed the earliest eye control input device. This system adopted the interaction mode of fixation input and verified the advantages of eye control in quickly selecting target objects [14]. In 1999, Zhai combined the fixation input system with gestures to improve the accuracy and naturalness of the single-channel mode [15]. In 2002, Ward et al. developed a device for disabled people to type quickly using the eye control interaction mode [16]. In 2011, Carrino combined wearable visual indications, icons, and voice input commands to achieve multi-channel human-computer interaction, but wearable devices affect the flexibility and freedom of human-computer interaction [17]. In 2013, Heekyung Lee introduced eye control technology into TV devices. By tracking the user's eye movement trajectory and obtaining high-resolution eye images, it is possible to interact with various multimedia on a long-distance screen [18]. In 2014, the Cymek team used smooth gaze tracking to execute trigger button commands [19]. In 2015, Yang helped bedridden patients build an interaction system that controlled the hospital bed to its designated position through eye control [20]. In the same year, the team of Dalian University of Technology developed an eye control mouse, which completed the

single and double clicks of the mouse through controlling the length of the smile time and ensured the accuracy of eye control. In the medical field, patients with Amyotrophic lateral sclerosis(ALS) are difficult to communicate with the outside world through conventional methods (touch control, voice control, etc.). Eye control technology combined with the delayed trigger mode can help them achieve information input and is a reliable and efficient means of life assistance. For example, in 2008, Intel designed an auxiliary communication system for Hawking. This device can trigger the letters appearing on the interactive screen by controlling eye movements [21]. With the development of eye control technology, researchers have begun to pay attention to key factors affecting human-machine ergonomics such as eye control recognition accuracy and interaction efficiency. In 2010, Mollenbach et al. proved that the eye movement speed in the horizontal direction is faster than that in the vertical direction, and the long-distance eye movement interaction mode is not as easy to trigger as the short-distance one [22]. In 2014, Murata et al. studied the influencing factors of the efficiency of eye control fixation input and found that when a rectangular cursor is used on the interaction interface, it takes users a long time to complete the specified tasks [23]. In 2019, Zhu Xiaoxiao explored the characteristics of single-step eye gesture interaction actions and found that the 16 eye control actions in different directions and distances do not interfere with each other, and the corresponding eye control actions can be designed according to the priority of interaction needs [24]. In 2022, Zhu Guangming and others used clustering and Bayesian inference methods to establish an eye movement intention algorithm and built a new simulation business platform. The research found that the effective eye control accuracy of the mouse based on the eye movement intention prediction algorithm reached 95.0%, and the efficiency of eye movement-assisted hand-controlled mouse movement increased by 24.4%, which greatly improved the interaction efficiency and user experience [13].

In the military field, Jiang Guihu and others believe that eye control has the characteristics of initiative, timeliness, openness, and intelligence, which can increase the information transmission flux and accelerate the OODA (detection-confirmation-decision-attack) closed loop, and can effectively shorten the reaction time of pilots [13]. Moreover, compared with the dependence of voice control on environmental safety, eye control is more suitable for air combat scenarios with rapid information changes and harsh combat situations. However, the fighter cockpit interaction system is precise and complex, and the single-channel interaction mode with only eye control has the following shortcomings: (1) the limitation of information transmission; (2) poor adaptability and inability to deal with complex and changeable communication scenarios and needs; (3) the monotony of the human-computer interaction process and insufficient interactivity, and inability to establish a deep human-computer relationship. Therefore, the multi-channel interaction mode that combines eye control with other sensory channels is the key to optimizing the interaction design of the fighter cockpit.

3.2. Research Status of Multi-Channel Eye Control Technology in Fighter Cockpit Design

Vision has the advantages of high sensitivity in information acquisition, strong adaptability, and being able to simultaneously perceive multiple attribute information of the target, but it has disadvantages such as limited visual field, strong dependence on light, and prone to produce illusions after fatigue. Especially for fighter pilots,

these will increase the probability of information perception errors. The multi-channel interaction mode system integrates two or more information input channels such as touch, gesture, voice, and line of sight, which can make up for the deficiencies of each channel to a certain extent [25], achieve efficient information transmission, enrich information expression, reduce misunderstandings, and meet the diverse interaction needs and habits of users.

In 2016, Chen Huijuan selected two typical flight mission types (feedback delay tasks and tasks with a large visual field) to conduct experiments on the subjects. The experiments showed that the human-computer interaction mode combining touch and hearing can reduce the load of the visual channel and assist in improving the visual perception ability, which is conducive to improving the operation efficiency and task performance of pilots [25]. In 2020, Feng Yue and others proposed to intelligently control the machine by setting some eye movement behaviors (such as positioning and locking the position of the human eye fixation) by comparing and analyzing the cockpit human-computer interaction modes of the first to fourth generation fighter jets [26]. In 2021, Wang Wai and others proved that the measurement method combining eye movement and EEG can improve the accuracy of user intention recognition and provide technical support for the adaptive design of the aircraft human-computer interaction system [27]. In 2022, Jiang Guihu and others proposed the fusion logic of eye movement interaction and traditional voice interaction, and iteratively designed the existing fighter cockpit human-computer interaction system. The human-computer interaction system includes an eye movement tracking calibration module, an eye movement signal processing module, and an eye movement interaction mode recognition module, which can effectively improve the human-computer interaction efficiency of the fighter cockpit and reduce the cognitive load of pilots [12]. In 2024, Liu Guanghui and others pointed out that the future fighter smart cockpit integrating new interaction methods such as eye control, gesture, somatosensory, and voice will help pilots quickly capture combat information and achieve agile confrontation on the battle field [28].

At present, the aircraft cockpit is facing problems such as a single human-computer interaction mode, a complex human-computer interface, a heavy information perception load, and a narrow cockpit field of view. These factors all restrict flight safety and combat efficiency. The multi-channel interaction mode combined with eye control can enable pilots to operate more flexibly in a complex combat environment, improve the human-machine synergy effect, complete combat tasks, and meet the natural, efficient, and comprehensive requirements put forward by the new battlefield for the fighter's human-computer interaction system. At present, domestic and foreign research scholars have carried out experiments on other types of machinery and equipment and civil aircraft, explored and verified some reasonable eye control interaction actions, the best eye control parameters, and the combination mode of multi-channel interaction, etc., but in the field of fighter design, the majority of scholars still need to supplement the corresponding action mechanisms, gradually improve the above experimental research, and explore the best eye control multi-channel interaction mode under the premise of ensuring the safety of pilots and completing combat tasks.

3.3. Problems Existing in Eye Control in Fighter Cockpit Design

In military aviation, while ensuring that pilots complete combat tasks, it is also necessary to iteratively optimize the system to improve information acquisition

efficiency, reduce pilots' cognitive load, enhance pilots' situational awareness ability, and improve the ease of use and satisfaction of human-computer interaction [29]. The multi-channel interaction mode combining eye control and other sensory channels is expected to become the first choice to solve this problem. However, the application of eye control technology in the design of new aircraft is still in the exploration stage, and the technology is not mature enough. To truly be applied to the human-computer interaction system of fighter aircraft, problems in eye movement tracking calibration, eye movement signal setting, eye movement signal processing, and eye movement interaction mode recognition need to be solved:

(1) Difficulties exist in information processing and processing: The nystagmus caused by the eye's own movement and extreme combat scenarios and the electromagnetic interference have a great impact on the acquisition and processing of eye movement data. Adaptive smoothing filtering processing is needed to avoid the phenomenon of "errors, omissions, and losses"; (2) The eye movement calculation method based on software and hardware needs to balance the relationship between the user's head freedom degree and the calculation accuracy; (3) Reasonably design eye control interaction actions, which should be different from unconscious eye movements and not be too complicated to increase the cognitive load of pilots; (4) The information processing of different sensory channels has interference. The best eye control technology mode of multi-channel fusion and the corresponding parameter settings should be explored according to the characteristics of different flight situations; (5) Powerful algorithm support and deep learning are needed to quickly process large-scale eye movement data and identify eye movement interaction modes to understand user intentions, speed up the execution of tasks, and ensure the accuracy of operations; (6) There are differences in the eye physiological characteristics, habits, and preferences of different pilots. It is necessary to establish models and algorithms that can adapt to individual differences to ensure the universality and reliability of the system; (7) In the fighter combat environment, the reliability of the system is crucial. The eye movement interaction system must have high stability and fault tolerance to deal with equipment failures and emergencies.

4. Conclusions

At present, countries are making every effort to develop fifth-generation fighter jets. The development trend of the future fighter cockpit human-computer interaction system is more intelligent, natural, and efficient, aiming to improve the safety of pilots and the performance of fighter jets. The fighter cockpit human-computer interaction system based on eye control has the advantage of being able to naturally and directly obtain the pilot's focus of attention and behavioral intention, so as to carry out information interaction, decision-making, and operation control quickly and accurately. At present, eye movement technology shows more and more extensive application scenarios. The multi-channel interaction mode combining eye control and other sensory channels is bound to become a core technology for optimizing the fighter human-computer interaction system, but there are still many problems in practical applications. For example, factors such as the movement characteristics of the eyeball itself, cabin vibration, high load, and electromagnetic interference will interfere with the collection of eye movement data; the user intention judgment (Midas contact) problem will cause visual fatigue of the pilot and lead to a decrease in the efficiency of the interaction system; it is difficult to balance the fixation accuracy of eye movement control and the head freedom of the pilot; there is a lack of relevant

human-machine ergonomics standards and specifications, etc. Relevant personnel should continuously overcome the technical difficulties of eye control in fighter design to provide pilots with better flight guarantee and human-computer interaction experience.

Conflicts of Interest

The authors guarantee that this paper is an original work and has not been published.

This paper has no disclosure.

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