Game Development Based on Physiological Signals

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Abstract: The paradigm of gaming is shifting from mere entertainment products to intelligent emotional interaction platforms. Integrating physiological signals—such as electroencephalography (EEG), electrocardiography (ECG), galvanic skin response (GSR), eye tracking, and electromyography (EMG)—significantly enhances user immersion and engagement. This study systematically analyzes the differential contributions of unimodal and multimodal physiological signals in game development. The perceptual mechanisms and interaction potential of key signals—including EEG encompassing（Steady-State Visual Evoked Potential (SSVEP), P300, and Motor Imagery (MI)), eye tracking, electrooculography (EOG), and EMG—are examined. Comparative case studies demonstrate unimodal implementations (e.g., EEG focus-controlled games, MI-based parkour games, EMG-driven Virtual Reality (VR) rehabilitation) and multimodal integrations (e.g., EEG-EOG hybrid systems for intent recognition, EEG-eye tracking synchronization in VR). Results indicate that unimodal approaches offer implementation efficiency and task-specific effectiveness, yet exhibit limited experiential dimensionality. Conversely, multimodal integration substantially enriches the user experience and enhances system robustness, albeit presenting significant technical integration challenges. This research concludes that overcoming multimodal fusion bottlenecks is critical for future advancement. Refining signal optimization mechanisms will accelerate the application of emotionally interactive gaming paradigms in entertainment and therapeutic domains.

1 INTRODUCTION

Games have profoundly integrated into daily life and are undergoing a transformative shift—evolving from pure entertainment products toward intelligent affective interaction and immersive experience platforms. To continuously enhance player immersion, engagement, and interest, game designers and researchers persistently pursue more precise and profound methods for insight into player states. Traditionally, game design relied predominantly on questionnaires, playtesting sessions, and designers' intuition/experience to evaluate player experience and guide optimization. Crucially, these approaches exhibit fundamental limitations: most provide only post-hoc and superficial insights, lacking the capacity for real-time, uninterrupted, and objective detection of players' complex, dynamically fluctuating internal physiological and psychological states during gameplay (e.g., excitement, boredom, frustration, flow state, cognitive load, startle response). This constrains designers' understanding of authentic player experiences and impedes precise tuning of gameplay and personalized adaptation. To elevate user immersion, engagement, and interest, researchers increasingly integrate physiological signals—such as electroencephalography (EEG), electrocardiography (ECG), galvanic skin response (GSR), eye tracking, and electromyography (EMG)—into game design. These signals offer inherent objectivity, continuity, and accuracy, thereby opening novel pathways for game development. Consequently, integrating physiological signals into game design not only serves as a powerful complement to traditional evaluation methods but more significantly propels games toward greater intelligence, emotional resonance, and deep experiential engagement, substantially enhancing player interest.

This paper first introduces the physiological signals employed in game research and development, outlining the advantages of incorporating them. Subsequently, it presents case studies of game

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development utilizing unimodal physiological signals, followed by an exploration of the benefits of multimodal signal integration and corresponding multimodal game development examples. A comparative analysis concludes that unimodal and multimodal physiological signal integration serve distinct roles in game development. This paper aims to provide a foundation for understanding how physiological signals can enhance interactive experiences, and to encourage broader applications in next-generation game design.

2 COMMON PHYSIOLOGICAL SIGNALS

EEG is a non-invasive technique for mapping brain signals, providing direct measurement of cortical activity with sub-millisecond temporal resolution (Vaid, Singh, & Kaur, 2015). It measures voltage fluctuations arising from ionic currents within neurons. EEG signals are typically represented as a two-dimensional matrix, where one dimension corresponds to the spatial arrangement of electrodes (channels) and the other dimension corresponds to time, reflecting task-related brain potentials (Altaheri et al., 2023). Key EEG-derived signals include: Steady-State Visual Evoked Potential (SSVEP) This refers to the response detected in the visual cortex when a user fixates on a visual stimulus flickering at a specific frequency. The user's intent can be identified based on this frequency-locked response (Huang, 2021). Compared to other EEG signals, SSVEP offers the advantages of operational simplicity, strong signal stability, and superior noise resistance (Müller-Putz, Scherer, Brauneis, & Pfurtscheller, 2005). In gaming, players can interact by simply gazing at specific elements (e.g., fixating on a flashing icon can be interpreted as a command to select or activate a function).P300 This is an event-related potential (ERP) component, specifically a positive deflection in the EEG waveform occurring approximately 300 ms after the presentation of an infrequent or significant target stimulus (e.g., a flashing letter). It plays a critical role in Brain-Computer Interfaces (BCIs), particularly in applications like the P300 speller, where detecting this waveform allows users to select characters on a screen (Cecotti & Graser, 2011). In games, it may occur when a player focuses on a specific event (e.g., their character being attacked). Detecting the P300 wave can be used to infer player intent, potentially triggering hints or dynamically reducing game difficulty. Motor Imagery (MI): This denotes the mental rehearsal of a movement without any physical execution. In the context of EEG, MI signals are complex and exhibit high-dimensional structure (Altaheri et al., 2023). When a user imagines limb movement, characteristic changes occur in the power of μ (8-12 Hz) and β (13-30 Hz) frequency bands within the EEG. MI enables players to control game mechanics through thought (e.g., mentally grasping objects).

Eye Tracking involves monitoring eye movements (gaze points, pupil changes) using cameras or infrared sensors. Eye tracking technology has emerged as a promising tool for enhancing user experience and interaction in Virtual Reality (VR) games. Research indicates that smooth pursuit eye movements can be effectively utilized for object selection and interaction within VR environments (Khamis et al., 2018). Furthermore, eye tracking metrics can assess user experience, satisfaction, and attention in VR games, enabling the development of adaptive games that respond in real-time to player performance and behavior (Soler-Dominguez et al., 2017).

Electrooculography (EOG) is a technique for measuring eye movements by recording the electrical potential around the eyes. It is based on the chorioretinal potential, which changes with eye movement. EOG technology offers significant advantages for VR game interfaces. EOG-based systems provide hands-free, natural interaction, thereby enhancing the immersive experience within VR environments (Kumar & Sharma, 2016).

EMG is a technique used to record the electrical activity produced by muscles. It measures the electrical potentials generated during voluntary or involuntary muscle contractions. This method is crucial for various applications, including muscle fatigue detection, control of robotic mechanisms and prosthetics, and the clinical diagnosis of neuromuscular disorders (Boyer, Bouyer, Roy, & Campeau-Lecours, 2023).

3 HARNESSING PHYSIOLOGICAL SIGNALS FOR GAME DEVELOPMENT: UNIMODAL AND MULTIMODAL APPROACHES

3.1 Integration of Unimodal Physiological Signals in Game Development

Integrating physiological signals into game development has emerged as a transformative approach, significantly enhancing both gameplay experience and entertainment value. Game development based on unimodal physiological signals offers relative technical simplicity and demonstrates high efficacy for direct control or affective state monitoring, substantially improving user immersion and overall experience.

Lü et al. designed a BCI game utilizing the TGAM EEG module and the Unity engine. Their method involved extracting features from EEG waves via the TGAM module and processing these features to derive user focus levels and blink signals. The Unity engine was then employed to control a ball's speed changes and jumping behavior based on the extracted focus data and blink signals. This approach markedly enhanced user immersion and experience during gameplay while also improving player attention. It represents a successful experimental application of BCI technology within the gaming domain (Lv et al., 2024).

Du proposed a comprehensive method for constructing an online MI BCI gaming platform using portable devices. The method first involved designing a data acquisition paradigm and incorporating both offline and online training to enhance subjects' MI capabilities. Secondly, the author presented a preprocessing scheme tailored for offline training to improve the signal-to-noise ratio (SNR) and conducted a comprehensive analysis of various feature extraction methods—including Common Spatial Patterns (CSP) and Riemannian geometry—to optimize feature selection. Subsequently, the study focused on analyzing the generalization capability and robustness of Riemannian geometry classifiers, conducting comparative experiments using CSP + Linear Discriminant Analysis (LDA) as a benchmark across different sessions and subjects. These experiments validated the method's effectiveness and feasibility on a self-collected dataset. Finally, a complete BCI platform—encompassing data acquisition to game control—and an online MI-controlled parkour game were designed and implemented. Following offline training, all 4 subjects successfully achieved real-time control of the game, attaining a maximum game control success rate of 87.5%. This platform also serves as an application testing framework for other BCI systems (Du, 2022).

Duan et al. developed a VR wrist rehabilitation training system based on EMG signals. This research involved acquiring surface EMG signals from wrist movements and decoding movement intention using muscle synergy theory to control the VR game. Concurrently, stochastic disturbance forces were introduced within the game environment, and impedance control was employed to facilitate interaction between the user and the virtual environment, encouraging the exploration of different movement control strategies. Experiments confirmed the system's feasibility. Comparative training experiments (with vs. without stochastic disturbance forces) evaluated its effectiveness, demonstrating that training with disturbance forces reduced task completion time by 24% and increased path efficiency by 26%compared to training without such forces. These results prove that the system effectively promotes the adoption of more efficient motor control strategies by users, thereby enhancing training efficiency (Duan, Zeng, & Song, 2024).

3.2 Game Development Based on Multimodal Physiological Signals

Compared to unimodal approaches, multimodal integration provides users with richer, more adaptive gaming experiences and enables more accurate emotion detection. The fusion of multiple signals enhances interaction richness and system robustness, making it particularly suitable for highly immersive scenarios such as VR.

Li et al. proposed a hybrid BCI system method based on EEG and blink EOG for recognizing MI intentions. The system's performance was tested in both 3D Tetris and 2D game environments. The study focused on: 1) extracting features from EEG, CSP methods against a proposed multi-feature extraction approach; and 2) developing game-BCI control strategies to improve players' BCI control proficiency. To validate the effectiveness of the 3D game environment in enhancing players' ability to generate Event-Related Desynchronization (ERD)/Event-Related Synchronization (ERS), the 2D screen-based game served as the control experiment. Statistical results demonstrated that the group executing MI tasks within the 3D Tetris environment exhibited a significantly greater enhancement in generating MI-related ERD/ERS. Game score analysis revealed a clear upward trend in player scores within the 3D environment, whereas no significant decreasing trend was observed in the 2D environment. These findings indicate that an immersive and control-rich MI environment can improve relevant mental imagery and enhance MI-based BCI skills (Li et al., 2017).

Larsen et al. presented a synchronization method for multimodal physiological data streams, specifically integrating EEG with eye-tracking within a VR headset. They implemented a hybrid SSVEP-based BCI speller within a fully immersive VR environment as a proof-of-concept use case. Hardware latency analysis indicated an average offset of 36 ms and an average jitter of 5.76 ms between the EEG and eye-tracking data streams. The proposed VR-BCI speller concept demonstrated its potential for real-world applications. These results confirm the feasibility of combining EEG and VR technology for neuroscientific research, establishing new pathways for studying brain activity within VR environments. This work also lays the groundwork for refining synchronization methods and exploring application scenarios such as learning and social interaction (Larsen et al., 2024).

4 CURRENT LIMITATIONS AND FUTURE OUTLOOK

Game development based on unimodal physiological signals is relatively mature. Unimodal signals, such as Electrodermal Activity (EDA) and EEG, provide valuable insights into player emotions during gameplay. This approach enables developers to create games that adapt to players' emotional responses, enhancing engagement and immersion. By leveraging physiological signals, games can dynamically adjust based on player reactions. For instance, game difficulty or narrative elements can be modified in real-time according to a player's stress or excitement levels, leading to more personalized gaming experiences. The commercial viability of games incorporating physiological signals is growing. The release of controllers with integrated physiological sensors, such as Sony's Dualshock 5, signifies a trend toward mainstream acceptance of biofeedback in gaming. This development will likely drive broader adoption of physiological signals in game design (Hughes & Jorda, 2021). Conversely, multimodal integration combines multiple physiological signals to deliver richer, more accurate gaming experiences, significantly boosting player interest. Nevertheless, multimodal game development faces substantial technical challenges. Effectively integrating and optimizing these heterogeneous physiological signals remains a primary hurdle. Future research should prioritize Optimizing signal utilization to enhance player experience and therapeutic outcomes and exploring the full potential of multimodal approaches to overcome current limitations.

5 CONCLUSIONS

As games evolve from entertainment products toward intelligent affective interaction media, integrating physiological signals (EEG, ECG, GSR, eye tracking, EMG, etc.) into game design is becoming a critical technological pathway to enhance user immersion, engagement, and interest. This paper systematically reviews the sensing mechanisms of common physiological signals and examines the distinct contributions and applications of uni-modal versus multi-modal physiological signals in game development.

The research first explains the principles and game interaction potential of EEG (including SSVEP, P300, MI), eye tracking, EOG, and EMG signals. It then focuses on two key dimensions: applications of uni-modal physiological signals in games, and game development under multi-modal physiological signals. In the unimodal analysis, highlight its technical simplicity through case studies including brain-controlled games (focus/blink-controlled ball movement, MI-based running games) and EMG-driven VR rehabilitation training, demonstrating its effectiveness in enhancing immersion and enabling specific functional control. For multi-modal fusion, explore techniques such as EEG+EOG for MI intention recognition and EEG+eye tracking integration in VR, establishing multimodal approaches' significant value in delivering richer adaptive experiences, improving interaction robustness (especially in VR scenarios), and facilitating user skill acquisition.

This study constructs a methodological framework for physiological signal selection and fusion design, summarizing key technologies. This paper concludes that while unimodal approaches offer simplicity, they provide limited experiential dimensions; multimodal integration substantially enhances experiential richness and accuracy but faces challenges in technical integration. Future research should prioritize overcoming multimodal fusion bottlenecks to advance optimized applications in gaming and therapeutic domains. This work establishes theoretical and technical foundations for developing next-generation intelligent affective interaction games.

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