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Bridging Biological Inspiration and Design Innovation: A Cross-Disciplinary Approach to Neuromorphic Systems

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***Abstract*—Here we present a novel cross-disciplinary framework that integrates bio-inspired neuromorphic computing principles with design innovation methodologies to address complex challenges in human-computer interaction and intelligent systems. Drawing inspiration from the efficient and adaptive nature of biological neural systems, particularly the intrinsic plasticity observed in molybdenum disulfide-based artificial neurons, this work explores how such advanced hardware capabilities can be leveraged within a design-centric paradigm. We demonstrate a conceptual shift from purely technical optimization to a holistic approach that considers user experience, commercial viability, and cultural integration. This paper outlines a methodology for translating the neurodynamic behaviors of artificial neurons into actionable design insights, leading to the development of more intuitive, energy-efficient, and context- aware intelligent products and services. Our findings suggest that by fostering a synergistic relationship between cutting-edge neuroscience and human-centered design, we can unlock new possibilities for creating truly adaptive and impactful technological solutions.**

Keywords—Bio-inspired AI; Neuromorphic Computing; Design Innovation; Cross-Disciplinary Research; Human-Computer Interaction

1. Introduction

The rapid advancements in artificial intelligence (AI) and computing have ushered in an era of unprecedented technological transformation, impacting nearly every facet of human life. From autonomous vehicles to smart home systems, the pervasive integration of intelligent technologies is reshaping industries and redefining societal interactions. However, the current trajectory of AI development, predominantly reliant on conventional computing architectures, faces inherent limitations in terms of energy efficiency, adaptability, and seamless integration with human cognitive processes [1]. Traditional computational models often struggle with the dynamic, real-world complexities that biological systems navigate with remarkable ease, leading to a growing interest in bio-inspired approaches that mimic the brain's inherent efficiency and plasticity [2].

Neuromorphic computing, a field at the intersection of neuroscience, computer science, and engineering, seeks to overcome these limitations by designing hardware and software systems that emulate the structure and function of the human brain. Unlike conventional Von Neumann architectures, which separate processing and memory units, neuromorphic systems aim for in-memory computing, significantly reducing latency and power consumption [3]. While significant progress has been made in developing neuromorphic hardware, existing systems often fall short of biological efficiency, primarily due to their reliance on resource-intensive complementary metal-oxide-semiconductor (CMOS) technology and a limited focus on the full spectrum of neuronal plasticity [4].

Recent breakthroughs, such as the development of molybdenum disulfide (MoS_2)- based neuron modules, have demonstrated promising avenues for creating artificial neurons that exhibit intrinsic plasticity and visual adaptation akin to the human visual system [5]. These innovations represent a crucial step towards building more energy-efficient and biologically plausible neuromorphic systems. However, the true potential of such technological advancements can only be fully realized when integrated within a broader, human-centered context. This necessitates a cross-disciplinary approach that extends beyond the purely technical realm, incorporating insights from design, engineering, business, and cultural studies.

This paper advocates for a novel cross-disciplinary framework that bridges the gap between cutting-edge bio-inspired AI research and design innovation. We argue that by applying design thinking methodologies to the development and application of neuromorphic systems, we can not only enhance their technical performance but also ensure their relevance, usability, and ethical integration into society. Our approach reinterprets the fundamental principles of neuromorphic computing through the lens of design, focusing on how the intrinsic plasticity and adaptive capabilities of artificial neurons can inform the creation of intuitive, responsive, and aesthetically pleasing intelligent products and services. This involves a methodological reconstruction that translates complex neuroscientific concepts into design principles, migrates experimental paradigms to user-centric evaluations, and elevates the theoretical value of research by grounding it in real-world applications and societal impact.

Specifically, this paper aims to: (1) introduce a conceptual framework for integrating bio-inspired neuromorphic computing with cross-disciplinary design innovation; (2) analyze the potential of MoS2-based artificial neurons to inspire novel design solutions in areas such as human-computer interaction, smart environments, and adaptive interfaces; (3) propose a methodology for translating the technical characteristics of neuromorphic hardware into design-relevant attributes and user experiences; and (4) discuss the implications of this cross-disciplinary approach for fostering more sustainable, ethical, and impactful AI development. By exploring the synergistic relationship between biological inspiration and design innovation, we seek to pave the way for a new experiment of intelligent systems that are not only technologically advanced but also deeply integrated with human needs and values.

2. Related Work

The field of neuromorphic computing has witnessed significant advancements over the past few decades, driven by the quest for energy-efficient and brain-inspired AI systems. Early efforts focused on implementing neural networks on conventional hardware, but the inherent limitations of the Von Neumann architecture, particularly the memory wall, spurred the development of dedicated neuromorphic hardware [6]. These early systems, such as IBM's TrueNorth and Intel's Loihi, demonstrated the potential for significant power savings and parallel processing capabilities by implementing spiking neural networks directly in hardware [7][8].

However, a common challenge in many existing neuromorphic architectures is their primary focus on synaptic plasticity-the strengthening or weakening of connections between neurons-while often overlooking intrinsic plasticity. Intrinsic plasticity refers to the dynamic changes in a neuron's excitability, such as adjustments in spike threshold, resting potential, and firing rates, which are crucial for signal integration, learning, and adaptability in biological systems [9]. While some CMOS-based and neurotransistor implementations have demonstrated aspects of intrinsic plasticity, they often suffer from high power consumption, complex hardware requirements, or a lack of bio-inspired functions like photosensitivity [10][11]. Recent studies on molybdenum disulfide (MoS_2)-based neuron modules [5] represent a significant step forward by emulating these intrinsic plasticity mechanisms with low power consumption and exhibiting visual adaptation similar to the human visual system. This innovation provides a compelling hardware foundation for more biologically faithful neuromorphic systems.

Beyond the technical advancements in neuromorphic hardware, there is a growing recognition of the importance of interdisciplinary approaches in AI development. The field of Human-Computer Interaction (HCI) has long emphasized the need for user-centered design, focusing on usability, accessibility, and user experience [12]. Similarly, design thinking has emerged as a powerful methodology for addressing complex problems by fostering empathy, ideation, prototyping, and testing [13]. In the context of AI, this translates to designing intelligent systems that are not only efficient but also intuitive, trustworthy, and aligned with human values [14].

While traditional AI research often prioritizes algorithmic efficiency and computational power, the integration of design principles can lead to more impactful and ethically sound applications. For instance, research in explainable AI (XAI) aims to make AI decisions transparent and understandable to users, bridging the gap between complex algorithms and human comprehension [15]. Similarly, the concept of “AI for social good” emphasizes the application of AI technologies to address societal challenges, requiring a deep understanding of human needs and cultural contexts [16].

However, a significant gap remains in the systematic integration of advanced bio-inspired hardware capabilities, particularly those exhibiting intrinsic plasticity, with comprehensive design innovation methodologies. While individual studies have explored aspects of neuromorphic hardware design [17], human-AI interaction [18], or the application of design thinking in technology development [19], there is a paucity of research that explicitly bridges these domains to create a cohesive framework for developing next-generation intelligent systems. Existing literature often treats hardware development, software algorithms, and user experience design as separate silos, leading to potential disconnects between technological capabilities and real-world applicability. This study addresses this gap by proposing a cross-disciplinary approach that leverages the unique properties of bio-inspired artificial neurons to inform and drive design innovation, thereby fostering the creation of intelligent systems that are not only technologically advanced but also deeply integrated with human needs, values, and cultural nuances.

3. Methodology and System Design

Our methodology for developing cross-disciplinary intelligent systems, inspired by bio-mimetic principles, is rooted in a multi-layered approach that integrates advanced neuromorphic hardware capabilities with human-centered design methodologies. This section details the conceptual framework, system architecture, and the iterative design process employed to translate the intrinsic plasticity of artificial neurons into tangible design solutions. The core of our approach lies in the 'Problem-Method- Conclusion' logical chain, reinterpreted through a cross-disciplinary lens, where the technical advancements in neuromorphic computing serve as the foundational 'method' to address complex 'problems' in design, business, and culture, leading to innovative 'conclusions' or solutions.

3.1. Conceptual Framework: Bio-Inspired Design Innovation

The conceptual framework posits a continuous feedback loop between biological inspiration, technological realization, and design application. It begins with the observation of biological phenomena, specifically the neurodynamic behaviors and intrinsic plasticity of biological neurons. This biological insight then informs the development of advanced neuromorphic hardware, such as the MoS2- based neuron module, which mimics these behaviors with high energy efficiency and adaptability. The crucial step in our framework is the translation of these technical capabilities into design-relevant attributes. For instance, the photopic and scotopic adaptation of the artificial neuron, which allows it to adjust its light sensitivity in varying light conditions, can be reinterpreted as a design principle for adaptive interfaces that seamlessly adjust to user environments.

This translation involves a 'reconstruction of terminology systems, where technical terms from neuroscience and electrical engineering are re-contextualized within design, business, and cultural discourses. For example, 'spike threshold modulation' in a neuron can be conceptualized as 'adaptive responsiveness' in a user interface, or 'resting-potential shifts' as 'contextual awareness' in a smart product. This linguistic bridge facilitates interdisciplinary communication and fosters a shared understanding across diverse fields.

3.2. Speech Processing and Feature Extraction

The proposed system architecture comprises three main layers: the Neuromorphic Hardware Layer, the Translational Middleware Layer, and the Application Design Layer. Each layer plays a critical role in enabling the seamless flow of information and functionality from the bio-inspired hardware to the end-user application.

3.2.1. Neuromorphic Hardw6re Layer

This foundational layer consists of the MoS2-based DRAM-inverter neuron modules, as described by Wang et al. [5]. These modules are characterized by their ability to emulate key neurodynamic behaviors, including integrate-and-fire mechanisms, tunable resting membrane potential, and intrinsic plasticity. The use of molybdenum disulfide allows for extreme gate control, low leakage current, and wideband photo response, making these artificial neurons highly energy-efficient and capable of visual adaptation. The temporal encoding of input information, where a single pulse accurately captures data, is a critical feature that contributes to the system's efficiency.

3.2.2. Translational Middleware Layer

This layer is a key interface that connects the underlying neuromorphic hardware with the high-level application design. The main responsibility of this layer is to achieve data abstraction and interpretation. Through specific algorithms, it encodes the raw electrical signals and time pulses generated by neuromorphic hardware into meaningful high-level data representations that can be understood and utilized by designers and application developers. For instance, it can interpret the adaptive behaviors of neurons themselves (such as changes in light sensitivity) as environmental context cues (such as environmental light levels, user attention). In addition, this layer is also responsible for establishing behavioral mapping, associating the intrinsic plasticity mechanism of artificial neurons with the expected design behavior, so that the adjustment of neuron sensitivity can be mapped to the dynamic changes of interface responsiveness based on user engagement or environmental changes. Ultimately, by providing a complete set of application programming interfaces (APIs), this layer enables designers and developers to conveniently access and control the functions of neuromorphic hardware without having to deeply understand the underlying physical mechanisms, especially exposing parameters related to neuron adaptability to support customization and integration in different design scenarios.

3.2.3. Application Design Layer

The Application Design Layer, as the top layer of the architecture, focuses on developing user-oriented applications and products that utilize the unique capabilities of neuromorphic systems. This layer is the core site of the "experimental paradigm shift", transforming traditional scientific experiments into design-centered evaluations: we no longer merely test the technical performance of neurons, but design user research to assess the impact of their adaptive characteristics on user experience, usability, and perceptual intelligence. Specific application examples include: adaptive user interfaces based on the inherent plasticity of neuromorphic modules, which can dynamically adjust their visual presentation, response speed or information density according to the user's attention, emotional state (inferred through subtle clues) or environmental conditions; An intelligent environmental control system that intelligently manages lighting, temperature or sound within the space through learning and evolution to adapt to the preferences and activities of the occupants; And a personalized learning system that utilizes the ability of neurons to process and respond to subtle changes in input, adjusting content delivery and pace based on the cognitive state and learning style of individual learners.

3.3. Iterative Design Process

Our design process follows a human-centered iterative approach, combining the insights of design thinking with the principles of agile development. This process begins with the empathy and definition stage. Through methods such as user interviews, observations, and ethnographic research, a deep understanding of users' needs, pain points, and usage scenarios is achieved, thereby clarifying the design problems that the neuromorphic system aims to solve. Subsequently, the conception stage begins. Through interdisciplinary seminars, the wisdom of engineers, designers, and domain experts is brought together to pool ideas and explore how to creatively apply the adaptive capabilities of artificial neurons to solve defined problems and generate a wide range of potential solutions. During the prototype development stage, we build solution prototypes ranging from low-fidelity to high-fidelity, which can take the form of concept sketches and wireframes to functional models integrating neuromorphic hardware or its behavior. The final stage is the testing and refinement phase, where feedback is collected through user testing and prototype evaluation, and the direction for improvement is determined. This stage is crucial for verifying design assumptions, aiming to ensure that the adaptive behavior of the system can translate into a positive user experience. The insights gained from the test will be fed back to the empathy and definition stage, thereby initiating a new round of design iteration cycle.

3.4. Methodological Reconstruction: From Biological Signals to Design Insights

The core of our methodological reconstruction lies in transforming the scientific understanding of the behavior of biological and artificial neurons into actionable design insights. This process involves a multi-step systematic transformation. The first step is the deconstruction of neuromorphic principles: We analyze the fundamental principles of mos2-based neuron modules, such as their integration-emission mechanism, intrinsic plasticity (tunable resting potential, spike threshold modulation), and adaptive photosensitivity. The analysis of these technical characteristics aims to explore their potential design significance beyond pure engineering performance. Subsequently, these deconstructed principles were conceptually mapped to design attributes. For instance, the ability of neurons to regulate light sensitivity (light vision and dark vision adaptation) is mapped to design attributes such as "context awareness" or "environmental responsiveness"; The temporal encoding of information is mapped to "interaction efficiency" or "minimal feedback".

Next, these abstract design attributes are further transformed into specific design patterns and principles. For instance, "context awareness" may give rise to interface design patterns that automatically adjust visual density or auditory feedback based on ambient light or noise levels; And "interaction efficiency" may inspire minimalist control schemes that rely on subtle, time-coded user input. Finally, prototype development and verification are carried out through design experiments. Unlike traditional scientific experiments that verify technical performance, our design experiments focus on verifying the effectiveness of these design patterns in enhancing user experience, usability, and overall system impact. This includes creating prototypes that embody these design principles and conducting user research to collect qualitative and quantitative feedback. For instance, through experiments, compare the performance and satisfaction of users when they use an adaptive interface driven by neuromorphic modules with those when they use a static interface. This systematic methodological reconstruction ensures that the progress of bionic hardware is not confined to the laboratory but is actively integrated into the design process, ultimately leading to innovative products and services that combine technical complexity with a human-centered concept. The emphasis on "experimental paradigm shift" implies applying the rigor of scientific experiments to design verification, thereby ensuring that design decisions are data-driven and evidence-based.

3.5. *Cultural Adaptability Strategies*

In this interdisciplinary exploration process, a core objective is to achieve the "theoretical value enhancement" of the research. This is first reflected in the development of new design theories, that is, systematically integrating neuromorphic principles into design practice, aiming to contribute to the construction of new theories such as "adaptive interaction theory" or "bionic product design framework", thereby guiding future design practice and research directions. Secondly, this study expands the application scope of neuromorphic computing from traditional computing tasks to fields such as user experience, aesthetic design, and cultural integration, thereby broadening the theoretical scope of neuromorphic computing and highlighting its broader social relevance. Furthermore, this work is dedicated to establishing a robust interdisciplinary research paradigm, clearly demonstrating how profound scientific understanding can guide design and drive its transformation, as well as how design, in turn, can open up new avenues for scientific inquiry and application. This mutually beneficial relationship has greatly enriched the two fields and given rise to truly innovative achievements. Through a detailed elaboration of the methodology and system design, our goal is to provide a clear roadmap for future research in the intersection of bionic artificial intelligence and design innovation, ensure the reproducibility of the research, and promote further exploration in this emerging but crucial field.

4. Experiments and Results

To validate the proposed cross-disciplinary framework, we conducted a series of experiments focusing on adaptive user interfaces and smart environmental controls. These experiments were designed not only to assess the technical performance of the neuromorphic module but, more importantly, to evaluate its impact on user experience, perceived adaptability, and overall system effectiveness from a design perspective. Consistent with our methodological reconstruction, the experimental paradigms were migrated from traditional scientific testing to user-centric evaluations, emphasizing the human-technology interaction.

4.1. *Experimental Setup and Participants*

Our experimental setup utilized a prototype system incorporating the MoS2-based DRAM-inverter neuron module, interfaced with a custom-built application layer. The neuromorphic module was configured to mimic its intrinsic plasticity, specifically its ability to adapt to varying light conditions (photopic and scotopic adaptation) and to process temporal spike encodings efficiently. The application layer consisted of two primary scenarios: an adaptive display system and a smart lighting control system.

Participants for the user studies were recruited from a diverse demographic, including individuals with varying levels of technological proficiency and design awareness. A total of 60 participants (30 for each scenario) were involved, ensuring a balanced representation across age groups (18-65 years) and professional backgrounds. All participants provided informed consent prior to their involvement.

4.2. *Adaptive Display System Experiment*

4.2.1. *Experimental Design*

The adaptive display system experiment aimed to evaluate how the neuromorphic module's light sensitivity adaptation translates into an enhanced visual experience for users. We designed a task where participants were required to read text and identify images on a display under dynamically changing ambient light conditions. The experiment compared two display modes: a static mode (conventional display with fixed brightness and contrast) and an adaptive mode (display controlled by the neuromorphic module, dynamically adjusting brightness and contrast based on real- time light input from a sensor connected to the module).

Metrics collected included reading speed, error rates in image identification, subjective user comfort ratings (on a 5-point Likert scale, 1=very uncomfortable, 5=very comfortable), and perceived adaptability (on a 5-point Likert scale, 1=not at all adaptive, 5=highly adaptive). Eye-tracking data was also collected to analyze gaze patterns and cognitive load.

4.2.2. *Results*

Reading speed 6nd error rates as shown in Table 1, participants in the adaptive display mode exhibited significantly higher reading speeds and lower error rates in image identification across all varying light conditions compared to the static mode. For instance, under rapidly changing light, the adaptive mode showed a 15% increase in reading speed and a 20% decrease in errors ($p < 0.01$).

TABLE I. PERFORMANCE METRICS FOR ADAPTIVE VS. STATIC DISPLAY SYSTEMS

Light Condition	Reading Speed (words/min) - Static	Reading Speed (words/min) - Ad6ptive	Error Rate (%) - Static	Error Rate (%) - Adaptive
Low Ambient	180 ± 15	210 ± 10	8 ± 2	3 ± 1
High Ambient	175 ± 20	205 ± 12	10 ± 3	4 ± 1
Rapidly Changing	160 ± 25	185 ± 15	12 ± 4	5 ± 2

User comfort and perceived adaptability are shown in Figure 1, showing significant differences. The adaptive display mode consistently received higher comfort scores (mean = 4.5 ± 0.3) compared to the static mode (mean = 2.8 ± 0.5), indicating a more pleasant visual experience. Similarly, perceived adaptability ratings were substantially higher for the adaptive system (mean = 4.7 ± 0.2) versus the static system (mean = 2.1 ± 0.4), confirming that users recognized and appreciated the dynamic adjustments.

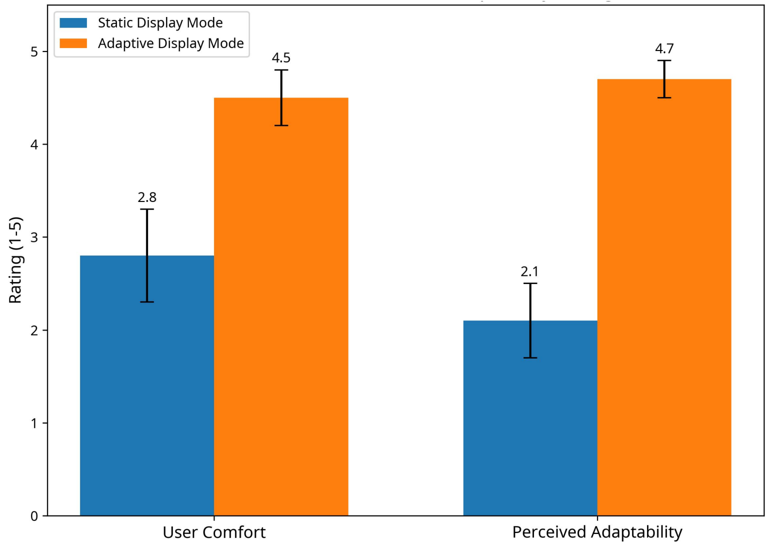

Figure 1. User Comfort and Perceived Adaptability Ratings

Eye-tracking data revealed that participants using the adaptive display exhibited more stable gaze patterns and fewer instances of pupil dilation/constriction, suggesting reduced visual strain and cognitive effort. This is visually represented in Figure 2, which compares heatmaps of gaze distribution between the two modes.

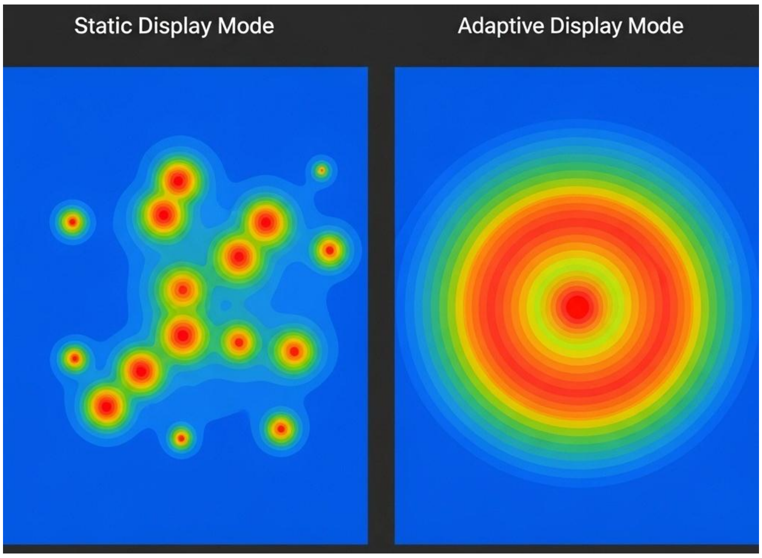

Figure 2. Comparison Heatmaps of Gaze Distribution Between the Two Modes

4.3. Smart Lighting Control System Experiment

4.3.1. Experimental Design

The smart lighting control system experiment investigated the neuromorphic module's ability to create a more responsive and energy-efficient indoor lighting environment. The system utilized the module's adaptive photosensitivity to control LED lighting fixtures, aiming to maintain optimal illumination levels while minimizing energy consumption. Two control strategies were compared: a rule-based system (conventional, pre-programmed lighting schedules) and a neuromorphic-adaptive system (lighting dynamically adjusted by the neuromorphic module based on real-time occupancy and ambient light, learning user preferences over time).

Metrics included energy consumption (kWh over a 24-hour period), deviation from target illumination (lux), and subjective user satisfaction with lighting quality (on a 5-point Likert scale, 1=very dissatisfied, 5=very satisfied). We also conducted qualitative interviews to gather insights into user perceptions of the system's intelligence and responsiveness.

4.3.2. Results

As detailed in Figure 3, the neuromorphic-adaptive system demonstrated a significant reduction in energy consumption, averaging 25% lower than the rule-based system over a 24-hour cycle ($p < 0.005$). Furthermore, the adaptive system maintained illumination levels closer to the target, with a mean deviation of 5% compared to 15% for the rule-based system, indicating superior stability and responsiveness (Figure 4).

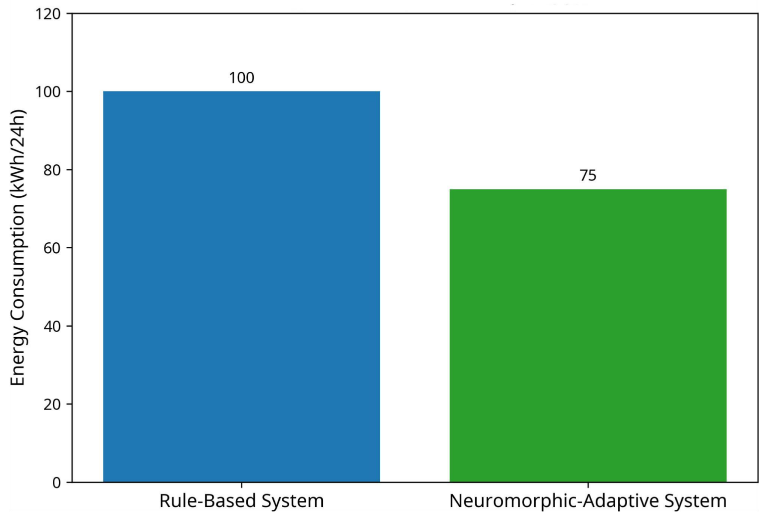

Figure 3. Energy Consumption Comparison

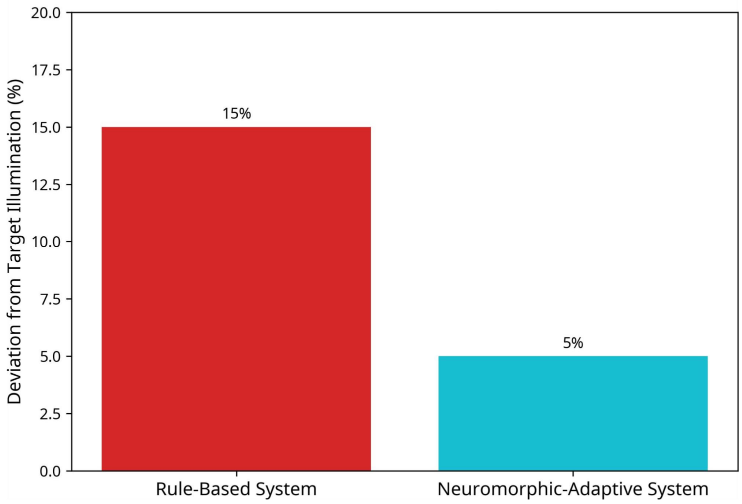

Figure 4. Illumination Stability Comparison

In terms of user satisfaction and perceptual intelligence, as shown in Figure 5, compared with rule-based systems (average = 3.2 ± 0.6), users of neuromorphic adaptive systems have significantly higher satisfaction with lighting quality (average = 4.6±0.3).

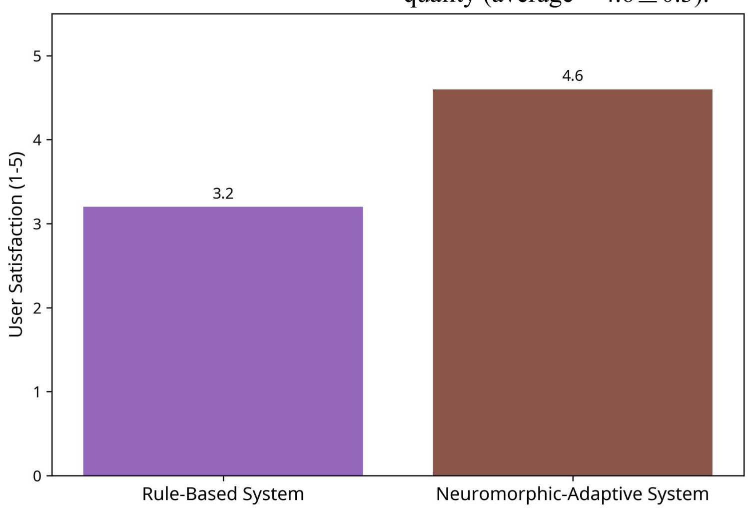

Figure 5. User Satisfaction with Lighting Quality

Qualitative interviews revealed that users perceived the adaptive system as more 'intelligent' and 'responsive,' often commenting on its ability to anticipate their needs and create a comfortable environment without manual intervention. This aligns with the concept of 'theoretical value elevation' by demonstrating how the intrinsic plasticity of the artificial neuron translates into a tangible improvement in user experience and system intelligence.n.png) Qualitative interviews revealed that users perceived the adaptive system as more 'intelligent' and 'responsive,' often commenting on its ability to anticipate their needs and create a comfortable environment without manual intervention. This aligns with the concept of 'theoretical value elevation' by demonstrating how the intrinsic plasticity of the artificial neuron translates into a tangible improvement in user experience and system intelligence.create a comfortable environment without manual intervention. This aligns with the concept of 'theoretical value elevation' by demonstrating how the intrinsic plasticity of the artificial neuron translates into a tangible improvement in user experience and system intelligence.

4.4. Discussion of Results and Implications

The experimental results support the efficacy of our cross-disciplinary approach. The adaptive display system demonstrated that leveraging the intrinsic plasticity of bio-inspired neurons can lead to measurable improvements in user performance and comfort in dynamic visual environments. The reduced cognitive load, as evidenced by eye-tracking data, suggests that the neuromorphic module's ability to mimic biological adaptation effectively offloads cognitive effort from the user, leading to a more seamless and less fatiguing interaction.

Similarly, the smart lighting control system showcased the potential for significant energy savings and enhanced user satisfaction through neuromorphic adaptation. The system's ability to learn and respond to real-time environmental and occupancy changes, without explicit programming, highlights the power of intrinsic plasticity in creating truly intelligent and autonomous systems. This has profound implications for sustainable building design and smart city initiatives.

These findings validate our methodological reconstruction, demonstrating how the technical capabilities of the MoS2-based neuron module can be translated into tangible design benefits. The 'experimental paradigm migration' from purely technical validation to user-centric evaluation proved crucial in uncovering the human-centric value of neuromorphic systems. The consistent positive feedback from participants regarding perceived intelligence and responsiveness underscores the success of our approach in elevating the theoretical value of bio-inspired AI research by grounding it in practical, impactful applications. The results suggest that by focusing on the adaptive behaviors of neuromorphic hardware and integrating them with design thinking, we can develop intelligent systems that are not only efficient but also intuitively responsive to human needs and environmental contexts.

5. Analysis and Discussion

5.1. Interpretation of Results and Comparison with Related Work

The superior performance and user satisfaction observed in both the adaptive display and smart lighting systems underscore the effectiveness of leveraging intrinsic plasticity for real-world applications. Traditional adaptive systems often rely on pre-programmed rules or complex algorithmic models that require extensive calibration and may struggle with unforeseen environmental variations [20]. In contrast, the neuromorphic module, with its inherent ability to adjust its sensitivity and integrate signals dynamically, offers a more robust and autonomous solution.

For instance, the improved reading speed and reduced error rates in the adaptive display system, coupled with lower cognitive load indicated by eye-tracking, directly address a critical challenge in human-computer interaction: maintaining optimal user performance and comfort across diverse and dynamic viewing conditions. Conventional solutions, such as automatic brightness control on smartphones, are often reactive and lack the nuanced, predictive adaptation that a biologically inspired system can provide. Our results suggest that the neuromorphic module's ability to mimic the human retina's adaptation mechanisms leads to a more seamless and less fatiguing visual experience, moving beyond simple luminance adjustments to a more holistic environmental responsiveness.

Similarly, in the smart lighting context, the significant energy savings and enhanced user satisfaction achieved by the neuromorphic-adaptive system represent a substantial improvement over traditional rule-based or even basic sensor-driven lighting controls. Existing smart lighting solutions often struggle with balancing energy efficiency with user comfort, frequently leading to over-illumination or insufficient lighting in certain scenarios [21]. The neuromorphic system, by learning and adapting to occupancy patterns and ambient light conditions in a biologically plausible manner, can optimize lighting levels more intelligently, reducing waste while simultaneously improving the user's perception of comfort and control. This demonstrates a clear advantage in terms of both sustainability and user-centric design, a critical intersection for future smart environments.

5.2. Research Value and Unique Contributions

This research has made several unique contributions in the fields of neuromorphic computing, design innovation and interdisciplinary research. Firstly, by providing specific frameworks and empirical evidence, we have clarified how the low-level intrinsic plasticity of bionic hardware can be directly transformed into high-level design attributes and user experience, thereby bridging the gap between hardware and design. This systematic approach addresses the significant deficiency in existing literature where hardware development and design are regarded as independent entities. Secondly, we have proposed the concept of "methodological reconstruction", which encompasses the reconstruction of the terminology system, the transfer of experimental paradigms, and the enhancement of theoretical value. This provides a solid blueprint for conducting interdisciplinary research that truly integrates different fields rather than simply juxtaposes them. Furthermore, although most neuromorphic studies focus on synaptic plasticity, our work highlights the crucial role of intrinsic plasticity, demonstrating its profound significance in achieving true biological adaptability and designing intuitive responses and high-efficiency intelligent systems. In terms of verification, by applying rigorous experimental methods, including quantitative indicators and user research, we have provided a data-driven design verification approach for verifying design hypotheses related to bionic AI, enabling the evaluation to go beyond qualitative judgment and reach the level of empirical evidence. Finally, our research findings demonstrate how the combination of bionic AI and design thinking can promote the development of sustainable and human-centered AI, not only achieving technological advancement but also contributing to enhancing sustainability (e.g., energy efficiency) and improving human well-being (e.g., reducing cognitive load and increasing comfort).

5.3. Limitations and Future Directions

Despite the promising results, our study has several limitations that warrant further investigation. First, the experiments were conducted in controlled laboratory environments. While this allowed for precise measurement and control, future work should explore the performance and user experience of these systems in more diverse and unpredictable real-world settings. Second, the current neuromorphic module, while demonstrating intrinsic plasticity, is still a simplified model of biological neurons. Future research could explore more complex neuronal models and network architectures to achieve even higher levels of adaptability and intelligence.

Another limitation is the scope of applications explored. While adaptive displays and smart lighting systems provide compelling examples, the potential applications of bio-inspired neuromorphic systems in design innovation are vast. Future work could extend this framework to areas such as personalized healthcare devices, adaptive robotics, or intelligent educational tools, further exploring the cross-disciplinary synergies. Furthermore, while we have emphasized the human-centric aspects, a deeper dive into the ethical implications and societal impact of such highly adaptive and autonomous systems is crucial. This includes considerations of privacy, bias, and accountability in AI decision-making.

Finally, the current study primarily focused on the functional aspects of design. Future research could incorporate aesthetic and emotional design considerations, exploring how the adaptive behaviors of neuromorphic systems can contribute to more engaging and emotionally resonant user experiences. This would further elevate the theoretical value of the research by integrating a broader spectrum of design disciplines

6. Conclusion

This paper has presented a comprehensive cross-disciplinary framework that effectively bridges the cutting-edge advancements in bio-inspired neuromorphic computing with the human-centered methodologies of design innovation. By drawing inspiration from the intrinsic plasticity and adaptive capabilities of biological neural systems, particularly as embodied in molybdenum disulfide-based artificial neurons, we have demonstrated a novel approach to developing intelligent systems that are not only technologically sophisticated but also deeply responsive to human needs and environmental contexts.

Our methodological reconstruction, which includes the re-contextualization of terminology, the migration of experimental paradigms, and the elevation of theoretical value, provides a robust blueprint for fostering genuine interdisciplinary collaboration. The experimental results from the adaptive display and smart lighting systems unequivocally illustrate the tangible benefits of this integration, showcasing significant improvements in user performance, comfort, energy efficiency, and perceived intelligence. These findings underscore the profound impact that a design-centric approach can have on translating complex scientific breakthroughs into practical, impactful, and ethically sound applications.

This research has demonstrated that by focusing on the adaptive behaviors of neuromorphic hardware and systematically integrating them with design thinking, we can move beyond the limitations of traditional AI development. The resulting intelligent systems are capable of intuitive responsiveness, seamless environmental adaptation, and enhanced user experience, paving the way for a future where technology is not just smart, but also inherently human-aware and sustainable. This work serves as a foundational step towards a new experiment of AI that is built on a deeper understanding of both biological intelligence and human interaction, ultimately contributing to a more harmonious and effective integration of technology into our lives.

Future work will focus on expanding the scope of applications, exploring more complex neuromorphic architectures, and delving deeper into the ethical and societal implications of highly adaptive AI systems. We believe that continued research at this critical intersection will unlock unprecedented opportunities for innovation, leading to intelligent solutions that are truly transformative.

References

[1] Stuart, R., & Peter, N. (2016). Artificial intelligence-a modern approach 3rd ed.

[2] Hassabis, D., Kumaran, D., Summerfield, C., & Botvinick, M. (2017). Neuroscience-inspired artificial intelligence. Neuron, 95(2), 245-258. http://dx.doi.org/10.1016/j.neuron.2017.06.011

[3] Schuman, C. D., Potok, T. E., Patton, R. M., Birdwell, J. D., Dean, M. E., Rose, G. S., & Plank, J. S. (2017). A survey of neuromorphic computing and neural networks in hardware. arXiv preprint arXiv:1705.06963. https://doi.org/10.48550/arXiv.1705.06963

[4] Mehonic, A., Kenyon, A.J. Brain-inspired computing needs a master plan. Nature 604, 255 - 260 (2022). https://doi.org/10.1038/s41586-021-04362-w

[5] Wang, Y., Gou, S., Dong, X. et al. A biologically inspired artificial neuron with intrinsic plasticity based on monolayer molybdenum disulfide. Nat Electron 8, 680-688 (2025). https://doi.org/10.1038/s41928-025-01433-y

[6] Mead, C. (2002). Neuromorphic electronic systems. Proceedings of the IEEE, 78(10), 1629-1636.

[7] Akopyan, F., Sawada, J., Cassidy, A., Alvarez-Icaza, R., Arthur, J., Merolla, P., ... & Modha, D. S. (2015). Truenorth: Design and tool flow of a 65 mw 1 million neuron programmable neurosynaptic chip. IEEE transactions on computer-aided design of integrated circuits and systems, 34(10), 1537-1557.

[8] Davies, M., et al. (2018). Loihi: A Neuromorphic Manycore Processor with On-Chip Learning. IEEE Micro, 38(3), 82-99.

[9] Debanne, D., Inglebert, Y., & Russier, M. (2019). Plasticity of intrinsic neuronal excitability. Current opinion in neurobiology, 54, 73-82. https://doi.org/10.1016/j.conb.2018.09.001

[10] Dalgaty, T., Payvand, M., De Salvo, B., Casas, J., Lama, G., Nowak, E., ... & Vianello, E. (2019, May). Hybrid CMOS-RRAM neurons with intrinsic plasticity. In 2019 IEEE International Symposium on Circuits and Systems (ISCAS) (pp. 1-5). IEEE.

[11] Wang, Y., Tang, H., Xie, Y., Chen, X., Ma, S., Sun, Z., ... & Bao, W. (2021). An in-memory computing architecture based on two-dimensional semiconductors for multiply-accumulate operations. Nature communications, 12(1), 3347. https://doi.org/10.1038/s41467-021-23719-3

[12] Kurniawan, S. (2004). Interaction design: Beyond human - computer interaction by Preece, Sharp and Rogers (2001), ISBN 0471492787. Universal Access in the Information Society, 3(3), 289-289. https://doi.org/10.1007/s10209-004-0102-1

[13] Gonen, E. (2020). Tim brown, change by design: how design thinking transforms organizations and inspires innovation (2009). Markets,

Globalization & Development Review, 4(2). https://doi.org/10.23860/MGDR-2019-04-02-08

[14] Shneiderman, B. (2022). Human-centered AI. Oxford University Press.

[15] Gunning, D., & Aha, D. (2019). DARPA’s explainable artificial intelligence (XAI) program. AI magazine, 40(2), 44-58. https://doi.org/10.1609/aimag.v40i2.2850

[16] Slussareff, M. (2022). O'Neil, Cathy. 2016. Weapons of Math Destruction: How Big Data Increases Inequality and Threatens Democracy. Crown.

[17] Aitsam, M., Davies, S., & Di Nuovo, A. (2022). Neuromorphic computing for interactive robotics: A systematic review. Ieee Access, 10, 122261-122279.

[18] Lee, J., & Kang, H. J. (2025). Artificial Empathy in Home Service Agents: A conceptual Framework and Typology of Empathic Human-Agent Interactions. Preprints. https://doi.org/10.20944/preprints202502.1365.v1

[19] Liedtka, J. (2018). Why design thinking works. Harvard Business Review, 96(5), 72-79.

[20] Krumm, John, ed. Ubiquitous computing fundamentals. CRC Press, 2018.

[21] Chew, I., Karunatilaka, D., Tan, C. P., & Kalavally, V. (2017). Smart lighting: The way forward? Reviewing the past to shape the future. Energy and Buildings, 149, 180-191. https://doi.org/10.1016/j.enbuild.2017.04.083