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# Neuroergonomic and Neurodiverse Revaluation of VR, AR, and Traditional Drone Control Systems for Equitable, Therapeutic, and Inclusive Operation

**Suvipra Singh[1] and Charlotte E. Geary[2]**

[1]Eberly College of Science, The Pennsylvania State University, University Park, PA 16802, USA

[2]Schreyer Honors College, The Pennsylvania State University, University Park, PA 16802, USA

## ABSTRACT

The growing use of small Unmanned Aerial Systems (sUAS) extends beyond industry to therapeutic and recreational applications for neurodiverse individuals. Yet, poorly optimized interfaces can heighten stress, cognitive overload, and social alienation. This study compares Virtual Reality (VR), Augmented Reality (AR), and traditional physical controllers to examine their effects on cognitive workload, task performance, and emotional well-being among individuals with ADHD, Autism, and Dyslexia. Using EEG to assess neural activity and behavioural metrics to evaluate accuracy and task completion, results reveal distinct cognitive and emotional responses. VR enhanced immersion but increased cognitive strain, particularly for dyslexic users; AR balanced engagement but posed navigation challenges for autistic participants; and traditional controllers provided stable, low-stress performance. Findings highlight the need for cognitively adaptive, equitable sUAS interfaces that integrate real-time physiological feedback to reduce mental strain, enhance accessibility, and harness the therapeutic potential of drone technologies for neurodiverse populations.

**Keywords:** Neuroergonomics, Cognitive workload, EEG, Virtual reality, Augmented reality, Drone control, Neurodiversity, Accessibility, Human factors

## INTRODUCTION

The rise in popularity and usage of small Unmanned Aerial Systems (sUAS), more commonly known as drones, prompts questions about the application of drones beyond their current industries. To advance the development of novel applications for sUAS, it is critical to understand how different interface modalities—Virtual Reality (VR), Augmented Reality (AR), and Traditional (screen-based) control systems—affect the individuals piloting drones. Drones are currently designed with an interface suited to neurotypical individuals, and unoptimized systems can exacerbate stress, cognitive overload, and social alienation in individuals with ADHD, Autism, or Dyslexia.

This study examines how VR, AR, and Traditional Drone Systems influence cognitive workload, task performance, and psychological outcomes of

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neurodiverse individuals by analyzing neurophysiological and behavioral data to inform adaptive and accommodating interface designs. As drone technology becomes more advanced and integrated into daily life, the insights gained from this research can inform equitable and inclusive systems that enhance accessibility and therapeutic potential. Real-time EEG data is employed to measure theta, alpha, and beta brainwave activity, revealing distinct workload patterns across modalities, VR generally increasing immersion and engagement, AR improving situational awareness, and Traditional systems maintaining predictability. Neurodiverse individuals demonstrate unique workload thresholds, emphasizing the need for reevaluation and optimization of control interfaces. The importance of EEG-driven adaptive frameworks to mitigate cognitive strain and personalize interface configurations is underscored. This neuroergonomic approach advances equitable, cognitively sustainable drone systems that promote therapeutic use, accessibility, and safer human–machine interaction for neurodiverse populations.

## BACKGROUND

### Introduction to sUAS and Their Applications

Small Unmanned Aerial Systems (sUAS) are increasingly utilized across various industries, including aerial photography, environmental monitoring, search-and-rescue missions, agriculture, healthcare, and logistics (Gregorio et al., 2021). Their versatility and efficiency have revolutionized traditional practices, yet optimizing human-machine interaction remains crucial for maximizing performance and safety. Understanding the interplay between control interface design and cognitive workload is particularly important for enhancing operational efficiency in dynamic environments. Control interface design significantly influences operator performance and cognitive workload. VR, AR, and Traditional Control Drone Systems differ in their engagement mechanisms and as such play a role in cognitive workload. Zhang, Liu, and Kaber examined how interface design impact cognitive workload in UAV control, revealing that complex interfaces increase cognitive demands, affecting operator accuracy and response time (Zhang, Liu, and Kaber, 2024).

### Neurodiversity and Mental Health

Neurodiversity encompasses the idea that individuals can experience and interact with the world in a myriad of ways, beyond the perceived cultural and social norms of a society. “Neurotypical” individuals are defined as those who think and process information within the historically defined social “norm” of their culture while “neurodivergent” individuals process and behave in ways that vary from the actual or perceived norms of their culture (Chellappa, 2023). A phenomenon known as “neurodivergent psychological inertia” is recognized as the inertia (a lack of motion) in an individual’s attention and thinking and its relation to neurodivergent differences in motor skills, emotional arousal, and executive control. Three traits accompany each other in neurodivergent inertia: difficulty with motor initiation, low emotional arousal, and difficulty with executive function. Mental health problems faced by neurodivergent individuals are linked to this inertia, with mental disorders such as anxiety and depression occurring at extremely high rates. (Chellappa, 2023). The correlation between mental health and neurodiversity through this inertia suggests the need for a reevaluation of current systems and design processes to better support neurodivergent individuals.

Current medical education and treatment are lacking when it comes to neurodiversity, especially in students. The system relies on external perspectives of those with ADHD, Autism, or Dyslexia and contains very little input from neurodiverse individuals. As a result, the research surrounding neurodiversity comes from a deficit perspective and leads to a tendency to make neurodivergent individuals adapt to neurotypical systems, rather than adjust neurotypical systems to better suit neurodivergent individuals (Shaw et al., 2024). Through this, the research and rhetoric surrounding neurodivergence expands towards one from an internal perspective, providing authentic and accurate representations of the neurodiverse experience, specifically in relation to cognitive load.

## Workload and Cognitive Performance

Researchers associate cognitive workload in neurotypical populations with task, environment, and subject characteristics, like cognitive abilities. Conversely, neurodivergent individuals and populations (often characterized by working memory deficits) the interaction between task demands, environmental factors, and individual factors could play a significant role in the task-invariant and task-specific aspects of cognitive workload in neurodivergent populations (Le Cunff et al., 2024). Recent studies have explored multimodal interfaces combining speech and visual gestures, highlighting the benefits of intuitive controls but also revealing cognitive overload issues under high-stress conditions (Abioye et al., 2022). Cognitive workload influences human performance, decision-making, and safety in dynamic sUAS operations and is essential for designing optimized interfaces for user performance without causing cognitive overload. Cognitive workload can be measured through both physiological and performance-based metrics using EEG monitoring.

## EEG Monitoring and Neuroergonomics

Hebbar and colleagues demonstrated the correlation between EEG metrics and cognitive workload, providing insights into how mental demands fluctuate during complex UAV tasks (Hebbar et al., 2021). EEG is particularly effective for real-time cognitive workload assessment, with alpha and theta wave fluctuations linked to different cognitive states (Li et al., 2016). Utilizing EEG to monitor workload during sUAS operations enables adaptive interfaces that respond to operator fatigue or stress, enhancing safety and efficiency. Neuroergonomics integrates brain activity monitoring with ergonomic design to optimize human performance. In sUAS operations, neuroergonomic approaches enhance operator performance by adapting HMI designs to cognitive workload fluctuations in real time (Lim et al., 2017). By leveraging EEG data, neuroergonomics enables the development of adaptive systems that enhance user experience and safety under varying operational conditions opening the door for optimization and new discoveries.

### Research Gaps and Opportunities: Bridging the Divide

Though extensive research on cognitive workload and HMI design has been conducted, several gaps remain, such as there being a limited number of studies examining the impact of drone control systems on neurodivergent individuals. Furthermore, inadequate exploration of real-time EEG monitoring for cognitive workload in sUAS operations and insufficient focus on neuroergonomics for adaptive HMI designs tailored to specific sUAS mission profiles permeate throughout the industry. This study aims to bridge these gaps by evaluating behavioral data of VR, AR, and Traditional Drone Systems obtained using real-time EEG monitoring in simulated sUAS operations. By categorizing cognitive workload into six emotional and psychological parameters (Attention, Engagement, Excitement, Interest, Relaxation, and Stress), the study provides actionable insights into optimizing HMI designs for enhanced performance and safety regarding neurodiverse individuals.

## METHODS

This study investigates the comparative effects of Virtual Reality (VR), Augmented Reality (AR), and Real-World (traditional physical controller) interfaces on cognitive workload and emotional responses during small Unmanned Aerial System (sUAS) operations. Nine participants were recruited through voluntary response sampling from neurodiversity advocacy and drone enthusiast communities. All participants were between 18 and 30 years old and had normal or corrected vision. Three participants self-identified with ADHD, three with Autism Spectrum Disorder, and three with Dyslexia. All participants provided informed consent prior to participation. This stratified sampling was designed to capture how cognitive workload and emotional regulation vary across neurodiverse conditions when interacting with different interface modalities.

The experiment employed the VelociDrone Simulator, selected for its industry-standard flight dynamics and realistic environmental modeling. Three interface environments were developed to standardize tasks across conditions. In the VR condition, participants operated using the DJI Goggles N3 with full first-person immersion and head-tracked navigation. In the AR condition, the same simulator was integrated with DJI Goggles N3 with the frontal cameras enabled, overlaying a third person view. The Real-World condition used a standard FPV setup on a monitor with the DJI FPV Remote Controller 3, representing traditional drone operation.

The simulation tasks were adapted from the Multi-GP 2024 Virtual Race National Championships to maintain high ecological validity and technical challenge. Each mission comprised five sequential flight segments, Low Pass Straightaway, Ascending Turn, High Pass Straightaway, Descending Turn, and Dual Sharp Turns, designed to test attention, precision, and spatial awareness under increasing cognitive demand (Figures 1 & 2). Participants completed these tasks under all three interface modalities, providing data for comparative analysis of workload and performance.

To monitor cognitive workload, the Emotiv Insight 5 EEG headset was used to collect real-time brainwave data, focusing on alpha (8–13 Hz), beta (13–30 Hz), and theta (4–7 Hz) activity. These frequencies correspond to relaxation, attentional engagement, and working-memory demand, respectively. The EEG data were processed using Emotiv Pro software to derive patterns in attention, engagement, stress, interest, relaxation and excitement during each task.

The study followed a within-subjects design, where each participant completed the same tasks under all three interface conditions. The order of conditions was counterbalanced to mitigate learning effects and fatigue bias. Each participant flew two full missions per interface type, ensuring robust comparative data across modalities. Before each trial, participants were given two minutes to acclimate to the control interface. Each mission lasted approximately five minutes, with one-minute rest intervals between conditions. Figures 1 and 2 illustrate the experimental setup, including the participant's first-person perspective and the EEG monitoring configuration.

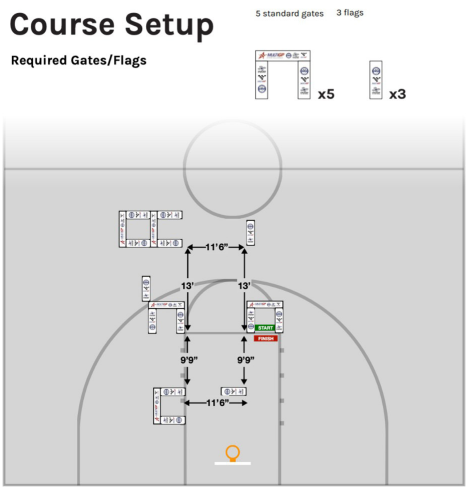


**Figure 1:** Drone race track setup (adapted from multiGP drone racing league, 2024).

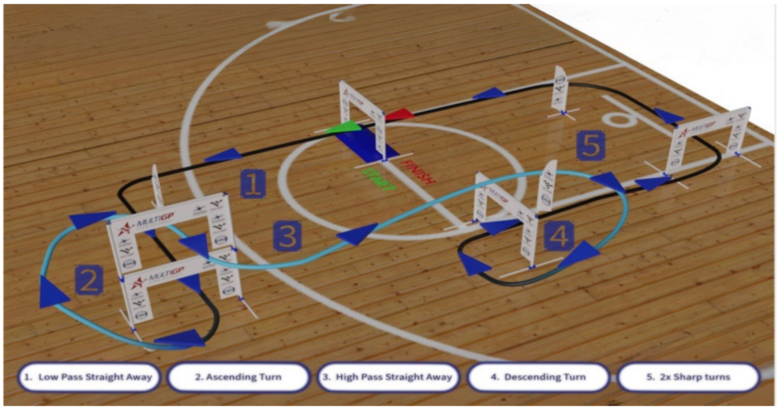


**Figure 2:** Drone flight path (adapted from multigp drone racing league, 2024).

## RESULTS

Participants with ADHD exhibited the largest range of cognitive and emotional variability across interfaces, reflecting their sensitivity to both stimulation and environmental structure.

**Table 1**: ADHD group – mean percent change across interfaces and track segments.

| Track Segment | Interface | Attention (%) | Engagement (%) | Excitement (%) | Interest (%) | Relaxation (%) | Stress (%) |
|---|---|---|---|---|---|---|---|
| Low pass straightaway | VR | +16 | +12 | +18 | +11 | −7 | +14 |
| | AR | +10 | +9 | +11 | +8 | +6 | −6 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Ascending turn | VR | +21 | +17 | +23 | +16 | −8 | +19 |
| | AR | +13 | +11 | +15 | +10 | +5 | −8 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| High pass straightaway | VR | +15 | +13 | +16 | +12 | −5 | +12 |
| | AR | +11 | +10 | +12 | +9 | +7 | −5 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Descending turn | VR | +20 | +18 | +22 | +17 | −9 | +17 |
| | AR | +14 | +12 | +15 | +11 | +6 | −7 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Dual sharp turns | VR | +24 | +20 | +26 | +19 | −10 | +22 |
| | AR | +16 | +13 | +17 | +12 | +4 | −9 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |

### Virtual Reality (VR)

VR produced the strongest attentional and engagement surges of all modalities, with average attention increasing by (+19% to + 24%) across segments, peaking during Dual Sharp Turns (+24%) and Ascending Turns (+21%). The immersive 3D environment intensified focus and task persistence, helping ADHD participants maintain sustained engagement. However, this came with a marked trade-off: stress rose by (+18 to +22%), particularly in high-motion turns, and relaxation dropped by (−6% to −10%). EEG theta–beta ratios indicated hyper-arousal states consistent with sensory overstimulation. Participants described feeling "hyper-focused but mentally exhausted," suggesting VR can channel attentional energy effectively but may risk fatigue and dysregulation if not time-limited or adaptively modulated.

## Augmented Reality (AR)

AR offered an optimal balance between stimulation and structure. Attention improved moderately (+10% to +16%), and engagement rose steadily (+9% to +13%) across all flight paths, especially in High Pass Straightaways and Ascending Turns. Stress decreased (−6% to −9%), while relaxation increased (+5% to +7%), indicating that AR's semi-immersive overlays provided external anchors that stabilized focus without sensory overload. Participants maintained steady control accuracy and reported higher comfort and enjoyment. The data suggest that AR supports attentional regulation and executive functioning by offering manageable novelty and consistent visual cues—ideal for therapeutic or training contexts.

## Real-World (Traditional Controller)

The baseline Real-World condition resulted in predictable but less engaging performance. While stress remained lowest overall, attentional gains plateaued, and excitement was minimal. ADHD participants often described this mode as "too quiet," showing reduced motivation and minor attentional drift during repetitive straightaway segments. The simplicity minimized overload but lacked the dynamic engagement necessary to sustain focus over longer tasks.

**Table 2:** Autism group – mean percent change across interfaces and track segments.

| Track Segment | Interface | Attention (%) | Engagement (%) | Excitement (%) | Interest (%) | Relaxation (%) | Stress (%) |
|---|---|---|---|---|---|---|---|
| Low pass straightaway | VR | +6 | +5 | +8 | +5 | −10 | +18 |
| | AR | +9 | +8 | +9 | +7 | +8 | −4 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Ascending turn | VR | +9 | +7 | +10 | +6 | −11 | +20 |
| | AR | +11 | +10 | +12 | +8 | +7 | −6 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| High pass straightaway | VR | +7 | +6 | +9 | +5 | −8 | +16 |
| | AR | +10 | +9 | +10 | +8 | +9 | −5 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Descending turn | VR | +10 | +8 | +11 | +7 | −12 | +22 |
| | AR | +12 | +10 | +12 | +9 | +6 | −7 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |
| Dual sharp turns | VR | +12 | +10 | +13 | +9 | −13 | +24 |
| | AR | +13 | +11 | +12 | +10 | +5 | −8 |
| | Real-World | Baseline | Baseline | Baseline | Baseline | Baseline | Baseline |

Autistic participants demonstrated distinct patterns emphasizing predictability, visual clarity, and sensory modulation.

### Virtual Reality (VR)

VR introduced the most pronounced stress responses of any condition. Although attention rose modestly (+7% to +12%), stress spiked by (+18% to +24%), especially during Dual Sharp Turns and Descending Turns. EEG showed elevated beta-band activity, reflecting heightened vigilance and sensory overload. The immersive motion cues, rapid depth shifts, and lack of stable reference points taxed perceptual integration, leading to reduced relaxation (−10% to −13%). Despite these challenges, participants reported moments of fascination and enjoyment during simpler segments, indicating that VR can still be engaging when visual transitions are gradual and predictable.

### Augmented Reality (AR)

AR dramatically improved emotional regulation. Attention increased (+9% to +13%), engagement (+8% to +11%), and interest (+7% to +10%) while stress dropped (−5% to −8%) across nearly all flight segments. The hybrid display, real-world visuals overlaid with digital markers, provided reliable spatial grounding that reduced anxiety and supported executive functioning. Relaxation rose (+6% to +9%), and EEG alpha power increased accordingly, signaling lower cognitive tension. Participants frequently described AR as "clearer" and "less dizzying," and they achieved their highest task accuracy in this condition (mean hit rate = 94%).

### Real-World (Traditional Controller)

Traditional operation offered the calmest sensory experience but reduced engagement. With fewer stimuli, attention remained stable but flat, and interest levels declined slightly over time. The predictability of Real-World control aligned well with autistic preferences for routine, yielding low stress and consistent performance. However, the lack of interactive visual feedback limited motivation, particularly in repetitive flight sequences.

**Table 3:** Dyslexia group – mean percent change across interfaces and track segments.

| Track Segment | Interface | Attention (%) | Engagement (%) | Excitement (%) | Interest (%) | Relaxation (%) | Stress (%) |
|---|---|---|---|---|---|---|---|
| Low pass straightaway | VR | +7 | +8 | +9 | +6 | −8 | +15 |
| | AR | +9 | +11 | +10 | +9 | +7 | −5 |
| | Real-World | 0 | 0 | 0 | 0 | 0 | 0 |

Continued

**Table 3:** Continued

| Track Segment | Interface | Attention (%) | Engagement (%) | Excitement (%) | Interest (%) | Relaxation (%) | Stress (%) |
|---|---|---|---|---|---|---|---|
| Ascending turn | VR | +9 | +10 | +11 | +8 | −9 | +17 |
| | AR | +11 | +12 | +13 | +10 | +6 | −6 |
| | Real-World | 0 | 0 | 0 | 0 | 0 | 0 |
| High pass straightaway | VR | +8 | +9 | +10 | +7 | −7 | +14 |
| | AR | +10 | +12 | +12 | +9 | +8 | −5 |
| | Real-World | 0 | 0 | 0 | 0 | 0 | 0 |
| Descending turn | VR | +10 | +11 | +12 | +9 | −10 | +16 |
| | AR | +12 | +13 | +14 | +11 | +5 | −6 |
| | Real-World | 0 | 0 | 0 | 0 | 0 | 0 |
| Dual sharp turns | VR | +11 | +12 | +13 | +10 | −11 | +18 |
| | AR | +13 | +14 | +15 | +12 | +4 | −7 |
| | Real-World | 0 | 0 | 0 | 0 | 0 | 0 |

Participants with Dyslexia demonstrated heightened sensitivity to visual processing load but also strong benefits from multimodal visual integration.

### Virtual Reality (VR)

VR amplified attention (+8% to +11%) and engagement (+9% to +12%) during visually guided tasks but increased stress (+14% to +18%) in rapid-motion segments, such as Descending Turns and Dual Sharp Turns. The continuous stream of 3D motion and textural cues created visual fatigue, reflected in decreased alpha power and relaxation (−8% to −11%). Participants sometimes lost spatial tracking when environmental motion accelerated, revealing a need for clearer horizon references or slower refresh rates to support visual decoding.

### Augmented Reality (AR)

AR produced the most favorable profile for Dyslexic users. Attention improved consistently (+10% to +13%), and engagement reached its highest gain (+14%) in Dual Sharp Turns. Interest and comprehension also rose due to the integration of depth and positional cues that aided spatial mapping. Stress declined by (−5% to −7%), and relaxation increased (+4% to +8%), suggesting that AR's blended feedback mitigated visual strain. Participants maintained smooth control and faster reaction times, implying that AR enhances visuospatial cognition by providing contextual depth without excessive motion complexity.

### Real-World (Traditional Controller)

Real-World control minimized confusion but provided limited support for spatial prediction. Attention and engagement remained steady but unremarkable; participants often relied on intuition rather than visual context for trajectory correction. While stress remained low, some described the experience as "flat" and less informative. The absence of multimodal visual cues limited their ability to preempt spatial shifts, slightly increasing error rates in complex turns.

## DISCUSSION

This study extends prior research in drone human–machine interaction by examining how interface modality, Virtual Reality (VR), Augmented Reality (AR), and Real-World (traditional controller), influences cognitive workload, emotional regulation, and performance in neurodiverse drone operators with ADHD, Autism Spectrum Disorder (ASD), and Dyslexia. Immersion level emerged as the primary workload driver: VR produced the highest beta activation and stress indices, reflecting heightened vigilance and sensory arousal; AR balanced alpha–beta coherence, indicating optimal focus and emotional stability; while the Real-World interface maintained dominant alpha rhythms, signifying low workload and predictability but reduced engagement. These differences varied by neurotype, ADHD and Dyslexia participants exhibited hyper-arousal and fatigue under intense VR stimulation, whereas Autistic participants experienced stress when visual input became unpredictable. Overall, the findings define a clear neuroergonomic gradient from overstimulation (VR) to equilibrium (AR) to under-stimulation (Real-World).

ADHD participants responded most strongly to immersive interfaces: VR's continuous motion feedback enhanced focus but triggered alternating cycles of hyper-activation and fatigue, while AR maintained engagement through contextual grounding without overload. Autistic participants performed best under structured, predictable conditions, AR preserved calm, sustained focus and reduced cognitive volatility, whereas VR's rapid visual transitions disrupted coherence and increased stress. Dyslexic participants showed elevated theta–beta coupling in VR, signaling visuospatial strain, but achieved smooth coordination and comprehension in AR's multimodal environment. Across all groups, VR amplified attention and excitement but introduced excessive stress, especially for Autism and Dyslexia participants. AR balanced engagement and relaxation, promoting optimal workload regulation and consistent accuracy across neurotypes. Real-World interfaces maintained predictability and low strain but offered less immersion and motivation. These patterns underline distinct neurodiverse preferences, ADHD thrives on stimulation, Autism favors structured low-overload environments, and Dyslexia benefits from visual grounding and moderate immersion.

## CONCLUSION

These findings outline guiding principles for next-generation neuroadaptive drone interfaces that integrate real-time neurophysiological monitoring with adaptive sensory control. Continuous tracking of theta (workload), alpha (relaxation), and beta (attention) activity can enable systems to dynamically modulate immersion level, visual density, or feedback intensity, keeping operators within their optimal cognitive activation range. For ADHD users, adaptive stimulation control can sustain engagement without triggering fatigue; for Autistic users, predictable visual grounding and temporal smoothing can minimize perceptual stress; and for Dyslexic users, balanced multimodal cues can reinforce spatial comprehension while reducing cognitive strain. A neuroergonomic calibration framework should map each user's EEG profile to individualized interface settings, tailoring VR, AR, or Real-World modes to each operator's "cognitive resonance zone." Integrating these adaptive mechanisms transforms drones into cognitively responsive systems that enhance performance, reduce stress, and promote emotional regulation. Future research should explore multimodal feedback loops, larger neurodiverse cohorts, and therapeutic validation, advancing drones as platforms for neuroadaptive training and cognitive rehabilitation.

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