The Ocular Command Center: How Eye Responses to Luminance, Color, Tunneling, and Visual Suppression Mediate Users' Physiological States in VR

Andreia Valente
The Empathic Computing Laboratory,
Auckland Bioengineering Institute,
The University of Auckland
Auckland, New Zealand
ITI / LARSyS, Lisbon, Portugal

Augusto Esteves
ITI / LARSyS
Instituto Superior Técnico
Universidade de Lisboa
Lisbon, Portugal

Mark Billinghurst
The Empathic Computing Laboratory,
Auckland Bioengineering Institute,
The University of Auckland
Auckland, New Zealand

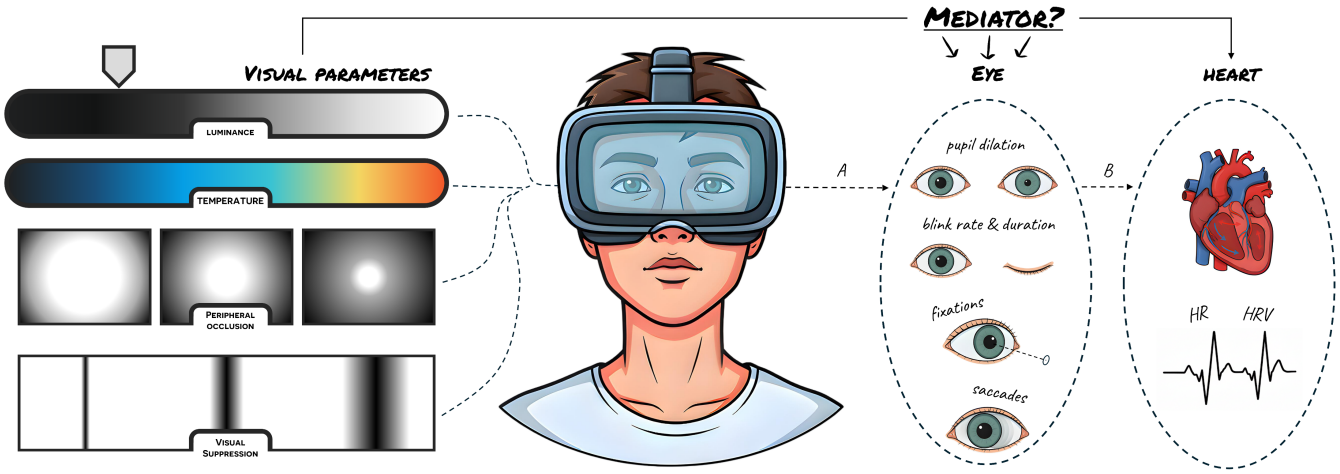

Figure 1: Conceptual framework for mediation analysis examining how eye metrics mediate the relationship between VR visual parameters and cardiovascular responses. Path (A) represents visual parameters (luminance, color temperature, peripheral occlusion, and visual suppression) to eye metrics (pupil dilation, blink rate and duration, fixations, and saccades), and path (B) eye metrics to cardiovascular outcomes (heart rate and heart rate variability).

Abstract

This work introduces the Ocular Command Center framework to investigate how eye responses mediate visual effects on physiology and user experience in virtual reality. In a controlled study (N=40), participants experienced variations in luminance, color temperature, peripheral occlusion, and periodic visual suppression while eye activity (pupil size, blinks, fixations, and saccades), cardiovascular responses (heart rate and heart rate variability), and subjective symptoms were measured. Luminance changes affected heart rate through pupillary reflexes. Color temperature affected heart rate variability without pupillary mediation, suggesting appraisal processes, and induced severe nausea. Peripheral occlusion and visual suppression modified oculomotor behavior without substantial cardiovascular effects. These findings demonstrate that visual manipulations could act through distinct reflexive, cognitive, and perceptual pathways, and not all extend equally to systemic physiology. This foundation supports adaptive VR design, regulating comfort, engagement, and physiological state.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**; **Empirical studies in HCI**; **Virtual reality**; *HCI theory, concepts and models*; • **Computing methodologies** → **Machine learning**.

Keywords

Eye tracking, Virtual Reality, Heart Rate, Heart Rate Variability, Emotions, Luminance, Color Temperature, Peripheral Occlusion, Tunneling, Visual Suppression, Mediation Analysis, Adaptive Systems, Perception Engineering

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1 Introduction

Virtual reality (VR) is increasingly used to shape human emotional and physiological responses, as it allows for the precise manipulation of visual conditions while eliminating environmental confounds. Clinical applications employ immersive environments for therapy [2, 9], biofeedback-based systems that foster empathy [19], and designers use chromatic encoding for data visualizations and affective communication [17, 46]. Beyond research, VR is also used for wellness and anxiety reduction [30]. A unifying assumption across these efforts is that systematically designed visual experiences can modulate psychophysiological states in predictable ways. Designers frequently adjust parameters such as lighting [47], color schemes [27], and visual occlusion [49] with the goal of shaping user affect and attention.

However, most frameworks assume that visual design affects users primarily through cognitive interpretation. This overlooks the possibility that low-level eye metrics—such as pupil dilation, blink activity, fixations, and saccades, which are the metrics more directly affected by visual parameters, may act as physiological mediators between these manipulations and emotional or physiological outcomes. Without understanding these mechanisms, developers cannot design adaptive visual systems that reliably predict or control affective impact.

Therefore, we conducted a controlled experiment using a Meta Quest 3 headset with an integrated Tobii Crystal XR5 eye-tracker to explore the effects of low-level eye metrics on arousal. Forty participants performed a spatial construction task while being exposed to systematic manipulations of luminance, color temperature, peripheral occlusion (i.e., tunneling), and periodic visual suppression (i.e., simulated blinks). We recorded eye metrics (pupil size, blinks, fixations, and saccades) and cardiovascular measures (heart rate and heart rate variability), and applied mediation analysis to assess whether eye activity served as the *causal bridge* between visual stimuli and physiological arousal (see our framework in Fig. 1).

Our key findings show that luminance could modulate heart rate through pupil-mediated pathways. Color temperature affected HRV and produced severe nausea without pupillary mediation, suggesting cognitive appraisal mechanisms. Peripheral occlusion increased pupil diameter and blink rate, elevated boredom, and reduced ocular symptoms without cardiovascular effects. Visual suppression increased blink rates and disrupted fixation patterns without substantially altering cardiovascular responses, demonstrating local oculomotor effects that did not cascade to systemic physiology.

This paper makes the following novel contributions: (i) establishes the *Ocular Command Center* conceptual framework for understanding how visual parameters in VR mediate physiology through eye activity, demonstrated through controlled manipulation of luminance, color temperature, peripheral occlusion, and periodic suppression while recording synchronized eye and cardiovascular data; (ii) reports empirical findings (N=40) that luminance modulates heart rate via pupil responses, color temperature affects HRV without pupillary mediation and produces severe nausea, peripheral occlusion increases boredom while reducing ocular symptoms without cardiovascular engagement, and visual suppression alters oculomotor behavior without substantial cardiovascular effects; (iii) provides evidence for distinct reflexive and cognitive pathways in visual–physiological coupling; (iv) provides design guidelines for adaptive VR systems, highlighting which visual parameters best regulate comfort, workload, and physiological state.

2 Related Work

Testing whether eye metrics mediate the relationship between visual parameters and physiological reactions requires establishing two foundational relationships: (1) that visual parameters reliably influence eye metrics (Path A), and (2) that eye metrics correlate with physiological responses (Path B). While prior research documents each relationship separately, these correlational findings cannot determine whether eye metrics actively mediate visual-physiological relationships or merely reflect them. This gap is particularly important for VR applications seeking to predictably modulate user physiology through environmental design. We review evidence for both paths, demonstrating why systematic mediation testing is necessary to move beyond correlational findings toward a mechanistic understanding.

2.1 Path A: Visual Stimuli → Eye Metrics

To establish that eye metrics can serve as mediators, we must first demonstrate that manipulating visual parameters produces reliable changes in eye responses. We have identified four effects that have shown strong eye metric modulation: luminance, color temperature, peripheral occlusion, and periodic visual suppression. However, existing studies document these effects in isolation without testing whether the induced eye changes subsequently drive physiological shifts, which is the critical B path in this mediation (see Figure 1).

2.1.1 Luminance. This refers to the objective amount of light reflected from or emitted by a surface. Pupil diameter exhibits an inverse relationship with luminance, with rapid constriction and sustained maintenance during light exposure persisting 15-30 seconds after offset [15, 16]. Blink rate typically decreases under higher luminance, while protective blink responses increase during transitions to bright lit areas [29]. Fixation duration increases as screen brightness decreases, while saccade amplitude shows small reductions under lower luminance conditions [51]. In VR environments, moderate luminance levels produce optimal stress recovery effects, with medium-brightness scenes showing lower arousal compared to extreme conditions [26]. White light produces the greatest pupil constriction amplitude and shortest response latency [29], with similar effects observed in VR [10]. These findings suggest that luminance may alter physiology indirectly by first triggering ocular responses, a possibility that our study aims to examine.

2.1.2 Color Temperature. Measured in Kelvin (K), it describes the spectral characteristics of light emitted by displays. Color temperature significantly influences ocular metrics, with higher temperatures (5000K) causing greater pupil constriction than lower temperatures (2700K) [12]. In VR, warm color temperatures produce higher arousal, while cool temperatures generate relaxation [28]. Pupil responses in VR are affected by displayed color temperature and adaptation to specific color conditions, with distinct pupillary responses correlating with subjective comfort [11]. These results imply that the comfort and arousal effects of color temperature may be mediated by ocular adjustments. However, no study has tested whether these ocular changes are the mechanistic link between color temperature and physiological relaxation/arousal in VR.

2.1.3 Peripheral Occlusion. Also known as "tunneling", it describes the phenomenon where an individual's peripheral visual field is reduced, creating a limited central viewing area resembling looking through a tunnel. Peripheral occlusion significantly increases pupil dilation in response to tunnel motion [24] and substantially modifies eye movement patterns, reducing large-amplitude saccades and exploratory movements while promoting more systematic fixation behavior [6]. VR tunneling produces similar effects with increased pupil dilation [44], increased blink frequency [44], and modified exploratory saccade patterns after extended exposure [32]. The physiological stress sometimes associated with tunneling can be plausibly explained by these ocular responses: enlarged pupils signal heightened arousal, and reduced exploratory saccades constrain sensory sampling. Yet, no work has examined whether tunneling-induced pupil dilation mediates physiological elevation.

2.1.4 Visual Suppression. Periodic visual suppression (hereafter referred to as visual suppression) refers to brief interruptions in visual input that occur naturally during eye blinks or can be artificially induced through controlled stimuli such as blank screens or flashing displays. Brief visual interruptions through artificial blinks, blurs, or flashes increase user blink rates by mimicking natural dry-eye responses [14, 52]. This suppression period has been used in VR applications for spatial retargeting during natural blinks and the development of novel locomotion and interaction techniques [33]. On desktop monitors, blank screens or flashing increase blink rates [52]. Blur mimics natural focus loss from dry eyes, stimulating reflexive blinking [14], while flashing triggers blink reflexes. In VR, simulated blinking effects increase blink frequency versus baseline, with black screens providing less intrusive blink entrainment than flashing stimuli [20]. These blink-entrainment techniques suggest a potential route to physiological modulation: artificially elevated blink rates may trigger parasympathetic activity that reduces visual strain and lowers arousal. However, prior work has used suppression primarily for interaction design, not to test whether induced blink changes mediate downstream physiological regulation.

2.2 Path B: Eye Metrics ↔ Physiological Responses

The second component required for mediation is evidence that eye metrics and physiological responses are related. While research into these correlations is extensive and suggests potential mediation, they do not explore whether eye responses actively drive autonomic changes to visual elements or simply reflect them, the critical distinction our study aims to resolve.

2.2.1 Pupil Dilation. Pupil responses correlate with skin conductance and heart rate during emotional tasks [45], with pupillary changes often preceding physiological shifts [7, 42], though this temporal precedence does not establish causation. Peak pupil dilation corresponds to emotional selection moments, with stronger responses to high-arousal stimuli regardless of valence [35]. These results suggest that pupil dilation could act as a trigger for autonomic responses. For instance, sympathetic activation may follow the early dilation signal, producing the later changes in skin conductance or heart rate. However, existing studies stop at these correlations without testing whether dilation mechanistically drives physiological shifts rather than simply co-occurring.

2.2.2 Blink Rate and Duration. Blink rate correlates negatively with attention periods that show increased arousal [31, 50], while both blink rate and heart rate increase together during fatigue states [53]. Blink duration variability correlates with different emotional states [40], indicating sensitivity to autonomic arousal. This pattern implies a possible mediating role: reduced blinking may maintain heightened arousal during focused tasks, while prolonged blinks may signal parasympathetic dominance during relaxation or fatigue. Yet, prior work has not tested whether blink metrics actively modulate physiology, or merely reflect broader arousal states.

2.2.3 Saccades and Fixations. Oculomotor metrics correlate with heart rate (HR) fluctuations, with increased HR corresponding to decreased fixation stability and increased saccade amplitude [18]. Eye movement features correlate more sensitively than other physiology with environmental stimuli, with saccadic changes often preceding physiological shifts [21]. While most evidence is correlational, Barrowcliff et al. found that horizontal eye movements during stress can reduce both heart rate and skin conductance [4], providing rare experimental evidence for potential causal influence. However, this study employed deliberate eye movements rather than testing whether naturally occurring, visually induced eye changes mediate physiological responses. These findings show that deliberate eye-movement patterns can influence stress physiology, which provides a rationale for exploring whether natural saccades might also serve as mediators in VR.

2.3 Testing the Command Role of the Eyes

While the evidence we reviewed establishes that visual parameters reliably alter eye metrics (path A) and that eye metrics correlate with physiological responses (path B), **no studies have systematically tested whether eye responses mediate these visual–physiological relationships**. For example, luminance-induced pupil constriction may decrease sympathetic activity and support stress recovery. Warm color temperatures may elevate arousal by suppressing blinks. Tunneling may amplify stress through dilation-driven arousal signals, and artificial blink induction during visual suppression may entrain parasympathetic regulation. Similarly, pupil dilation often precedes changes in heart rate, reduced blinking may help sustain arousal during attention-demanding

tasks, and exploratory saccades may act as precursors to sympathetic activation. Each of these represents a plausible causal pathway, yet all remain untested.

Crucially, prior work has typically focused on emotionally salient visual content to study physiological response, making it unclear whether low-level visual adjustments alone can shape autonomic outcomes. Our study deliberately takes a different approach: we manipulate objective, systematic visual parameters such as luminance, color temperature, peripheral occlusion, and visual suppression. These parameters are not inherently designed to carry strong emotional or cognitive meaning. Instead, they are comparable to adjusting display settings. By focusing on these controlled manipulations, we test whether eye metrics serve as the mechanistic bridge even with neutral visual inputs.

The novelty of this study lies not only in isolating these parameters in VR but also in being, to our knowledge, the first to systematically evaluate whether eye metrics mediate visual–physiological relationships in immersive environments. This is especially significant because transferring insights from real-world studies to VR is not straightforward: phenomena such as visual tunneling or luminance effects may operate differently when the visual world is computer-generated, immersive, and interactive. By clarifying these dynamics, we provide evidence on whether real-world visual findings can be reliably extended to VR contexts.

This approach has critical implications for theory and application. If eye metrics do indeed serve as active mediators of physiological changes under calibration-like manipulations, it would show that VR environments can be tuned at a fundamental visual level to reliably influence physiology without relying on emotionally charged stimuli. Our study aims to determine whether eye responses serve as active mediators or passive markers of visual–physiological relationships, enabling the design of adaptive VR systems that are both predictable and safe for therapeutic and everyday use.

3 User Study and Research Questions

Our study examined whether systematic manipulations of visual parameters in VR might not only alter eye activity but also serve as mechanisms linking vision to physiological and subjective outcomes. This was guided by four research questions:

- **RQ1** How do luminance, color temperature, occlusion, and suppression alter oculomotor activity?
- **RQ2** Which manipulations affect cardiovascular responses, and are these mediated by ocular dynamics?
- **RQ3** How do visual manipulations shape subjective symptoms (e.g., nausea, eyestrain, fatigue)?
- **RQ4** Do combinations of ocular responses, physiological outcomes, and subjective experience indicate reflexive, appraisal-driven, or discomfort-driven pathways linking visual input and bodily state?

3.1 Experimental Task

To answer these questions, participants engaged in a spatial construction task in VR that required visuospatial reasoning. The task presented a rotating three-dimensional reference object and seven component pieces of varying geometries positioned on a virtual table. Participants used a controller in their dominant hand to manipulate and assemble components, thereby replicating the reference object. Each task had one correct configuration. This paradigm was adapted from "Block by Block" by ThinFun[1]. Twenty medium-difficulty constructions were randomly assigned per trial without repetition. A visual example of the task can be seen on Figure 2.

3.2 Experimental Design

We employed a within-subjects factorial design with four experimental conditions manipulating visual parameters: luminance (L), color temperature (T), peripheral occlusion (PO), and periodic visual suppression (VS). The four visual parameters were selected based on prior evidence of the reliable oculomotor effects and physiological correlations, making them optimal for testing mediation pathways in controlled VR environments. The sequence of conditions followed a balanced Latin square to mitigate order effects.

Participants completed one training trial followed by four experimental trials, one for each visual condition. Each trial lasted approximately 4.5 minutes: an initial 30-second baseline period with standard rendering parameters (no manipulations), followed by 4 minutes of parameter variations. To control for directional effects, participants were evenly distributed between ascending-first sequences (initiating with parameter increases) and descending-first sequences (initiating with parameter decreases; Figure 4).

The VR experience was built using Unity (version 2022.3.23f1) and deployed on a Meta Quest 3 headset with a Tobii Crystal XR5 eye tracker, connected to a laptop with an RTX 4070 graphics card. All visual parameter manipulations were implemented through Unity's post-processing for the Universal Render Pipeline, with percentage values representing relative adjustments to the standard rendering parameters. Luminance modifications were applied through exposure adjustments in the post-processing stack, while color temperature changes utilized the white balance filter with exposure held constant to minimize luminance confounds. Peripheral occlusion was achieved through vignette effects, and simulated blinks were implemented as periodic screen occlusion events. Figure 3 shows visual examples of the range of the conditions for each of the four experimental manipulations implemented in the study.

3.2.1 Luminance Modulation (L). Luminance was continuously modulated within ±30% of baseline. The modulation progressed as $0 \rightarrow +30\% \rightarrow 0 \rightarrow -30\% \rightarrow 0$ or $0 \rightarrow -30\% \rightarrow 0 \rightarrow +30\% \rightarrow 0$. Each complete cycle followed a linear progression with transitions at 30-second intervals, maintaining peak values for 30 seconds before transitioning.

3.2.2 Color Temperature Modulation (T). Color temperature varied from −100% (warm/yellow bias) to +100% (cool/blue bias) relative to standard white point. The modulation progressed as $0 \rightarrow +100\% \rightarrow 0 \rightarrow -100\% \rightarrow 0$ or $0 \rightarrow -100\% \rightarrow 0 \rightarrow +100\% \rightarrow 0$. Each complete cycle followed a linear progression with transitions at 30-second intervals, maintaining peak values for 30 seconds before transitioning.

[1] "Block by Block": https://ravensburger.co.nz/products/thinkfun-block-by-block

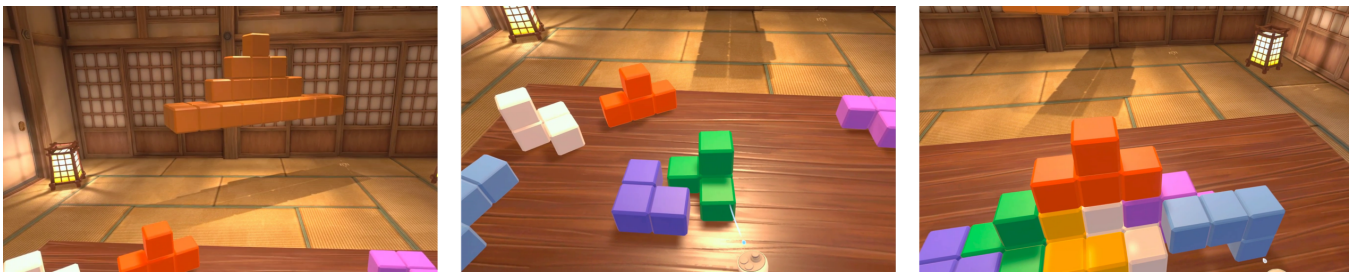

Figure 2: Screenshots from the VR spatial construction task showing the virtual environment with building blocks.

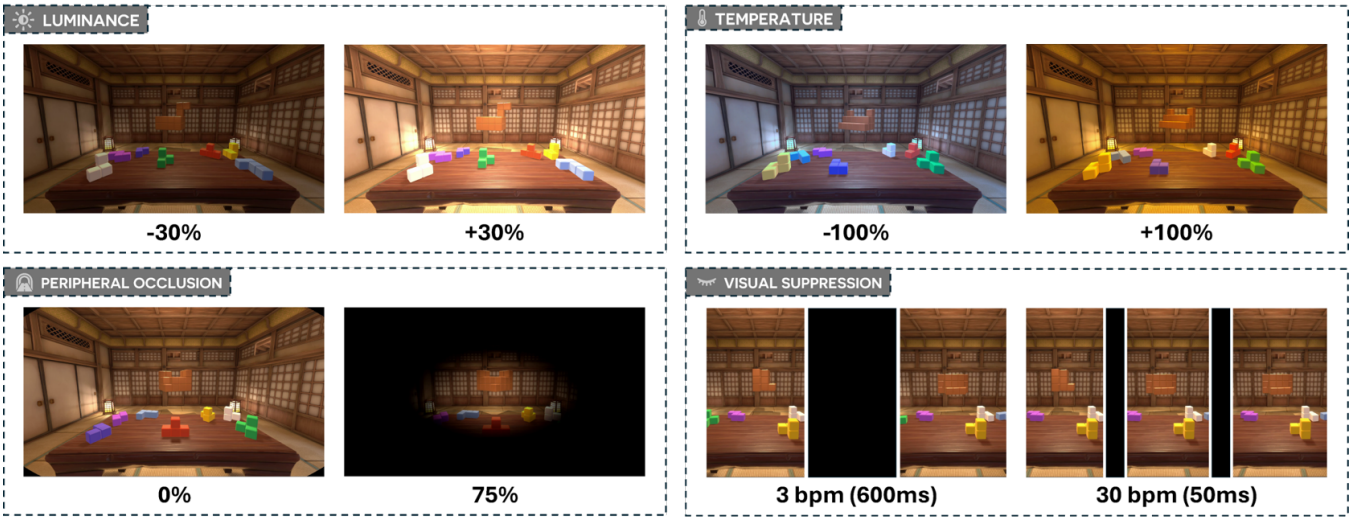

Figure 3: Visual examples of the extremes (low and high) parameters of the four experimental conditions implemented.

3.2.3 Peripheral occlusion (PO). Peripheral occlusion was manipulated between 0% and 75% of screen coverage, with 37.5% as standard. The modulation progressed as 37.5% → 75% → 37.5% → 0 → 37.5% or 37.5 → 0 → 37.5% → 75% → 37.5%. Each complete cycle followed a linear progression with transitions at 30-second intervals, maintaining peak values for 30 seconds before transitioning. This progression is illustrated in Figure 4.

3.2.4 Visual Suppression (VS). For periodic visual suppression, we simulated three distinct blink patterns using controlled screen occlusion, with blink rate and duration parameters derived from established research findings [1, 23]: slow blinks (3 blinks/min, 600ms duration, relaxed state), average blinks (18 blinks/min, 100ms duration, typical pattern), and fast blinks (30 blinks/min, 50ms duration, ocular stress). The blink sequences progressed either as average → fast → average → slow → average or as average → slow → average → fast → average. The average blink pattern served as a baseline for the first 30 seconds.

3.3 VR Task and Environment Design

The spatial construction task served as a cognitively engaging distractor to retain participant attention while minimizing confounds from task-specific emotional responses. This approach ensured that measured physiological changes could be attributed to visual parameter manipulations rather than task-induced affect. The puzzle components used a balanced color palette comprising all secondary colors to control for potential chromatic influences on arousal and valence. This color selection served dual purposes: (1) neutralizing potential color-induced emotional biases that could confound our visual parameter effects, and (2) providing sufficient visual contrast for accurate piece discrimination and manipulation.

The experimental environment was implemented using a modified Unity Universal Render Pipeline (URP) sample scene, selected for its capacity to support systematic post-processing manipulations while maintaining ecological validity. The environment featured a predominantly monochrome palette with neutral brown tones to establish an emotionally neutral baseline condition. The goal was to isolate the effects of our target visual parameters (luminance, color temperature, peripheral occlusion, and simulated blinks) without introducing competing emotional cues through environmental aesthetics. The neutral palette ensured that any measured physiological responses could be attributed to our controlled visual manipulations rather than existing emotional associations with environmental colors or themes.

Figure 4: Example of an ascending-first trial for the peripheral occlusion condition: baseline, low occlusion (0%, full field of view), standard occlusion (37.5%, moderate tunneling), high occlusion (75%, severe tunneling), and return to standard occlusion.

3.4 Metrics

Heart Metrics. We recorded Electrocardiogram (ECG) signals at 1000Hz using a BITalino board[2] to examine cardiovascular responses to visual parameter manipulations. ECG signal preprocessing utilized NeuroKit 2.0[3] with a third-order Butterworth bandpass filter (2–45Hz) applied to attenuate motion artifacts while preserving QRS morphology [8]. R-peak detection employed the Pan-Tompkins algorithm [36] to extract heart rate (HR), root mean square of successive differences (RMSSD), and the percentage of successive interbeat intervals differing by more than 50ms (pNN50). HR served as an index of overall cardiovascular arousal, with higher values reflecting greater sympathetic activation. RMSSD and pNN50, both time-domain measures of heart rate variability, were used to assess parasympathetic activity, with higher values typically indicating greater vagal tone and physiological states associated with calmness and positive valence, while lower values correspond to reduced vagal regulation and heightened arousal or negative affect [41]. All physiological and eye metrics were baseline-corrected using the first 30 seconds of each trial, so that outcome values reflect changes relative to each participant's initial state. HRV metrics (RMSSD and pNN50) were computed from 30-second ECG segments, following ultra-short recommendations [39].

Eye Metrics. Ocular data was collected using an integrated Tobii Crystal XR5 eye-tracking system in the Meta Quest 3 headset, which employs infrared illumination and camera sensors to record eye movements at 90Hz. The system provided raw metrics including pupil diameter, blink events, saccades, and fixations. Using the Tobii Ocumen tools[4], we derived secondary measures comprising blink rate and duration, saccade rate and duration, and fixation rate and duration.

All physiological data streams were temporally synchronized with experimental events through a common timestamping protocol, allowing for the precise attribution of physiological responses to specific visual parameter manipulations.

Self-Reported Symptom Assessment. Participants responded to the Virtual Reality Symptom Questionnaire (VRSQ) [22] after each trial. The VRSQ is a validated 13-item questionnaire particular to VR that includes eight nonocular symptoms (general discomfort, fatigue, boredom, drowsiness, headache, dizziness, difficulty concentrating, and nausea) and five ocular symptoms (tired eyes, sore/aching eyes, eyestrain, blurred vision, and difficulty focusing) [3]. Each symptom is rated on a seven-point scale (0-6) with qualitative descriptors ranging from "none" to "severe." The questionnaire takes approximately one minute to complete and captures symptoms that typically dissipate within six minutes post-viewing.

3.5 Participants

The study included $n = 40$ participants ($M_{age} = 27.8$, $SD = 6.5$, 17 females, 23 males) recruited from the university community. All participants reported having normal or corrected-to-normal vision and no history of photosensitive epilepsy, vestibular disorders, or significant susceptibility to motion sickness. The study protocol was reviewed and approved by the University of Auckland Human Participants Ethics Committee Application (reference number UAHPEC26829), and all participants provided informed consent.

3.6 Procedure

After obtaining informed consent and completing demographic questionnaires, participants were equipped with ECG electrodes (in a standard lead II configuration) and the Meta Quest 3 headset, which was adjusted for optimal fit and maintained at a consistent brightness. The integrated eye-tracking system was calibrated using the manufacturer's nine-point calibration procedure, with validation ensuring tracking accuracy within 1° visual angle. Participants completed a structured training session to familiarize themselves with the spatial construction task, including practice trials until they demonstrated proficiency in the task. This training phase took approximately 5 minutes.

The experimental protocol consisted of one 4.5-minute training trial and four 4.5-minute experimental trials, with 2-minute inter-trial intervals to mitigate carryover effects. During each experimental trial, participants engaged in the spatial construction task while exposed to condition-specific visual parameter manipulations. After each trial, participants first completed the Virtual Reality Symptom Questionnaire. Then, they were asked an open-ended question: "Did you notice any visual changes during the task? If so, please describe what you observed." They were required to provide written responses describing their perceptions of any visual manipulations. The experimental protocol, including instrumentation and debriefing, lasted approximately 40 minutes.

[2]BITalino (r)evolution: https://bitalino.com/products/plugged-kit-dual-mode-ble-bt
[3]NeuroKit 2.0: https://neuropsychology.github.io/NeuroKit/
[4]Tobii Ocumen SDK: https://www.tobii.com/products/software/data-analysis-tools/tobii-ocumen

Table 1: Summary of findings: comparison with prior work and contribution types

Visual Parameter	Phenomenon Tested	Previously Explored?	Our Results	Contribution
Luminance	Luminance → pupil diameter	Yes [15, 16, 29]	Higher luminance = smaller diameter	Replication
	Luminance → blink & oculomotor behavior	No	Higher luminance = higher blink rate, shorter duration, higher fixation rate	**Novel finding**
	Luminance → subjective VR symptoms	No	Elevated headache & ocular symptoms	**Novel finding**
	Luminance → heart **mediated** through eyes	No	**Pupil mediates luminance→HR**	**Novel finding**
Color Temperature	Temperature → pupil diameter	Yes [11, 12, 28]	Lower temperature = smaller diameter	Replication
	Temperature → blink & oculomotor behavior	Yes [28]	Lower temperature = shorter blink duration, higher fixation rate	Replication
	Temperature → subjective VR symptoms	No	Highest nausea	**Novel finding**
	Temperature → heart **mediated** through eyes	No	No mediation	**Novel negative**
Peripheral Occlusion	Occlusion → pupil diameter	Yes [24]	Higher occlusion = higher diameter	Replication
	Occlusion → blink & oculomotor behavior	Yes [6, 32]	Higher occlusion = higher blink rate	Extension
	Occlusion → subjective VR symptoms	No	Highest boredom, lowest ocular symptoms; low detection (42.5%)	**Novel finding**
	Occlusion → heart **mediated** through eyes	No	No mediation	**Novel negative**
Visual Suppression	Suppression → pupil diameter	No	No effect	**Novel negative**
	Suppression → blink & oculomotor behavior	Yes [14, 20]	Higher suppression = higher blink rate, shorter fixation duration	Replication
	Suppression → subjective VR symptoms	No	Highest eyestrain & fatigue	**Novel finding**
	Suppression → heart **mediated** through eyes	No	No mediation	**Novel negative**
General conceptual advance		No	Three exploratory pathways: reflexive, appraisal-based, discomfort-driven	**Framework**
Methodological advance		Correlational only	Systematic eye-physiology mediation analysis	**Method**

4 Results

All physiological and eye metrics were baseline-corrected using the first 30 seconds of each trial. Negative values indicate decreases relative to baseline, while positive values indicate increases. For eye metrics, only the left eye was analyzed for simplicity. For the sake of brevity, **the main findings from our study are:**

- Increased luminance decreased pupil diameter and was associated with higher blink rate, shorter blink duration, and higher fixation rate. Heart rate showed no condition effects. Heart rate variability was highest at standard luminance.
- Increased blue bias (cooler temperature) decreased pupil diameter and was associated with shorter blink durations. Heart rate showed no condition effects. Warm light reduced heart rate variability relative to cool light. Color temperature produced the highest nausea among all conditions.
- Increased peripheral occlusion increased pupil diameter and blink rate. Heart rate and heart rate variability showed no reliable condition effects. Peripheral occlusion increased boredom and was detected least often.
- Increased visual suppression frequency increased blink rate and affected fixation duration. Pupil diameter, heart rate, and heart rate variability showed no reliable condition effects. Visual suppression increased eyestrain and fatigue, and was often described as blinking rather than an external event.
- Across all manipulations, only the luminance to heart rate pathway showed significant mediation through pupil diameter. No other reliable mediation was observed.

Table 1 summarizes these findings alongside comparisons with prior work and our study's contributions.

Our analysis followed a two-step approach. First, we examined condition effects using Friedman tests (or repeated-measures ANOVAs where appropriate), with follow-up pairwise comparisons (Wilcoxon signed-rank tests or paired t-tests) adjusted using the Holm–Bonferroni procedure. Second, we conducted mediation analyses using Hayes' PROCESS macro [37] (Model 4) with bootstrapped confidence intervals (5,000 samples) for conditions showing significant visual-to-eye or visual-to-physiology effects. We refer to the unmanipulated condition as the "standard" condition to distinguish it from the initial 30 seconds of each trial, which were used for physiological and ocular baseline correction. Within each trial, the two standard periods were averaged into a single standard value of equal duration to the manipulated (low or high) segment. Figure 5 summarizes the effects of all visual parameters on eye metrics and physiology across conditions, and Figure 6 illustrates the mediation pathways identified in our analysis.

Reporting convention. To improve readability, detailed statistics for all metrics (including non-significant effects) are reported in Appendices A–E. In the main text, we focus on metrics showing a significant condition effect and/or at least one significant Holm-Bonferroni-corrected pairwise comparison. Mediation results are always reported in-line given their interpretive importance. Metrics not mentioned did not differ significantly across conditions.

4.1 Luminance Effects

Luminance was manipulated at ±30% relative to standard within each 4.5-minute trial. Low refers to ±30% below standard (darker) and high to ±30% above standard (brighter). Detailed statistics for luminance are reported in Appendix A.

4.1.1 Effects on Eye Metrics. **Pupil diameter** differed significantly across low (Mdn = .245), standard (Mdn = -.171), and high (Mdn = -.685) luminance conditions ($\chi^2(2) = 43.103$, $p < .001$). Pairwise comparisons were significant for all pairs: low–standard ($Z = -4.141$, $p < .001$), standard–high ($Z = -4.573$, $p < .001$), and low–high ($Z = -4.487$, $p < .001$), indicating a monotonic decrease

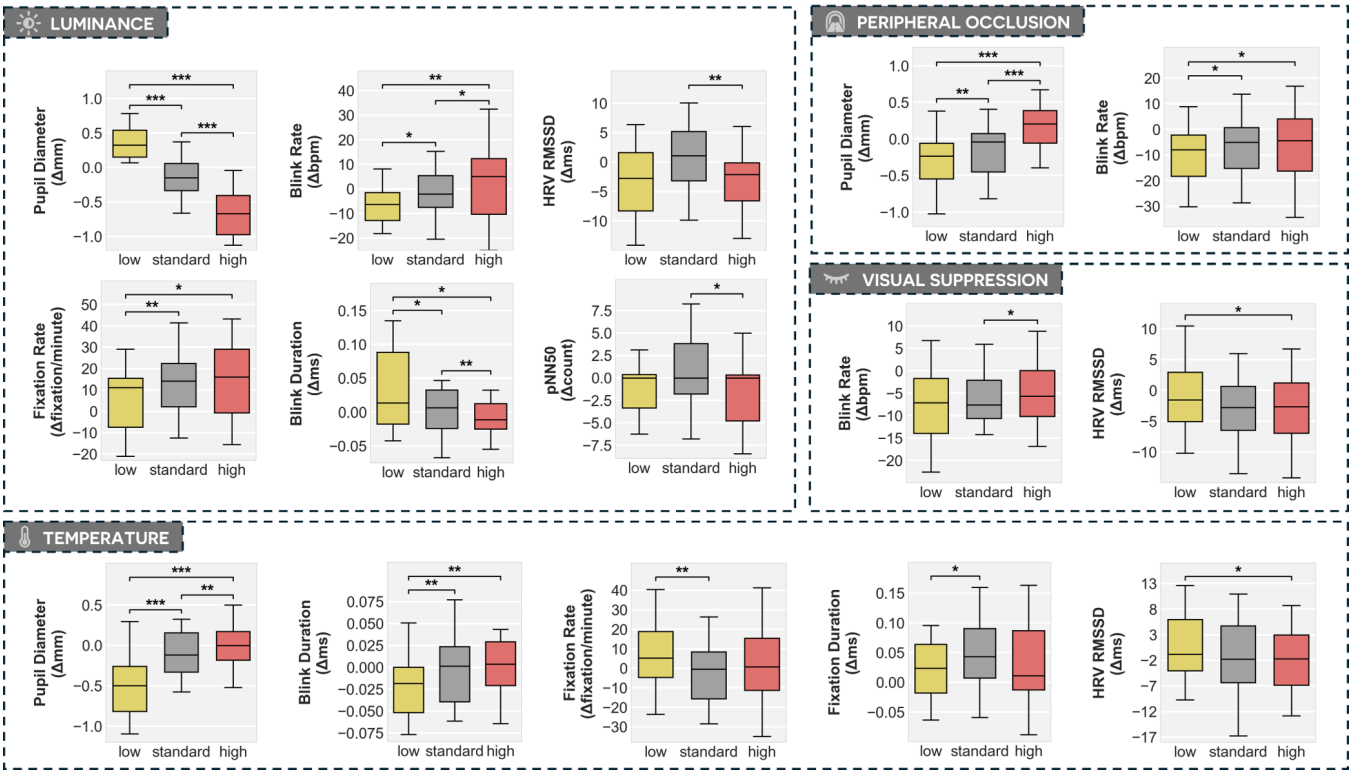

Figure 5: Results showing the effects of visual parameters on eye metrics and physiology (* p<.05, ** p<.01, *** p<.001)

in pupil diameter with increasing luminance. **Blink rate** also differed significantly across luminance ($\chi^2(2) = 11.655$, $p = .003$), increasing from low (M = -7.66 blinks/min) to standard (M = -2.89 blinks/min) to high luminance (M = 1.79 blinks/min). Pairwise comparisons were significant for all pairs: low–standard ($Z = -2.692$, $p = .014$), standard–high ($Z = -2.195$, $p = .028$), and low–high ($Z = -3.384$, $p = .003$). Although the omnibus test for **blink duration** did not reach conventional significance ($\chi^2(2) = 5.840$, $p = .054$), planned pairwise comparisons indicated shorter blinks at higher luminance: low–standard ($Z = -2.085$, $p = .037$), standard–high ($Z = -3.123$, $p = .006$), and low–high ($Z = -2.677$, $p = .014$).

Fixation rate differed significantly across low (Mdn = .02), standard (Mdn = 8.31), and high (Mdn = 12.47) luminance conditions ($\chi^2(2) = 12.069$, $p = .002$). Pairwise comparisons indicated higher fixation rates for low–standard ($Z = -3.146$, $p = .006$) and low–high ($Z = -2.714$, $p = .014$), with no reliable difference for standard–high ($Z = -.962$, $p = .336$). Fixation duration did not differ significantly across luminance conditions ($\chi^2(2) = 1.931$, $p = .381$). **Saccade rate** showed a significant omnibus effect ($\chi^2(2) = 6.276$, $p = .043$), although no pairwise comparisons reached significance after Holm-Bonferroni correction. Saccade duration did not differ significantly across conditions ($\chi^2(2) = 3.586$, $p = .166$).

4.1.2 Effects on Physiological Measures. **Heart rate** did not show a significant main effect of luminance (repeated-measures ANOVA; Greenhouse–Geisser corrected), $F(1.675, 65.325) = 0.747$, $p = .456$. In contrast, heart rate variability indices were sensitive to luminance. **RMSSD** differed significantly across low (Mdn = -2.00), standard (Mdn = 0.924), and high (Mdn = -3.12) luminance conditions ($\chi^2(2) = 14.973$, $p = .001$), with pairwise comparisons indicating lower RMSSD for standard–high ($Z = -3.191$, $p = .003$). **pNN50** showed a similar pattern, differing significantly across luminance levels (low: Mdn = -1.01; standard: Mdn = 0.433; high: Mdn = -2.17), $\chi^2(2) = 12.324$, $p = .002$, with a significant difference for standard–high ($Z = -2.508$, $p = .036$).

4.1.3 Pupil Diameter Mediation. For the luminance → **pupil diameter** → heart rate pathway, mediation analysis confirmed a significant indirect effect (Effect = −.0222, 95% CI [−.0414, −.0048]). The path from luminance to **pupil diameter** was strong and negative ($a = -.0155$, $t = -8.33$, $p < .001$), and the path from **pupil diameter** to heart rate was significant ($b = 1.4327$, $t = 1.99$, $p = .049$). The direct effect of luminance on heart rate was non-significant when **pupil diameter** was included as a mediator ($c' = .0172$, $t = .95$, $p = .345$), indicating that the luminance-heart rate association was primarily accounted for by pupil diameter. However, **pupil diameter** did not significantly mediate luminance effects on HRV measures: **RMSSD** (Effect = −.0128, 95% CI [−.0526, .0286]) and **pNN50** (Effect = .0169, 95% CI [−.0209, .0629]).

4.1.4 Blink Mediation. Although luminance significantly predicted both **blink rate** ($a = .1574$, $t = 2.64$, $p = .009$) and **blink duration** ($a = -.0014$, $t = -3.39$, $p = .001$), neither variable significantly mediated the relationship between luminance and physiological outcomes. For **blink rate**, despite a significant luminance → blink rate pathway, the indirect effects were non-significant for heart rate (Effect = −.0002, 95% CI [−.0073, .0069]), **RMSSD** (Effect = −.0016, 95% CI [−.0180, .0165]), and **pNN50** (Effect = .0026, 95% CI [−.0103, .0189]). For **blink duration**, the indirect effects were also non-significant across all physiological outcomes: heart rate (Effect = .0050, 95% CI [−.0061, .0153]), **RMSSD** (Effect = .0096, 95% CI [−.0122, .0383]), and **pNN50** (Effect = −.0109, 95% CI [−.0238, .0016]).

4.1.5 Fixation and Saccade Mediation. For **fixation** measures, the luminance → **fixation rate** pathway was non-significant in the mediation model, and all indirect effects were non-significant across physiological outcomes. **Fixation duration** effects were similarly non-significant, yielding no evidence of mediation for any physiological measure. For **saccade** measures, although **saccade duration** was significantly related to **pNN50** ($b = -77.24$, $t = -2.42$, $p = .017$), no mediation effects emerged because luminance did not significantly predict saccade duration ($a = .0000$, $t = -.58$, $p = .563$). Accordingly, the indirect effect for the luminance → saccade duration → **pNN50** pathway was non-significant (Effect = .0036, 95% CI [−.0088, .0181]), and all other saccade mediation effects were also non-significant across physiological outcomes.

4.2 Color Temperature Effects

Color temperature varied from ± − 100% (cool/blue) to ± + 100% (warm/yellow) relative to a standard white point. Detailed statistics for color temperature are reported in Appendix B.

4.2.1 Effects on Eye Metrics. **Pupil diameter** showed a significant main effect of color temperature (repeated-measures ANOVA; Greenhouse–Geisser corrected), $F(1.285, 50.115) = 35.595$, $p < .001$, increasing from low (M = -.49) to standard (M = -.11) to high (M = -.01). Pairwise comparisons were significant for all pairs: low–standard ($t(39) = -6.091$, $p < .001$), standard–high ($t(39) = -2.879$, $p = .007$), and low–high ($t(39) = -6.318$, $p < .001$). **Blink rate** did not differ significantly across color temperature conditions ($\chi^2(2) = 2.294$, $p = .318$). In contrast, **blink duration** differed significantly across low (Mdn = -.0338), standard (Mdn = -.0015), and high (Mdn = -.0011) color temperature conditions ($\chi^2(2) = 17.706$, $p < .001$), with pairwise comparisons indicating shorter blinks for low–standard ($Z = -3.462$, $p = .003$) and low–high ($Z = -3.120$, $p = .004$), but not for standard–high ($Z = -.419$, $p = .675$).

Fixation rate showed a trend across color temperature conditions ($\chi^2(2) = 5.471$, $p = .065$), with planned comparisons indicating higher fixation rate for low–standard ($Z = -2.932$, $p = .009$), but not for standard–high ($Z = -.453$, $p = .651$) or low–high ($Z = -1.821$, $p = .138$). **Fixation duration** showed a similar pattern ($\chi^2(2) = 5.473$, $p = .064$), with shorter fixations for low–standard ($Z = -2.829$, $p = .015$), and no reliable differences for standard–high ($Z = -1.428$, $p = .306$) or low–high ($Z = -1.034$, $p = .306$). Saccade measures did not differ significantly across conditions for **saccade rate** ($\chi^2(2) = 0.412$, $p = .814$) or **saccade duration** ($\chi^2(2) = 0.059$, $p = .971$).

4.2.2 Effects on Physiological Measures. **Heart rate** showed no significant main effect of color temperature (repeated-measures ANOVA; Greenhouse–Geisser corrected), $F(1.820, 70.980) = 0.127$, $p = .863$. **RMSSD** differed significantly across color temperature conditions ($\chi^2(2) = 8.629$, $p = .013$), with pairwise comparisons indicating lower RMSSD for low–high ($Z = -2.342$, $p = .047$). In contrast, **pNN50** did not differ significantly across color temperature conditions ($\chi^2(2) = 1.143$, $p = .565$).

Pupil Diameter Mediation. For the temperature → **pupil diameter** → heart rate pathway, the path from temperature to **pupil diameter** was strong and positive ($a = 0.0025$, $t = 5.45$, $p < .001$), but the path from **pupil diameter** to heart rate was non-significant ($b = -0.1124$, $t = -0.13$, $p = .900$). This resulted in a non-significant indirect effect (Effect = −0.0003, 95% CI [−0.0048, 0.0041]). **Pupil diameter** did not significantly mediate temperature effects on HRV measures: **RMSSD** (Effect = −0.0185, 95% CI [−0.0530, 0.0105]) and **pNN50** (Effect = −0.0023, 95% CI [−0.0160, 0.0115]). While the temperature to **pupil diameter** pathway remained significant across all models, the paths from **pupil diameter** to **RMSSD** ($b = -7.4444$, $t = -0.45$, $p = .654$) and **pNN50** ($b = -0.9044$, $t = -0.33$, $p = .745$) were non-significant.

Blink Duration Mediation. Despite significant temperature effects on blink duration in the condition analysis, mediation pathways were non-significant across all physiological outcomes: heart rate (Effect = 0.0011, 95% CI [−0.0009, 0.0039]), **RMSSD** (Effect = −0.0018, 95% CI [−0.0078, 0.0018]), and **pNN50** (Effect = 0.0011, 95% CI [−0.0009, 0.0039]).

Fixation Mediation. For **fixation rate** and **fixation duration**, despite significant pairwise temperature effects (Low–Standard comparisons), mediation pathways were non-significant. Indirect effects via **fixation duration** were non-significant for heart rate (Effect = 0.0015, 95% CI [−0.0001, 0.0038]), **RMSSD** (Effect = 0.0260, 95% CI [−0.0017, 0.0874]), and **pNN50** (Effect = 0.0015, 95% CI [−0.0001, 0.0038]). These findings indicate that despite significant effects of color temperature on multiple eye metrics, these metrics did not serve as mediators of cardiovascular responses.

4.3 Peripheral Occlusion Effects

We manipulated visual field restriction from 0% to 75%, with 37.5% serving as standard. Low refers to 0% occlusion (full vision), standard refers to 37.5% occlusion (moderate restriction), and high refers to 75% occlusion (severe tunnel vision). Detailed statistics for peripheral occlusion are reported in Appendix C.

4.3.1 Effects on Eye Metrics. **Pupil diameter** differed significantly across low (M = -.41), standard (M = -.20), and high (M = .04) occlusion conditions ($\chi^2(2) = 26.667$, $p < .001$), showing a progressive increase (dilation) with greater peripheral restriction. Pairwise comparisons were significant for all pairs: low–standard ($Z = -3.610$, $p < .001$), standard–high ($Z = -2.828$, $p = .005$), and low–high ($Z = -3.754$, $p < .001$). **Blink rate** showed a significant main effect of peripheral occlusion (repeated-measures ANOVA, sphericity assumed), $F(2, 78) = 3.289$, $p = .042$, increasing from low

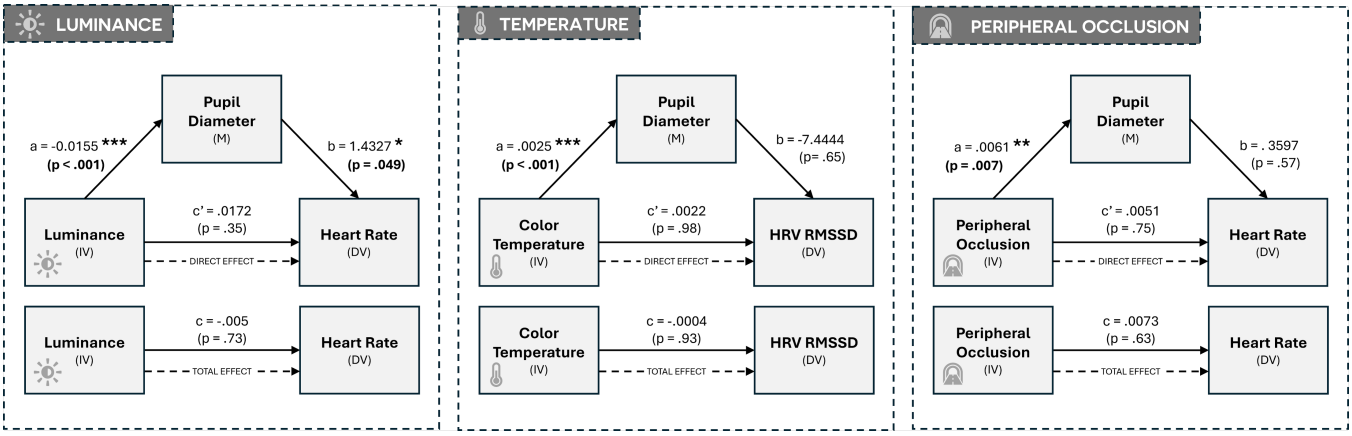

Figure 6: Mediation pathways tested between visual parameters and physiological responses through eye metrics; only luminance → pupil diameter → heart rate showed a significant indirect effect (* p<.05, ** p<.01, *** p<.001).

($M = -11.11$) to standard ($M = -7.89$) to high ($M = -6.71$) occlusion. Pairwise comparisons indicated significant differences for low–standard ($t(39) = -2.204$, $p = .016$) and low–high ($t(39) = -2.443$, $p = .021$), but not for standard–high ($t(39) = -.581$, $p = .566$).

Fixation and saccade metrics (rate and duration) did not differ significantly across occlusion conditions.

4.3.2 Effects on Physiological Measures. **Heart rate** showed no significant main effect of peripheral occlusion (repeated-measures ANOVA; Greenhouse–Geisser corrected), $F(1.820, 70.980) = 0.127$, $p = .863$. Heart rate variability measures **RMSSD** and **pNN50** likewise did not differ significantly across occlusion conditions, $\chi^2(2) = 1.947$, $p = .378$, and $\chi^2(2) = 2.309$, $p = .315$, respectively.

4.3.3 Pupil Diameter Mediation. For the peripheral occlusion → **pupil diameter** → heart rate pathway, the path from peripheral occlusion to **pupil diameter** was significant ($a = 0.0061$, $t = 2.77$, $p = .007$), but the path from **pupil diameter** to heart rate was non-significant ($b = 0.3610$, $t = 0.57$, $p = .569$). This resulted in a non-significant indirect effect (Effect = 0.0022, 95% CI $[-0.0048, 0.0107]$). The direct effect on heart rate was non-significant when **pupil diameter** was included as mediator ($c' = 0.0050$, $t = 0.32$, $p = .751$).

Pupil diameter did not significantly mediate peripheral occlusion effects on HRV measures: **RMSSD** (Effect = 0.0210, 95% CI $[-0.0056, 0.0648]$). While the peripheral occlusion to **pupil diameter** pathway was significant across all models, the path from **pupil diameter** to **RMSSD** ($b = 3.4211$, $t = 1.29$, $p = .199$) was non-significant, indicating no evidence of mediation for HRV measures.

4.3.4 Fixation Rate Mediation. Although peripheral occlusion did not have a significant effect on fixation rate ($a = 0.1419$, $t = 1.06$, $p = .290$), fixation rate showed a significant positive relationship with heart rate ($b = 0.0276$, $t = 2.71$, $p = .008$). However, this did not result in a significant indirect effect (Effect = 0.0039, 95% CI $[-0.0039, 0.0164]$). This finding suggests that while peripheral occlusion does not reliably modulate fixation rate, fixation rate itself may be associated with cardiovascular arousal.

4.4 Visual Suppression Effects

We used three simulated blink patterns: slow (3 blinks/min, 600 ms), average (18 blinks/min, 100 ms), and fast (30 blinks/min, 50 ms). Low refers to a slow pattern, standard refers to an average pattern, and high refers to a fast pattern. Detailed statistics for visual suppression are reported in Appendix D.

4.4.1 Effects on Eye Metrics. **Pupil diameter** showed no significant main effect of visual suppression condition (repeated-measures ANOVA; Greenhouse–Geisser corrected), $F(1.981, 77.259) = 0.496$, $p = .609$. In contrast, **blink rate** showed a main effect of visual suppression (univariate repeated-measures analysis, Greenhouse–Geisser corrected), $F(1.668, 65.052) = 3.51$, $p = .032$ (sphericity assumed: $F(2, 78) = 3.869$, $p = .025$), increasing from low ($M = -8.14$) to standard ($M = -7.11$) to high ($M = -5.15$) visual suppression. Pairwise comparisons indicated a significant difference for standard–high ($t(39) = -2.251$, $p = .048$).

Fixation duration differed significantly between low (M = .031), standard (M = .021), and high (M = .017) visual suppression conditions ($\chi^2(2) = 8.167$, $p = .017$), although post-hoc pairwise comparisons did not reach significance, suggesting only a modest trend toward shorter fixations with faster suppression. Other fixation and saccade metrics (rate and duration) did not differ significantly across visual suppression conditions.

4.4.2 Effects on Physiological Measures. **Heart rate** showed no significant overall effect of visual suppression ($\chi^2(2) = 4.054$, $p = .132$). **RMSSD** likewise showed no significant omnibus effect ($\chi^2(2) = 3.622$, $p = .164$), although a planned comparison indicated lower variability for low–high visual suppression ($Z = -2.029$, $p = .042$). **pNN50** did not differ significantly across visual suppression conditions ($\chi^2(2) = 3.323$, $p = .190$).

4.4.3 Blink Rate Mediation. For the periodic visual suppression → **blink rate** → heart rate pathway, the path from periodic visual suppression to **blink rate** was non-significant ($a = 0.1252$, $t = 1.62$, $p = .107$), and the path from **blink rate** to heart rate was also non-significant ($b = -0.0360$, $t = -1.23$, $p = .219$). This resulted in a non-significant indirect effect (Effect = −0.0045, 95%

CI [−0.0174, 0.0032]). **Blink rate** did not significantly mediate periodic visual suppression effects on HRV measures: **RMSSD** (Effect = 0.0076, 95% CI [−0.0088, 0.0329]) and **pNN50** (Effect = 0.0002, 95% CI [−0.0136, 0.0130]). In these models, the paths from **blink rate** to **RMSSD** (b = 0.0607, t = 0.78, p = .435) and to **pNN50** (b = −0.0019, t = −0.03, p = .974) were non-significant, indicating no evidence of mediation for either HRV measure.

4.4.4 Fixation Rate Mediation. For the periodic visual suppression → **fixation rate** → heart rate pathway, the path from periodic visual suppression to **fixation rate** was non-significant (a = 0.0464, t = 0.32, p = .752), and the path from **fixation rate** to heart rate was non-significant (b = 0.0243, t = 1.59, p = .114). This resulted in a non-significant indirect effect (Effect = 0.0011, 95% CI [−0.0067, 0.0125]). **Fixation rate** did not significantly mediate periodic visual suppression effects on HRV measures: **RMSSD** (Effect = −0.0010, 95% CI [−0.0175, 0.0113]) and **pNN50** (Effect = −0.0006, 95% CI [−0.0118, 0.0106]), indicating no evidence of mediation for either HRV measure.

4.5 Virtual Reality Symptom Questionnaire

To assess the differential impact of visual parameter manipulations on participant comfort, we analyzed VRSQ responses collected after each experimental trial. For each VRSQ outcome, we ran a Friedman test across the four conditions. We then conducted Holm-adjusted Wilcoxon signed-rank tests for all six pairwise comparisons between luminance adjustment (L), color temperature manipulation (T), peripheral occlusion (PO), and visual suppression (VS). Complete results including all pairwise comparisons are reported in Appendix E. The significant results from the VRSQ questionnaire can be seen in Figure 7.

4.5.1 Non-ocular Symptom Analysis. Mean non-ocular symptom ratings (general discomfort, fatigue, boredom, drowsiness, headache, dizziness, difficulty concentrating, nausea) differed significantly across conditions ($\chi^2(3) = 19.914$, $p < .001$). Luminance adjustment produced the highest non-ocular symptom severity (M = 1.77, SD = 0.66), followed by visual suppression (M = 1.70, SD = 0.79), peripheral occlusion (M = 1.60, SD = 0.63), and color temperature manipulation (M = 1.59, SD = 0.59). Post-hoc comparisons indicated higher non-ocular symptoms under luminance than occlusion ($Z = -3.299$, $p = .006$) and temperature ($Z = -3.337$, $p = .006$).

General discomfort showed significant effects ($\chi^2(3) = 19.684$, $p < .001$). Peripheral occlusion produced the lowest general discomfort (M = 1.35, SD = 0.48), which was lower than visual suppression (M = 1.80, SD = 0.91; $Z = -3.900$, $p < .001$), luminance (M = 1.65, SD = 0.83; $Z = -2.516$, $p = .036$), and color temperature (M = 1.55, SD = 0.75; $Z = -2.828$, $p = .020$). Visual suppression also produced higher general discomfort than temperature ($Z = -2.887$, $p = .020$).

Fatigue demonstrated significant effects ($\chi^2(3) = 68.253$, $p < .001$). Visual suppression produced the highest fatigue ratings (M = 2.42, SD = 0.98), exceeding peripheral occlusion (M = 1.55, SD = 0.81; $Z = -5.460$, $p < .001$), color temperature (M = 1.50, SD = 0.75; $Z = -5.548$, $p < .001$), and luminance (M = 1.93, SD = 0.94; $Z = -3.601$, $p < .001$). Luminance also exceeded occlusion ($Z = -3.000$, $p = .006$) and temperature ($Z = -3.400$, $p = .003$).

Boredom showed strong condition effects ($\chi^2(3) = 69.059$, $p < .001$). Peripheral occlusion produced the highest boredom ratings (M = 2.60, SD = 0.74), exceeding visual suppression (M = 1.45, SD = 0.82; $Z = -5.547$, $p < .001$), color temperature (M = 1.55, SD = 0.55; $Z = -5.160$, $p < .001$), and luminance (M = 1.83, SD = 0.93; $Z = -4.845$, $p < .001$). Luminance also produced higher boredom than visual suppression ($Z = -3.266$, $p = .003$).

Drowsiness showed moderate effects ($\chi^2(3) = 12.145$, $p = .007$). Visual suppression produced lower drowsiness (M = 1.43, SD = 0.75) than occlusion (M = 1.75, SD = 1.01; $Z = -2.625$, $p = .036$).

Headache demonstrated pronounced effects ($\chi^2(3) = 77.754$, $p < .001$). Luminance adjustment produced the highest headache severity (M = 2.55, SD = 1.11), exceeding visual suppression (M = 1.58, SD = 0.93; $Z = -4.257$, $p < .001$), color temperature (M = 1.37, SD = 0.49; $Z = -5.031$, $p < .001$), and peripheral occlusion (M = 1.35, SD = 0.48; $Z = -5.029$, $p < .001$). Visual suppression also produced higher headache ratings than peripheral occlusion ($Z = -2.530$, $p = .033$).

Dizziness showed significant effects ($\chi^2(3) = 21.241$, $p < .001$). Peripheral occlusion produced lower dizziness (M = 1.35, SD = 0.48) than luminance (M = 1.40, SD = 0.59; $Z = -2.780$, $p = .027$).

Difficulty concentrating showed moderate effects ($\chi^2(3) = 10.960$, $p = .012$), though no pairwise comparisons reached significance after Holm correction. Descriptively, visual suppression produced the highest ratings (M = 2.03, SD = 0.89), followed by luminance (M = 1.87, SD = 0.88), peripheral occlusion (M = 1.53, SD = 0.78), and color temperature (M = 1.52, SD = 0.78).

Nausea showed the strongest condition effects ($\chi^2(3) = 85.241$, $p < .001$). Color temperature manipulation produced the highest nausea (M = 2.33, SD = 0.97) and was higher than visual suppression (M = 1.45, SD = 0.75; $Z = -4.807$, $p < .001$), peripheral occlusion (M = 1.35, SD = 0.48; $Z = -5.126$, $p < .001$), and luminance (M = 1.35, SD = 0.48; $Z = -5.126$, $p < .001$).

4.5.2 Ocular Symptom Analysis. Mean ocular symptom ratings (tired eyes, sore/aching eyes, eyestrain, blurred vision, difficulty focusing) differed across conditions ($\chi^2(3) = 30.195$, $p < .001$). Luminance adjustment (M = 2.12, SD = 0.82) and visual suppression (M = 2.11, SD = 0.77) produced the highest ocular symptom scores, followed by color temperature manipulation (M = 1.91, SD = 0.73), with peripheral occlusion producing the lowest scores (M = 1.55, SD = 0.50). Post-hoc comparisons indicated that peripheral occlusion yielded lower ocular symptoms than visual suppression ($Z = -5.039$, $p < .001$), luminance ($Z = -3.844$, $p < .001$), and color temperature ($Z = -3.469$, $p = .004$).

Tired eyes showed significant effects ($\chi^2(3) = 44.016$, $p < .001$). Visual suppression produced the highest tired eyes ratings (M = 2.45, SD = 0.93) and exceeded peripheral occlusion (M = 1.48, SD = 0.60; $Z = -5.058$, $p < .001$) and luminance (M = 2.25, SD = 1.15; $Z = -4.294$, $p < .001$). Luminance exceeded peripheral occlusion ($Z = -3.455$, $p = .004$) and color temperature (M = 1.65, SD = 0.89; $Z = -2.639$, $p = .024$). Color temperature also exceeded peripheral occlusion ($Z = -4.294$, $p < .001$).

Sore/aching eyes demonstrated significant effects ($\chi^2(3) = 31.881$, $p < .001$). Peripheral occlusion produced the lowest sore/aching eyes ratings (M = 1.53, SD = 0.51), which was lower than visual

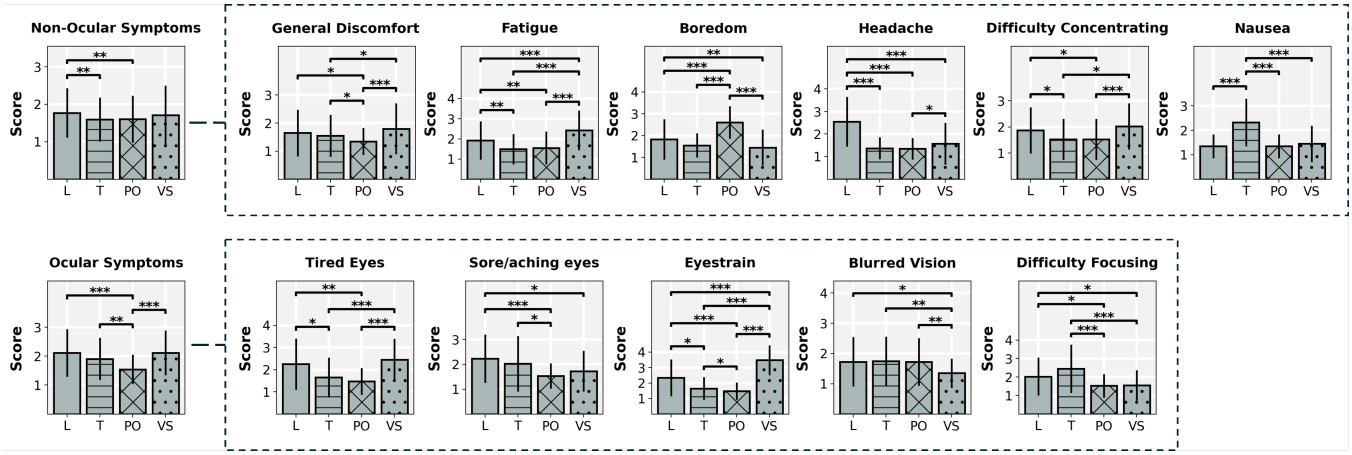

Figure 7: Virtual Reality Symptom Questionnaire (VRSQ) scores for non-ocular and ocular symptoms across conditions: L (Luminance), T (Color Temperature), PO (Peripheral Occlusion), VS (Visual Suppression) (* p<.05, ** p<.01, *** p<.001).

suppression (M = 1.73, SD = 0.82; $Z = -4.360$, $p < .001$), color temperature (M = 2.03, SD = 1.12; $Z = -3.679$, $p = .002$), and luminance (M = 2.22, SD = 0.97; $Z = -3.195$, $p = .006$).

Eyestrain demonstrated substantial condition effects ($\chi^2(3) = 56.991$, $p < .001$). Visual suppression produced the highest eyestrain ratings (M = 3.48, SD = 0.91), exceeding peripheral occlusion (M = 1.48, SD = 0.55; $Z = -5.679$, $p < .001$), color temperature (M = 1.95, SD = 1.01; $Z = -4.920$, $p < .001$), and luminance (M = 2.48, SD = 1.20; $Z = -4.033$, $p < .001$). Luminance exceeded peripheral occlusion ($Z = -3.925$, $p < .001$) and color temperature ($Z = -2.190$, $p = .029$). Color temperature also exceeded peripheral occlusion ($Z = -2.601$, $p = .018$).

Blurred vision showed moderate effects ($\chi^2(3) = 12.319$, $p = .006$). Visual suppression produced the lowest blurred vision ratings (M = 1.35, SD = 0.48), which was lower than peripheral occlusion (M = 1.72, SD = 0.78; $Z = -3.419$, $p = .006$), color temperature (M = 1.75, SD = 0.81; $Z = -3.358$, $p = .006$), and luminance (M = 1.73, SD = 0.82; $Z = -2.615$, $p = .036$).

Difficulty focusing demonstrated significant effects ($\chi^2(3) = 28.885$, $p < .001$). Peripheral occlusion produced the lowest difficulty focusing ratings (M = 1.53, SD = 0.64), which was lower than color temperature (M = 2.45, SD = 1.30; $Z = -3.963$, $p < .001$) and luminance (M = 2.02, SD = 1.02; $Z = -2.746$, $p = .018$). Visual suppression (M = 1.55, SD = 0.81) also produced lower difficulty focusing than color temperature ($Z = -3.675$, $p < .001$) and luminance ($Z = -2.875$, $p = .016$).

4.6 Visual Parameter Awareness

To assess participants' conscious awareness of visual parameter manipulations, we analyzed open-ended responses to the post-trial question: "Did you notice any visual changes during the task? If so, please describe what you observed." We conducted manual analysis of these qualitative responses to examine detection patterns, directional awareness, and the phenomenological language participants used to describe their experiences. This analysis revealed three key insights regarding participants' conscious perception of the experimental manipulations.

4.6.1 Detection Rates by Parameter Type. Participants showed varying levels of awareness across our four visual parameters: **visual suppression** achieved the highest detection rate at 90.0% (36/40 participants), followed by **luminance** at 85.0% (34/40 participants) and **color temperature** at 82.5% (33/40 participants). **Peripheral occlusion** showed significantly lower detection at 42.5% (17/40 participants). Overall, participants detected visual changes in 75.0% of trials (120/160), with peripheral occlusion being significantly less detectable than other parameters.

4.6.2 Bidirectional vs. Unidirectional Awareness. Despite our experimental design describing increases and decreases in each parameter, participants rarely demonstrated awareness of bidirectional changes. Among those who detected a change, **color temperature** showed the highest bidirectional awareness at 21.2% of detected cases (7/33), with examples including "Yellow and blue filter" (P12). **Luminance** showed minimal bidirectional awareness at 8.8% (3/34), with rare examples like "It got bright and then dark" (P16). **Peripheral occlusion** showed 5.9% bidirectional awareness (1/17). **Visual suppression** showed no bidirectional awareness (0/36), likely due to the discrete nature of the manipulation.

The vast majority of participants demonstrated unidirectional awareness, typically describing changes in one direction. Examples include: *luminance*: "bright" (P1), "yeah it got bright" (P5), "increases in brightness" (P6); *color temperature*: "yellow" (P1), "got yellow" (P5), "maybe it looked more yellow" (P3); *peripheral occlusion*: "black borders" (P4), "the surrounding was dark" (P12); *visual suppression*: "blinks" (P1), "screen blinked" (P5), "flashing" (P3).

4.6.3 Naturalistic vs. Objective Descriptions. Participants' descriptions fell into two distinct phenomenological categories: objective descriptions recognizing external changes versus naturalistic descriptions where participants used natural vision and biological eye behavior language to describe the artificial manipulations. **Luminance** and **color temperature** elicited exclusively objective descriptions, with all detected responses showing 100% objective attribution. *Luminance* objective examples included "bright" (P1), "the brightness definitely increased during parts of the task" (P2),

"luminance increased" (P4), and "yeah it got bright" (P5). *Color temperature* objective examples included "yellow" (P1), "the colors became more yellow and warm" (P2), "color temperature spectrum" (P4), and "got yellow" (P5).

In contrast, **Peripheral Occlusion** and **Visual Suppression** generated substantial naturalistic responses. For peripheral occlusion, 12/17 detected participants (70.6%) provided naturalistic descriptions: "Tunnel vision" (P39), "My field of view decreased until I was looking at a dark tunnel" (P18), "I had peripheral vision" (P34), "My vision reduced and then increased" (P24). The remaining 5/17 participants (29.4%) provided objective descriptions: "Black borders" (P4), "The room got dark sometimes" (P8), "The screen was dark" (P12). For visual suppression, 31/36 detected participants (86.1%) provided interoceptive descriptions like "blinks" (P1), interpreting screen blackouts as blinking behavior. The remaining 5/36 participants (13.9%) provided objective descriptions: "there were brief blackouts or blinks of the screen" (P2), "periodic black screen" (P4), "screen blackouts" (P8), "flashing" (P3).

5 Discussion

Before addressing each condition in detail, it is important to revisit our guiding research questions. We asked whether visual parameters in VR alter eye activity (**RQ1**), whether these changes extend to cardiovascular responses and are mediated by ocular dynamics (**RQ2**), how visual manipulations shape subjective symptoms (**RQ3**), and whether these combinations of ocular responses, physiological outcomes, and subjective experience indicate reflexive, appraisal-driven, or discomfort-driven pathways linking visual input and bodily state (**RQ4**). The following subsections discuss how each visual parameter relates to these questions.

5.1 Luminance directly influences the heart through the pupil, but produces high discomfort

The luminance condition produced the most classical and expected results in the eyes, directly addressing **RQ1**. Pupil diameter followed the pupillary light reflex, constricting under brighter conditions and dilating in darkness. Blink rate increased as luminance increased, suggesting protective or comfort-related blinking in response to higher light intensity. Blink duration also decreased significantly with increasing luminance, indicating faster, more frequent blinks under bright conditions. This pattern is consistent with protective responses to visual stress [5]. Fixation rate increased progressively from low to high luminance, suggesting reduced visual exploration when luminance is diminished.

On the physiological side (**RQ2**), heart rate did not differ significantly, but heart rate variability was highest at standard luminance and reduced under brighter settings. Both RMSSD and pNN50 indices converged on this pattern, with standard luminance maintaining significantly higher vagal tone than bright conditions. This inverted-U pattern resembles a Yerkes-Dodson-like optimization [43], where moderate luminance supports parasympathetic regulation while extremes shift the system toward sympathetic dominance. Mediation analysis revealed that changes in pupil diameter fully accounted for the effect of luminance on heart rate, indicating that the heart responded to luminance through its influence on the pupil. However, luminance effects on heart rate variability were not mediated by pupil size. This dissociation reflects different regulatory timescales: heart rate captures rapid, beat-to-beat adjustments aligned with pupil dynamics, while HRV reflects sustained parasympathetic regulation over longer intervals, explaining why pupil mediated luminance effects on one but not the other. Overall, luminance functioned as a bottom-up visual parameter with the pupil mediating vision-cardiac relationships, exemplifying a reflexive pathway (**RQ4**).

The VRSQ results reinforce this physiological picture by showing that luminance adjustments produced the highest ocular symptom scores and were also associated with the strongest headache ratings (**RQ3**). Nonocular symptoms were also elevated, making luminance the most discomforting condition. While the pupil translated luminance changes into physiological modulation, these manipulations carried costs in visual strain and headache.

5.2 Color temperature shapes physiology

Color temperature manipulations revealed a distinct mechanism from reflexive visual pathways and inform both **RQ1** and **RQ2**. Warm (yellow-biased) light produced larger pupils than cool (blue-biased), consistent with prior findings [12]. Blink rate did not differ reliably, but duration was shorter under cool light than under standard and warm conditions. Shorter fixation durations under cool light suggested enhanced visual sampling under blue-biased illumination.

These findings diverge from typical arousal patterns with warm versus cool colors. Prior work found warm colors increase physiological arousal in passive viewing [47], yet our active VR task revealed a different pattern. Blue-biased light produced shorter blinks and denser fixation sequences, suggesting facilitated attentional control. This interpretation is consistent with recent findings that blue light stimulates intrinsically photosensitive retinal ganglion cells (ipRGCs), which activate attentional control regions and accelerate saccadic disengagement [25].

Mediation analysis further clarified these effects (**RQ2**). Pupil size did not transmit color temperature changes to cardiovascular physiology, and heart rate remained stable. However, HRV showed a selective effect, with RMSSD lower under warm compared to cool light. This suggests cognitive appraisal routes rather than reflexive photic responses, though this mechanism was not directly measured. Participants may have associated cooler light with clarity and warmer with stimulation, consistent with [12], leading to adjustments in blink strategy and fixation behavior.

The most striking outcome was the dissociation between objective physiology and subjective symptoms (**RQ3**). Color temperature produced the highest nausea scores, with yellow-biased light ratings approximately one full point higher than any other manipulation. Participants selectively noticed yellow shifts but were largely unaware of blue changes, suggesting that conscious detection of the yellow shift may have driven elevated nausea perception. This detection asymmetry suggests distinct pathways linking back to **RQ4**: blue light's attentional effects may bypass conscious appraisal through direct ipRGC stimulation, enhancing vigilance without increasing discomfort, while yellow light's nausea induction may

require conscious detection and cognitive interpretation, though further research is needed.

5.3 Peripheral occlusion increases boredom

Prior work has shown that restricting peripheral vision reduces visual competition and improves attentional stability, as participants only need to monitor the central field [6, 24]. Ocular measures partly supported this expectation (**RQ1**). Pupil diameter increased progressively with greater peripheral restriction, showing significant dilation across all occlusion levels. Pupil diameter and blinking under occlusion partly match the luminance pattern. High (black) occlusion likely reduces effective luminance, explaining the larger pupils observed, similar to those in the low-luminance condition. Blink rate, however, does not map cleanly onto the pupil effect, suggesting blinking is driven less by luminance and more by task demands, like a reduced need to suppress blinks with no peripheral input, allowing more frequent blinking without losing critical information [48]. This suggests a constrained attentional focus consistent with tunnel vision. Further research is needed to separate luminance from information-loss effects under occlusion.

Peripheral occlusion did not alter physiological indicators such as heart rate or HRV (**RQ2**). One explanation is that the 30-second gradual transition made the manipulation seamless, minimizing the abrupt entering-a-tunnel experience reported in research [6, 24]. Participants' awareness data support this view: fewer than half detected occlusion, and those who did described it in naturalistic terms, such as tunnel vision, rather than as an external manipulation. Without conscious detection of a sudden, disruptive restriction, peripheral occlusion may not have triggered the autonomic arousal responses studies observed. This suggests that the temporal profile of visual manipulations, not just their magnitude, may determine whether effects remain oculomotor or cascade to physiology.

Instead, the main effect was subjective boredom, answering **RQ3**. VRSQ ratings showed peripheral occlusion produced the highest boredom of any condition, significantly above luminance, color temperature, and visual suppression, consistent with research linking reduced visual stimulation to disengagement [34]. Because the manipulation was seamless, participants were not consciously disturbed, but reduced engagement manifested in subjective boredom rather than physiological strain. Notably, peripheral occlusion produced the lowest ocular symptom scores, suggesting reduced visual load may alleviate eye strain even as it increases disengagement.

This dissociation between stable physiology and increased boredom supports a cognitive-processing account of tunnel vision, directly addressing **RQ4**. Rather than evoking reflexive stress responses, peripheral restriction may have been processed as a gradual reduction in environmental richness, leading to disengagement and lowered vigilance. Gradual parameter transitions may enable physiological modulation without conscious disruption, though at the potential cost of user engagement and task motivation.

5.4 Visual suppression entrains the eyes but produces fatigue and eyestrain without altering physiology

The simulated blink conditions showed that frequent imposed blackouts did not strongly alter physiology, addressing **RQ1** and **RQ2**. Pupil diameter remained stable across blink patterns, while blink rate increased modestly, particularly between standard and high suppression frequencies. Fixation duration showed a significant omnibus effect, suggesting a trend toward shorter fixations with faster suppression, though pairwise comparisons did not survive correction. Heart rate and HRV remained stable, with only a selective reduction in RMSSD under fast compared to slow suppression. No mediation effects emerged. The lack of a substantial physiological impact suggests that participants may have categorized the artificial blinks as non-affective noise, thereby preserving their autonomic state while entraining minimally at the ocular level.

However, VRSQ results demonstrate that visual suppression was highly uncomfortable (**RQ3**). It produced the highest eyestrain scores and greatest fatigue ratings and elevated ocular symptoms. This indicates that even when physiological systems remain stable, artificial blink manipulations are experienced as visually taxing. This dissociation between autonomic stability and subjective fatigue, consistent with a discomfort-driven pathway **RQ4**, suggests visual entrainment techniques produce strain through local ocular fatigue mechanisms that do not engage cardiovascular responses.

5.5 The pupil selectively transmits some visual changes, while others bypass physiology and shape discomfort through cognition

Overall, the pupil serves as a mediator between certain visual inputs and physiological outcomes, directly addressing **RQ4**. For luminance, pupil diameter-mediated effects on heart rate demonstrated a reflexive pathway (**RQ1–RQ2**). Luminance also produced an inverted-U in HRV, with standard luminance maintaining higher vagal tone than bright conditions, though not mediated by pupil diameter. Color temperature modulated pupil size but did not transmit effects to the heart, instead associating with HRV changes and pronounced nausea, suggesting appraisal-based mechanisms (**RQ2–RQ3**). Peripheral occlusion altered pupil diameter and blinking without changes in heart rate, suggesting that oculomotor adjustments may serve as attentional regulators without engaging autonomic pathways (**RQ1–RQ3**). Visual suppression entrained blinking and fixation patterns with selective HRV reductions but no heart rate effects (**RQ1–RQ2**). Blink duration and fixation rates varied across conditions but did not mediate physiological responses, reinforcing the selectivity of the pupil-heart pathway.

This selective mediation pattern extended to subjective symptoms (**RQ3**), suggesting distinct pathways linking visual input to discomfort. Luminance-induced headaches and ocular strain aligned with its reflexive pupil-heart coupling. The extreme nausea associated with color temperature occurred despite minimal ocular mediation, with conscious detection of yellow shifts possibly driving perception through cognitive appraisal. Peripheral occlusion's boredom and visual suppression's eyestrain emerged without cardiovascular involvement, suggesting that subjective discomfort may operate somewhat independently of ocular physiological bridges.

The results suggest a layered system (**RQ4**): luminance acts through reflexive pupil–heart pathways, while temperature acts through higher-level appraisals, and peripheral occlusion and suppression shape subjective strain without penetrating to physiology. Critically, even when visual parameters modulated pupil diameter,

only luminance transmitted changes to heart rate, suggesting the pupil-heart connection may engage only under visual conditions.

5.6 Visual manipulations can generate interoceptive illusions

The visual suppression condition shows how visual manipulations can alter interoception rather than triggering ocular reflexes, expanding on **RQ4**. Interoception refers to the perception and interpretation of bodily signals such as heartbeats, breathing, or visceral sensations [13]. The finding that externally imposed blackouts increased blink frequency might be seen as a straightforward stimulus–response pattern (**RQ1**), with the system reacting to interruptions in the visual stream. However, evidence suggests this interpretation is insufficient. First, the imposed blinks did not elicit substantial heart rate changes, though HRV showed a selective reduction with RMSSD lower under fast compared to slow suppression (**RQ2**). The minimal systemic arousal suggests participants may have incorporated the suppression into their sense of bodily rhythms rather than processing it as an external perturbation.

Second, VRSQ results show visual suppression produced the highest eyestrain and fatigue among all conditions (**RQ3**). Importantly, these symptoms are not explained by external stimulation alone, since the imposed blackouts were brief and noninvasive compared to the continuous discomfort produced by luminance or color temperature manipulations. Instead, they align more closely with misattributing external events as self-generated. IIf participants internalized the imposed blackouts as part of their own blinking activity, the result would be overtaxing of ocular and attentional systems, consistent with high fatigue and eyestrain scores.

Third, qualitative reports indicate that 86.1% of participants who detected the manipulation described suppression in terms consistent with natural blinking (e.g., "blinks") rather than as an externally imposed overlay (e.g., "screen blackouts"). This aligns with prior evidence that manipulations resembling endogenous bodily events are more likely to be embodied as self-generated [38]. By simulating a process that normally originates within the body, the system blurred the line between external and internal, potentially creating an interoceptive illusion in which an externally generated signal is interpreted as originating from one's own body.

Overall, the ocular adjustments, symptom reports, and minimal autonomic arousal suggest visual suppression has the potential to induce interoceptive illusions, contributing a novel dimension to **RQ4** that warrants further investigation.

5.7 Design Implications

These findings provide initial pointers for developers of adaptive affective VR systems. Our results suggest that visual manipulations do not act through a single mechanism: luminance triggers reflexive processes through direct pupil-heart coupling (**RQ1–RQ2**), color temperature operates through cognitive appraisal without pupillary mediation of cardiovascular effects (**RQ2–RQ3**), peripheral occlusion produces oculomotor adjustments serving attentional regulation without engaging autonomic pathways (**RQ1–RQ3**), and visual suppression produces strong subjective strain without engaging substantial cardiovascular physiology (**RQ3**). However, these outcomes were obtained in a single VR environment with a specific construction task, and further research is needed to determine the generalizability of these findings. For system designers, visual parameters should not be treated as interchangeable levers on physiology. Instead, each manipulation may need to be matched to its underlying pathway (reflexive, cognitive, or subjective) when designing adaptive feedback loops (**RQ4**).

In therapeutic contexts, such as stress recovery, luminance has emerged as a potentially powerful yet fragile lever. The inverted-U trend in HRV alongside elevated discomfort scores suggests a trade-off. Applications prioritizing comfort and parasympathetic recovery should maintain near-baseline luminance levels to optimize vagal tone. Those seeking to modulate arousal through luminance extremes must account for accompanying increases in ocular strain and headache symptoms. Designers might implement luminance boundaries preventing extreme deviations or incorporate user-reported discomfort as a safety constraint.

Peripheral occlusion presents a different opportunity: it offers a way to narrow attention without triggering cardiovascular stress, making it potentially valuable for reducing cognitive load during high-pressure VR tasks. However, the boredom trade-off suggests this technique works best in brief interventions. Designers could implement occlusion strategically during specific task phases requiring focus, then release it to restore engagement. The finding that gradual transitions prevented autonomic arousal implies that adaptive systems should prioritize slow, continuous adjustments over abrupt changes when manipulating the field of view.

Color temperature presents a more complex design space. The finding that cool lighting enhanced attentional control without conscious detection, while warm lighting triggered severe nausea when noticed, suggests a "stealth enhancement" strategy: systems could use subtle blue biasing to support vigilance during demanding tasks, but must avoid yellow shifts that users consciously perceive. Additionally, the task-dependency of our findings (blue light enhances vigilance in active engagement rather than inducing relaxation) suggests that color temperature effects may vary based on user activity. Adaptive systems might need to consider task context when selecting spectral manipulations, applying cool light during active phases and potentially warmer tones during passive rest periods, though the nausea risk requires careful testing.

Visual suppression appeared to be the least promising for future use. The combination of high eyestrain, minimal cardiovascular benefit, and potential for interoceptive confusion suggests this technique is unsuitable for wellness applications. However, the interoceptive illusion path opens possibilities for perceptual research and artistic VR experiences that intentionally blur body boundaries. Designers exploring these applications should monitor user discomfort closely and provide clear opt-out mechanisms.

Finally, the mediation analyses underscore the potential value of eye tracking as a diagnostic tool, with caveats. The selectivity of pupil-heart coupling (present only for luminance) implies that adaptive systems cannot universally predict cardiovascular effects based on ocular changes. Developers should validate which ocular metrics predict physiological outcomes in their particular manipulation space before building closed-loop systems. For luminance-based systems, pupil diameter offers a reliable proxy for cardiac modulation. For other parameters, ocular metrics may be better suited for detecting user discomfort or cognitive load. This suggests a two-tier

monitoring strategy: use pupil diameter to govern luminance-based interventions, while relying on subjective symptom reports or direct physiological measures to guide other visual manipulations.

Design guidelines

Overall, the tentative design implications can be summarized with the following design guidelines:

(1) **Match manipulations to mechanisms:** Recognize that different visual parameters act through distinct pathways. Design intervention strategies specific to each pathway: reflexive manipulations (luminance) can target autonomic outcomes directly, cognitive manipulations (color temperature) require consideration of user awareness and task context, while attentional manipulations (occlusion) and subjective manipulations (suppression) may shape experience without cardiovascular effects.
(2) **Use luminance carefully:** Maintain near-baseline levels to optimize parasympathetic activity for recovery applications. If modulating arousal through luminance changes, implement boundaries preventing extreme deviations, and incorporate user-reported discomfort as a safety constraint. Use pupil diameter as an indicator for luminance-driven cardiac modulation.
(3) **Balance attention and engagement with occlusion:** Deploy peripheral restriction strategically during task phases requiring focus, then release to restore engagement. Use gradual transitions (e.g., 30 seconds) to prevent autonomic arousal. Pair with dynamic content to mitigate boredom in longer exposures.
(4) **Apply color temperature subtly and contextually:** Use cool lighting to support vigilance during active tasks, but keep shifts subtle to avoid conscious detection. Avoid color shifts that users can notice, as these trigger severe nausea. Consider the task phase when selecting spectral manipulations, as effects may reverse between active and passive contexts.
(5) **Avoid visual suppression for recovery tasks:** Reserve for entertainment or artistic contexts where discomfort is intentional. If exploring interoceptive effects deliberately, provide clear user warnings and opt-out mechanisms, as users may not recognize the manipulation as external.
(6) **Use eye tracking selectively for adaptive feedback:** Validate which ocular metrics predict physiological outcomes in your manipulation space. Use pupil diameter to govern luminance interventions, but rely on subjective reports or direct physiological measures for other parameters. Implement a two-tier monitoring strategy distinguishing markers of autonomic change from markers of discomfort or cognitive load.

More broadly, physiological computing in VR may need to account for both the gatekeeping role of the pupil and the interpretive role of cognition, designing interventions that align with embodied reflexes and users' perceptual and affective expectations. However, these conclusions are preliminary and drawn from a single task context. Further research across different VR environments and user groups is necessary to confirm and refine these implications.

6 Limitations

This work has several limitations that should be acknowledged. First, all findings are based on a single VR environment and task. It is unclear whether the same visual manipulations would have a similar effect in other VR settings or under tasks that require different levels of engagement or emotional responses. Future studies should replicate these manipulations in varied environments and task contexts to determine generalizability.

Second, parameter levels for luminance, color temperature, peripheral occlusion, and visual suppression were selected by researchers rather than derived from prior empirical standards. Because systematic guidelines for appropriate ranges in VR are lacking, the chosen values reflect exploratory design decisions and may not have captured subtler but meaningful ranges. Future work should systematically map these parameter spaces to establish validated thresholds for ocular and physiological effects.

Third, trial durations (4.5 min per condition, 30 sec per segment) may have been insufficient to capture slower-developing effects. For example, changes in temperature or peripheral occlusion might require sustained exposure before exerting physiological or perceptual influence. Longer trial designs would help clarify whether null or weak findings reflect true insensitivity or insufficient time.

Fourth, symptom data were collected with the Virtual Reality Symptom Questionnaire (VRSQ) once per trial, aggregating experiences across opposing parameter states within the same manipulation (e.g., blue vs. yellow for color temperature, low vs. high for luminance). This means the VRSQ could not isolate direction-specific or level-specific effects. Future work should include repeated measures within conditions or use alternative questionnaires to better ascertain symptom directionality. Further, it would have been valuable to assess whether participants noticed the visual changes and how salient they were to help disentangle whether discomfort stemmed from conscious detection or unconscious processing.

Finally, several methodological constraints limit interpretation. Manipulations were implemented as relative post-processing adjustments on a single headset/display pipeline, restricting generalization to absolute photometric values or to other devices. Eye tracking relied on system-reported metrics at native sampling rate, limiting temporal precision. Although counterbalancing and inter-trial intervals were used, adaptation within trials and carryover effects cannot be fully excluded. The university-based sample and emotionally neutral task context limit generalizability to demographics and ecological contexts. Moreover, mediation analyses were conducted on condition-level aggregates without time-lag modeling, and cognitive appraisal was inferred rather than directly measured. Future studies should employ higher-precision measurement systems, diverse participant samples, and direct assessments of appraisal to strengthen causal attribution and external validity.

7 Future Work

Future work should advance in two directions. First, toward adaptive and personalized control. The present study relied on fixed thresholds, but future systems must test whether adaptive approaches can reliably learn and adjust to individuals in real-time. Moving beyond static rules to adaptive policies that tune to each user's physiology, baseline states, and evolving context could transform

thresholding into continual personalization. Such personalization should be viewed as a promising direction requiring replication and validation across diverse users and scenarios.

Second, toward embodied and ecologically valid contexts. The present results were obtained in a single VR environment with a single task type, which limits generalizability. Future studies should replicate these manipulations across a range of VR environments and task types to investigate whether the same mechanisms hold in settings that vary in terms of immersion, content, or emotional load. Beyond this, the broader potential lies in supporting performance in motor, perceptual–motor, and collaborative activities. Extending adaptive systems into physical tasks, tested longitudinally under fatigue, stress, or exertion and informed by multimodal sensing, would reveal whether these methods can sustain effectiveness in real-world environments. This shift reframes the work from cognitive experiments to a framework for augmenting human capability across mental and physical domains.

8 Conclusion

This study, to our knowledge, is the first systematic attempt to test mediation pathways between visual parameters, ocular metrics, and physiology in immersive VR. By introducing and empirically evaluating the Ocular Command Center framework, we directly addressed our research questions: showing that luminance translated to cardiovascular change through pupillary reflexes (**RQ1–RQ2**), color temperature modulated pupils and HRV without pupillary mediation of cardiovascular effects, suggesting appraisal processes (**RQ2–RQ3**), and occlusion and suppression altered oculomotor behavior without substantially engaging cardiovascular physiology (**RQ1–RQ3**). This approach demonstrates how mediation analysis can be used to separate reflexive, appraisal-based, and discomfort-driven pathways (**RQ4**), establishing a methodological foundation for future VR psychophysiology research.

The implications extend beyond the specific manipulations tested. Not all visual changes are equal: some engage autonomic pathways, while others influence subjective comfort or attentional strategies. Recognizing the layered roles of the ocular system (as a reflexive mediator, cognitive interpreter, and generator of interoceptive illusions) enables the design of precise and safer immersive systems.

Immediate next steps include replicating these findings in more diverse VR environments and task contexts, testing longer exposure durations, and incorporating measures that directly assess the detectability of visual changes. Further work should explore finer-grained parameter ranges and combine eye tracking with other modalities to strengthen causal attribution.

In the long term, this framework suggests adaptive systems that utilize ocular responses as key control signals for co-regulating physiology, comfort, and engagement. Imagine headsets that subtly adjust luminance to support stress recovery, or systems that detect the build-up of strain and intervene before discomfort escalates. By confirming and extending these findings, future research can move us closer to immersive technologies that not only represent reality but also interact intelligently with the body to create more human-centered worlds.

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A Appendix A - Luminance results

Table 2: Luminance manipulation: omnibus tests and Holm–Bonferroni-corrected pairwise comparisons for all eye and cardiovascular metrics across low (−30%), standard, and high (+30%) luminance conditions.

Metric	Omnibus test	Low–Standard	Standard–High	Low–High
Pupil diameter	$\chi^2(2) = 43.103$ **p < .001**	$Z = -4.141$ **p < .001**	$Z = -4.573$ **p < .001**	$Z = -4.487$ **p < .001**
Blink rate	$\chi^2(2) = 11.655$ **p = .003**	$Z = -2.692$ **p = .014**	$Z = -2.195$ **p = .028**	$Z = -3.384$ **p = .003**
Blink duration	$\chi^2(2) = 5.840$ $p = .054$	$Z = -2.085$ **p = .037**	$Z = -3.123$ **p = .006**	$Z = -2.677$ **p = .014**
Fixation rate	$\chi^2(2) = 12.069$ **p = .002**	$Z = -3.146$ **p = .006**	$Z = -.962$ $p = .336$	$Z = -2.714$ **p = .014**
Fixation duration	$\chi^2(2) = 1.931$ $p = .381$	$Z = -1.654$ $p = .294$	$Z = -.573$ $p = .567$	$Z = -1.654$ $p = .294$
Saccade rate	$\chi^2(2) = 6.276$ **p = .043**	$Z = -1.914$ $p = .168$	$Z = -1.762$ $p = .168$	$Z = -.746$ $p = .456$
Saccade duration	$\chi^2(2) = 3.586$ $p = .166$	$Z = -1.676$ $p = .282$	$Z = -.919$ $p = .412$	$Z = -1.265$ $p = .412$
Heart rate	$F(1.675, 65.325) = 0.747$ $p = .456$	$t(39) = 1.186$ $p = .732$	$t(39) = -.861$ $p = .790$	$t(39) = .482$ $p = .790$
RMSSD	$\chi^2(2) = 14.973$ **p = .001**	$Z = -2.165$ $p = .060$	$Z = -3.191$ **p = .003**	$Z = -.189$ $p = .850$
pNN50	$\chi^2(2) = 12.324$ **p = .002**	$Z = -1.697$ $p = .180$	$Z = -2.508$ **p = .036**	$Z = -.076$ $p = .939$

Table 3: Descriptive statistics for all eye and cardiovascular metrics under the luminance manipulation. For each metric, the table reports the median and interquartile range (Mdn [IQR]) and the mean and standard deviation (M (SD)) for low (−30%), standard, and high (+30%) luminance conditions.

	Low		Standard		High	
Metric	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**
Pupil diameter	.245 [.408]	.245 (.464)	-.171 [.396]	-.171 (.329)	-.685 [.600]	-.685 (.432)
Blink rate (blinks/min)	-6.34 [12.73]	-7.66 (10.94)	-2.08 [13.50]	-2.89 (13.10)	4.98 [24.95]	1.79 (15.39)
Blink duration	.014 [.115]	.059 (.115)	.007 [.059]	.005 (.070)	-.015 [.041]	-.028 (.070)
Fixation rate	.02 [25.17]	.021 (35.78)	8.31 [21.46]	8.31 (31.25)	12.47 [31.86]	12.47 (34.61)
Fixation duration	-.007 [.114]	-.002 (.118)	-.018 [.085]	-.024 (.098)	-.034 [.116]	-.030 (.105)
Saccade rate	-.52 [32.76]	-.523 (28.05)	5.34 [25.54]	5.34 (25.42)	-1.30 [32.54]	-1.30 (26.46)
Saccade duration	.001 [.014]	-.003 (.019)	-.004 [.014]	-.007 (.017)	-.003 [.016]	-.006 (.019)
Heart rate	2.34 [4.67]	2.42 (3.06)	2.35 [4.20]	1.78 (3.31)	2.34 [4.89]	2.13 (3.06)
RMSSD	-2.00 [10.12]	-2.00 (8.06)	0.924 [8.41]	.924 (9.83)	-3.12 [6.50]	-3.12 (6.97)
pNN50	-1.01 [4.88]	-1.01 (6.90)	0.433 [5.96]	.433 (5.52)	-2.17 [5.99]	-2.17 (6.44)

B Appendix B - Color Temperature results

Table 4: Color temperature manipulation: omnibus tests and Holm–Bonferroni-corrected pairwise comparisons for all eye and cardiovascular metrics across cool (−100%), standard, and warm (+100%) color temperature conditions.

Metric	Omnibus test	Low–Standard	Standard–High	Low–High
Pupil diameter	$F(1.285, 50.115) = 35.595$ **p < .001**	$t(39) = -6.091$ **p < .001**	$t(39) = -2.879$ **p = .007**	$t(39) = -6.318$ **p < .001**
Blink rate	$\chi^2(2) = 2.294$ $p = .318$	$Z = -.487$ $p = .626$	$Z = -1.958$ $p = .114$	$Z = -2.077$ $p = .114$
Blink duration	$\chi^2(2) = 17.706$ **p < .001**	$Z = -3.462$ **p = .003**	$Z = -.419$ $p = .675$	$Z = -3.120$ **p = .004**
Fixation rate	$\chi^2(2) = 5.471$ $p = .065$	$Z = -2.932$ **p = .009**	$Z = -.453$ $p = .651$	$Z = -1.821$ $p = .138$
Fixation duration	$\chi^2(2) = 5.473$ $p = .064$	$Z = -2.829$ **p = .015**	$Z = -1.428$ $p = .306$	$Z = -1.034$ $p = .306$
Saccade rate	$\chi^2(2) = 0.412$ $p = .814$	$Z = -.795$ $p = 1.000$	$Z = -.795$ $p = 1.000$	$Z = -.350$ $p = 1.000$
Saccade duration	$\chi^2(2) = 0.059$ $p = .971$	$Z = -.419$ $p = 1.000$	$Z = -.641$ $p = 1.000$	$Z = -.436$ $p = 1.000$
Heart rate	$F(1.820, 70.980) = 0.127$ $p = .863$	$t(39) = 0.065$ $p = 1.000$	$t(39) = 0.511$ $p = 1.000$	$t(39) = 0.377$ $p = 1.000$
RMSSD	$\chi^2(2) = 8.629$ **p = .013**	$Z = -1.587$ $p = .113$	$Z = -1.949$ $p = .102$	$Z = -2.342$ **p = .047**
pNN50	$\chi^2(2) = 1.143$ $p = .565$	$Z = -0.793$ $p = .614$	$Z = -1.351$ $p = .531$	$Z = -1.021$ $p = .614$

Table 5: Descriptive statistics for all eye and cardiovascular metrics under the color temperature manipulation. For each metric, the table reports Mdn [IQR] and M (SD) for cool (−100%), standard, and warm (+100%) color temperature conditions.

	Low		Standard		High	
Metric	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**
Pupil diameter	-.50 [.61]	-.49 (.45)	-.12 [.53]	-.11 (.30)	.00 [.38]	-.01 (.31)
Blink rate (blinks/min)	-3.27 [15.75]	-6.70 (21.32)	-4.21 [11.72]	-7.86 (13.34)	-8.85 [11.58]	-11.11 (13.85)
Blink duration	-.0338 [.05]	-.034 (.061)	-.0015 [.07]	-.002 (.071)	-.0011 [.06]	-.001 (.075)
Fixation rate	5.22 [24.62]	8.82 (21.46)	-.38 [25.72]	-3.44 (18.21)	.82 [27.64]	-1.57 (24.59)
Fixation duration	.02 [.09]	.012 (.068)	.04 [.09]	.051 (.065)	.01 [.11]	.037 (.092)
Saccade rate	7.26 [34.57]	9.20 (22.44)	5.08 [19.71]	5.99 (20.12)	10.14 [25.43]	7.77 (23.02)
Saccade duration	-.005 [.016]	-.005 (.013)	-.003 [.015]	-.005 (.012)	-.003 [.010]	-.004 (.010)
Heart rate	2.12 [5.12]	2.43 (3.76)	2.40 [4.63]	2.43 (3.41)	2.89 [4.21]	2.18 (3.76)
RMSSD	-.22 [11.57]	-2.38 (34.85)	-1.64 [11.72]	7.66 (66.91)	-1.69 [10.78]	-6.67 (38.61)
pNN50	0.00 [9.75]	.458 (8.64)	0.00 [8.65]	.707 (12.29)	0.00 [5.50]	-.736 (8.42)

C Appendix C - Peripheral Occlusion results

Table 6: Peripheral occlusion manipulation: omnibus tests and Holm–Bonferroni-corrected pairwise comparisons for all eye and cardiovascular metrics across low (0% occlusion), standard (37.5% occlusion), and high (75% occlusion) conditions.

Metric	Omnibus test	Low–Standard	Standard–High	Low–High
Pupil diameter	$\chi^2(2) = 26.667$ **p < .001**	$Z = -3.610$ **p < .001**	$Z = -2.828$ **p = .005**	$Z = -3.754$ **p < .001**
Blink rate	$F(2, 78) = 3.289$ **p = .042**	$t(39) = -2.204$ **p = .016**	$t(39) = -0.581$ $p = .566$	$t(39) = -2.443$ **p = .021**
Blink duration	$\chi^2(2) = 2.483$ $p = .289$	$Z = -1.546$ $p = .366$	$Z = -1.039$ $p = .530$	$Z = -1.114$ $p = .530$
Fixation rate	$\chi^2(2) = 0.467$ $p = .792$	$Z = -0.854$ $p = 1.000$	$Z = -0.216$ $p = 1.000$	$Z = -0.771$ $p = 1.000$
Fixation duration	$\chi^2(2) = 0.800$ $p = .670$	$Z = -0.381$ $p = .742$	$Z = -1.162$ $p = .735$	$Z = -0.895$ $p = .742$
Saccade rate	$\chi^2(2) = 5.000$ $p = .082$	$Z = -1.820$ $p = .207$	$Z = -0.319$ $p = .750$	$Z = -1.800$ $p = .207$
Saccade duration	$\chi^2(2) = 1.067$ $p = .587$	$Z = -0.134$ $p = .894$	$Z = -0.936$ $p = .349$	$Z = -0.195$ $p = .845$
Heart rate	$F(1.820, 70.980) = 0.127$ $p = .863$	$t(39) = -1.415$ $p = .498$	$t(39) = -0.024$ $p = .981$	$t(39) = -1.091$ $p = .564$
RMSSD	$\chi^2(2) = 1.947$ $p = .378$	$Z = -0.471$ $p = 1.000$	$Z = -0.109$ $p = 1.000$	$Z = -0.848$ $p = 1.000$
pNN50	$\chi^2(2) = 2.309$ $p = .315$	$Z = -0.433$ $p = 1.000$	$Z = -0.616$ $p = 1.000$	$Z = -0.771$ $p = 1.000$

Table 7: Descriptive statistics for all eye and cardiovascular metrics under the peripheral occlusion manipulation. For each metric, the table reports Mdn [IQR] and M (SD) for low (0% occlusion), standard (37.5% occlusion), and high (75% occlusion) conditions.

	Low		Standard		High	
Metric	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**
Pupil diameter	-0.236 [0.502]	-0.41 (0.78)	-0.041 [0.556]	-0.20 (0.57)	0.204 [0.538]	0.04 (0.55)
Blink rate (blinks/min)	-7.91 [16.61]	-11.11 (12.01)	-4.99 [9.22]	-7.89 (12.91)	-4.40 [21.38]	-6.71 (14.82)
Blink duration	0.0173 [0.0647]	0.017 (0.088)	0.0234 [0.0488]	0.031 (0.056)	0.0111 [0.0413]	0.031 (0.117)
Fixation rate	-2.78 [35.47]	-13.91 (36.97)	-4.08 [22.59]	-9.89 (31.77)	-4.15 [29.29]	-3.42 (48.77)
Fixation duration	0.0389 [0.0894]	0.061 (0.103)	0.0453 [0.1170]	0.043 (0.079)	0.0430 [0.1353]	0.028 (0.112)
Saccade rate	0.11 [30.39]	-3.82 (27.40)	5.65 [31.40]	2.54 (19.55)	4.53 [32.70]	7.96 (31.21)
Saccade duration	-0.008 [0.014]	-0.007 (0.010)	-0.005 [0.011]	-0.006 (0.010)	-0.008 [0.014]	-0.007 (0.010)
Heart rate	1.57 [5.44]	1.14 (3.93)	1.34 [4.85]	1.78 (4.12)	1.31 [4.30]	1.79 (3.72)
RMSSD	-2.81 [11.35]	-2.78 (18.69)	-1.17 [10.31]	-4.20 (15.64)	-2.24 [12.72]	-3.49 (17.43)
pNN50	0.00 [8.33]	-1.01 (7.77)	0.00 [4.31]	-1.32 (8.74)	0.00 [4.78]	-1.76 (9.83)

D Appendix D - Visual Suppression results

Table 8: Visual suppression manipulation: omnibus tests and Holm–Bonferroni-corrected pairwise comparisons for all eye and cardiovascular metrics across slow (3 blinks/min), standard (18 blinks/min), and fast (30 blinks/min) simulated blink patterns.

Metric	Omnibus test	Low–Standard	Standard–High	Low–High
Pupil diameter	$F(1.981, 77.259) = 0.496$ $p = .609$	$t(39) = -0.889$ $p = 1.000$	$t(39) = 0.840$ $p = 1.000$	$t(39) = -0.111$ $p = 1.000$
Blink rate	$F(1.668, 65.052) = 3.51$ **p = .032**	$t(39) = -0.713$ $p = .481$	$t(39) = -2.251$ **p = .048**	$t(39) = -2.071$ $p = .093$
Blink duration	$\chi^2(2) = 1.167$ $p = .558$	$Z = -0.204$ $p = 1.000$	$Z = -0.848$ $p = 1.000$	$Z = -0.361$ $p = 1.000$
Fixation rate	$F(1.715, 66.885) = 0.987$ $p = .368$	$t(39) = -1.082$ $p = .798$	$t(39) = -0.213$ $p = .833$	$t(39) = -1.131$ $p = .798$
Fixation duration	$\chi^2(2) = 8.167$ **p = .017**	$Z = -0.896$ $p = .542$	$Z = -1.100$ $p = .542$	$Z = -1.885$ $p = .177$
Saccade rate	$F(1.924, 75.036) = 0.204$ $p = .807$	$t(39) = -0.588$ $p = 1.000$	$t(39) = 0.395$ $p = 1.000$	$t(39) = -0.279$ $p = 1.000$
Saccade duration	$\chi^2(2) = 1.167$ $p = .558$	$Z = -0.566$ $p = .810$	$Z = -0.833$ $p = .810$	$Z = -1.367$ $p = .516$
Heart rate	$\chi^2(2) = 4.054$ $p = .132$	$Z = -1.833$ $p = .201$	$Z = -0.173$ $p = .862$	$Z = -0.988$ $p = .646$
RMSSD	$\chi^2(2) = 3.622$ $p = .164$	$Z = -1.184$ $p = .472$	$Z = -0.973$ $p = .472$	$Z = -2.029$ **p = .042**
pNN50	$\chi^2(2) = 3.323$ $p = .190$	$Z = -0.670$ $p = 1.000$	$Z = -0.895$ $p = 1.000$	$Z = -0.774$ $p = 1.000$

Table 9: Descriptive statistics for all eye and cardiovascular metrics under the visual suppression manipulation. For each metric, the table reports Mdn [IQR] and M (SD) for slow (3 blinks/min), standard (18 blinks/min), and fast (30 blinks/min) simulated blink patterns.

	Low		Standard		High	
Metric	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**	**Mdn [IQR]**	**M (SD)**
Pupil diameter	-0.0691 [0.220]	-0.056 (0.188)	-0.0280 [0.286]	-0.032 (0.196)	-0.0372 [0.335]	-0.053 (0.209)
Blink rate (blinks/min)	-7.09 [12.82]	-8.14 (9.57)	-7.66 [9.04]	-7.11 (7.50)	-5.71 [10.56]	-5.15 (7.88)
Blink duration	0.0043 [0.052]	0.016 (0.066)	0.0111 [0.056]	0.016 (0.051)	0.0005 [0.050]	0.010 (0.063)
Fixation rate	1.13 [20.38]	1.67 (15.58)	1.59 [19.27]	3.76 (13.06)	6.02 [20.71]	4.07 (17.73)
Fixation duration	0.0320 [0.103]	0.031 (0.074)	0.0102 [0.056]	0.021 (0.065)	0.0044 [0.091]	0.017 (0.083)
Saccade rate	5.82 [17.99]	8.48 (16.81)	7.49 [24.59]	9.74 (15.80)	7.52 [25.07]	9.03 (15.39)
Saccade duration	-0.0049 [0.012]	-0.0046 (0.009)	-0.0047 [0.009]	-0.0049 (0.008)	-0.0042 [0.012]	-0.0033 (0.008)
Heart rate	1.74 [3.97]	1.33 (2.60)	2.22 [3.34]	1.99 (2.21)	2.19 [3.60]	1.90 (2.54)
RMSSD	-1.53 [8.60]	-1.96 (8.25)	-2.80 [0.92]	-2.69 (7.26)	-2.67 [8.48]	-3.25 (7.88)
pNN50	-1.71 [5.38]	-1.25 (6.51)	-0.81 [4.01]	-1.16 (5.81)	-0.20 [5.91]	-1.71 (5.20)

E Appendix E - Virtual Reality Symptom Questionnaire Results

Table 10: VRSQ non-ocular outcomes. Omnibus Friedman tests and Holm adjusted Wilcoxon signed rank pairwise comparisons across luminance (L) color temperature (T) peripheral occlusion (PO) and visual suppression (VS).

Metric	Omnibus test	L–T	L–PO	L–VS	T–PO	T–VS	PO–VS
Non ocular symptoms	$\chi^2(3) = 19.914$ **p < .001**	$Z = 3.337$ **p = .006**	$Z = -3.299$ **p = .006**	$Z = -2.125$ $p = .136$	$Z = -0.556$ $p = .578$	$Z = -1.989$ $p = .141$	$Z = -1.757$ $p = .158$
General discomfort	$\chi^2(3) = 19.684$ **p < .001**	$Z = 0.655$ $p = .536$	$Z = -2.516$ **p = .036**	$Z = -1.107$ $p = .536$	$Z = -2.828$ **p = .020**	$Z = -2.887$ **p = .020**	$Z = -3.900$ **p < .001**
Fatigue	$\chi^2(3) = 68.253$ **p < .001**	$Z = 3.400$ **p = .003**	$Z = -3.000$ **p = .006**	$Z = -3.601$ **p < .001**	$Z = -0.554$ $p = .579$	$Z = -5.548$ **p < .001**	$Z = -5.460$ **p < .001**
Boredom	$\chi^2(3) = 69.059$ **p < .001**	$Z = 1.831$ $p = .201$	$Z = -4.845$ **p < .001**	$Z = -3.266$ **p = .003**	$Z = -5.160$ **p < .001**	$Z = 1.291$ $p = .197$	$Z = -5.547$ **p < .001**
Drowsiness	$\chi^2(3) = 12.145$ **p = .007**	$Z = 0.171$ $p = 1.000$	$Z = -0.430$ $p = 1.000$	$Z = -0.843$ $p = 1.000$	$Z = -0.317$ $p = 1.000$	$Z = 0.682$ $p = 1.000$	$Z = -2.625$ **p = .036**
Headache	$\chi^2(3) = 77.754$ **p < .001**	$Z = 5.031$ **p < .001**	$Z = -5.029$ **p < .001**	$Z = -4.257$ **p < .001**	$Z = -0.250$ $p = 1.000$	$Z = 0.369$ $p = 1.000$	$Z = -2.530$ **p = .033**
Dizziness	$\chi^2(3) = 21.241$ **p < .001**	$Z = 1.163$ $p = .490$	$Z = -2.780$ **p = .027**	$Z = -1.791$ $p = .219$	$Z = -1.791$ $p = .219$	$Z = 0.504$ $p = 1.000$	$Z = -1.400$ $p = .486$
Difficulty concentrating	$\chi^2(3) = 10.960$ **p = .012**	$Z = 2.411$ $p = .064$	$Z = -0.679$ $p = 1.000$	$Z = -1.142$ $p = .507$	$Z = -1.731$ $p = .168$	$Z = -2.450$ $p = .056$	$Z = -1.273$ $p = .406$
Nausea	$\chi^2(3) = 85.241$ **p < .001**	$Z = 5.126$ **p < .001**	$Z = 0.000$ $p = 1.000$	$Z = 0.000$ $p = 1.000$	$Z = 5.126$ **p < .001**	$Z = 4.807$ **p < .001**	$Z = 0.000$ $p = 1.000$

Table 11: VRSQ non-ocular outcomes. Descriptive statistics Mean (Standard Deviation) for luminance (L) color temperature (T) peripheral occlusion (PO) and visual suppression (VS).

Metric	L	T	PO	VS
Non-ocular symptoms	1.77 (0.66)	1.59 (0.59)	1.60 (0.63)	1.70 (0.79)
General discomfort	1.65 (0.83)	1.55 (0.75)	1.35 (0.48)	1.80 (0.91)
Fatigue	1.93 (0.94)	1.50 (0.75)	1.55 (0.81)	2.42 (0.98)
Boredom	1.83 (0.93)	1.55 (0.55)	2.60 (0.74)	1.45 (0.82)
Drowsiness	1.58 (0.78)	1.53 (0.64)	1.75 (1.01)	1.43 (0.75)
Headache	2.55 (1.11)	1.37 (0.49)	1.35 (0.48)	1.58 (0.93)
Dizziness	1.40 (0.59)	1.37 (0.49)	1.35 (0.48)	1.47 (0.82)
Difficulty concentrating	1.87 (0.88)	1.52 (0.78)	1.53 (0.78)	2.03 (0.89)
Nausea	1.35 (0.48)	2.33 (0.97)	1.35 (0.48)	1.45 (0.75)

Table 12: VRSQ ocular outcomes. Omnibus Friedman tests and Holm adjusted Wilcoxon signed rank pairwise comparisons across luminance (L) color temperature (T) peripheral occlusion (PO) and visual suppression (VS).

Metric	Omnibus test	L–T	L–PO	L–VS	T–PO	T–VS	PO–VS
Ocular symptoms	$\chi^2(3) = 30.195$ **p < .001**	$Z = 1.346$ $p = .356$	$Z = -3.844$ **p < .001**	$Z = -0.230$ $p = .818$	$Z = -3.469$ **p = .004**	$Z = -2.115$ $p = .102$	$Z = -5.039$ **p < .001**
Tired eyes	$\chi^2(3) = 44.016$ **p < .001**	$Z = 2.639$ **p = .024**	$Z = -3.455$ **p = .004**	$Z = -0.910$ $p = .488$	$Z = -1.165$ $p = .488$	$Z = -4.294$ **p < .001**	$Z = -5.058$ **p < .001**
Sore/aching eyes	$\chi^2(3) = 31.881$ **p < .001**	$Z = 0.756$ $p = .900$	$Z = -3.195$ **p = .006**	$Z = -0.240$ $p = 1.000$	$Z = -3.679$ **p = .002**	$Z = -1.529$ $p = .252$	$Z = -4.360$ **p < .001**
Eyestrain	$\chi^2(3) = 56.991$ **p < .001**	$Z = 2.190$ **p = .029**	$Z = -3.925$ **p < .001**	$Z = -4.033$ **p < .001**	$Z = -2.601$ **p = .018**	$Z = -4.920$ **p < .001**	$Z = -5.679$ **p < .001**
Blurred vision	$\chi^2(3) = 12.319$ **p = .006**	$Z = -0.177$ $p = 1.000$	$Z = -0.032$ $p = 1.000$	$Z = -2.615$ **p = .036**	$Z = -0.189$ $p = 1.000$	$Z = -3.358$ **p = .006**	$Z = -3.419$ **p = .006**
Difficulty focusing	$\chi^2(3) = 28.885$ **p < .001**	$Z = -1.824$ $p = .136$	$Z = -2.746$ **p = .018**	$Z = -2.875$ **p = .016**	$Z = -3.963$ **p < .001**	$Z = -3.675$ **p < .001**	$Z = -0.190$ $p = .850$

Table 13: VRSQ ocular outcomes. Descriptive statistics Mean (Standard Deviation) for luminance (L) color temperature (T) peripheral occlusion (PO) and visual suppression (VS).

Metric	L	T	PO	VS
Ocular symptoms	2.12 (0.82)	1.91 (0.73)	1.55 (0.50)	2.11 (0.77)
Tired eyes	2.25 (1.15)	1.65 (0.89)	1.48 (0.60)	2.45 (0.93)
Sore/aching eyes	2.22 (0.97)	2.03 (1.12)	1.53 (0.51)	1.73 (0.82)
Eyestrain	2.48 (1.20)	1.95 (1.01)	1.48 (0.55)	3.48 (0.91)
Blurred vision	1.73 (0.82)	1.75 (0.81)	1.72 (0.78)	1.35 (0.48)
Difficulty focusing	2.02 (1.02)	2.45 (1.30)	1.53 (0.64)	1.55 (0.81)