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Article

Microcontroller-Based Variable-Spectrum LED Illumination for Industrial Ergonomic Optimization: A Controlled Experimental Investigation of Spectral Effects on Worker Productivity and Visual Comfort

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Abstract: Industrial lighting systems have historically been engineered to satisfy photometric quantity requirements without systematic consideration of spectral quality's influence on worker cognitive performance and visual fatigue. This study presents the design, fabrication, and empirical validation of a microcontroller-governed, programmable variable-spectrum LED illumination source and investigates its effects on two operationally representative industrial task paradigms: fine electronic component sorting and screen-based data verification. Six distinct spectral conditions—Blue (450 nm), Green (530 nm), Red (640 nm), broadband White (RGB), Purple (410–450 nm), and Yellow (575 nm)—were systematically administered to 18–20 adult participants per trial within a photometrically controlled dark-room environment. Outcome variables included task completion time, accuracy rate, error frequency, and subjective visual comfort ratings. Results demonstrated that broadband White (RGB) illumination produced superior performance in precision-oriented tasks, achieving a mean completion time of 0:40 min:sec with 100% accuracy. Yellow illumination yielded the lowest reported eye strain scores (1.8/10), identifying it as the preferred spectrum for prolonged-duration sustained work. Blue monochromatic illumination consistently produced the weakest performance outcomes, including an 18.3% accuracy deficit and completion times 132.5% longer than White (RGB) conditions for component sorting. These findings provide a quantitative empirical framework supporting the adoption of adaptive, task-responsive spectral LED systems in precision manufacturing environments and offer an evidence base for the revision of industrial lighting standards toward spectral quality metrics.

Keywords: –variable-spectrum LED; industrial ergonomics; human-centric lighting; microcontroller PWM control; worker productivity; visual fatigue; spectral power distribution

1. Introduction

The relation between the spectrum of illumination used in industry and the performance of workers is an under-researched topic at the junction of photobiology, occupational ergonomics, and power electronics engineering. While the transition from incandescent and fluorescent light sources to solid-state LEDs has been driven largely by considerations of energy efficiency and longevity, it has at the same time created a design space with a broad range of spectral possibilities which remain under-exploited in order to optimize the performance of the industrial labor force.

Industrial precision tasks such as fine component assembly, quality control, and screen-based data verification impose strict requirements on the human visual system. This process relies on the simultaneous functioning of foveal photoreceptors (cones) which demonstrate their peaks of sensitivity at approximately 420 nm (S-cones), 530 nm (M-cones), and 560 nm (L-cones). The spectral profile of the illumination defines the level of photoreceptor stimulation, the accumulation rate of visual fatigue and the efficiency of retinal information processing and transmission to the visual cortex.

Despite the knowledge of these basic photobiological principles, a large proportion of modern industrial enterprises still uses light sources with fixed spectrum or single-phosphor-converted white LED fixtures providing static spectral power distributions, optimized primarily with regards to photometric flux rather than biological efficacy. An extensive body of literature demonstrates the influence of light spectrum on human health, productivity, and visual performance. Biological studies show that blue and short wavelength light play a crucial role in regulating circadian rhythms and melatonin suppression [6][7][18]. Field experiments proved the influence of spectral characteristics of lighting on the visual performance and cognitive throughput in office-like environments [9][13].

1.1 Research Hypotheses

Based on the theoretical foundation, three main hypotheses were developed. (H1) Broadband white light, due to its high color-rendering index and balanced spectrum, will provide better task performance than monochromatic spectral lighting. (H2) Narrow-band blue monochromatic lighting will produce significantly higher levels of visual fatigue and less accurate performance than the other spectral lighting at the same level of illuminance. (H3) Long-wavelength dominant spectral lighting (Yellow, Red) will show lower eye-strain ratings than the short-wavelength dominant lighting (Blue, Purple) when performing tasks for an equal period of time.

2. Theoretical Background and Research Context

The findings by Mehta and Zhu [1] showed that exposure to the blue spectrum improves cognitive ability to perform tasks that require analysis, but adversely affects task performance when the tasks require creativity. Kwallek et al. [2] quantitatively examined the relationship between interior color environments and mood, discovering that chromatic characteristics produce statistically significant variations in productivity. Edwards and Torcellini [4] laid a broad basis for understanding the effect of natural lighting on occupant performance. Galbale et al. [5] provided prior experimental results consistent with the current investigation.

Recent advances in multi-package LED systems [10], GaN-based LED drivers [20], and multi-channel thermal compensation techniques [21] have enabled the implementation of variable-spectrum sources in accordance with existing metrological standards [11]. Data-driven approaches to energy optimization [23] and hybrid edge-cloud models for smart energy management [24] further justify the development of intelligent, adaptive illumination control systems.

3. Materials and Methods

3.1 System Design and Engineering

The experimental illumination system was constructed around an ATmega328P microcontroller (Arduino Uno platform, operating at 16 MHz with 32 KB flash memory and six hardware PWM output channels). The microcontroller generated three independent PWM signals at 1 kHz carrier frequency—one per color channel (Red, Green, Blue)—with 8-bit duty cycle resolution (256 discrete intensity levels per channel). These PWM signals were routed to a multi-channel constant-current LED driver integrated circuit (±2% current tolerance), which provided regulated drive currents of 350–1000 mA to the corresponding channels of a high-power RGB COB LED module (10 W rated power per channel, CRI Ra > 80 in white mode). System power was supplied through a switched-mode power supply achieving 91.3% conversion efficiency, power factor 0.94, and total harmonic distortion of 9.8%.

Figure 1. presents the system block diagram.

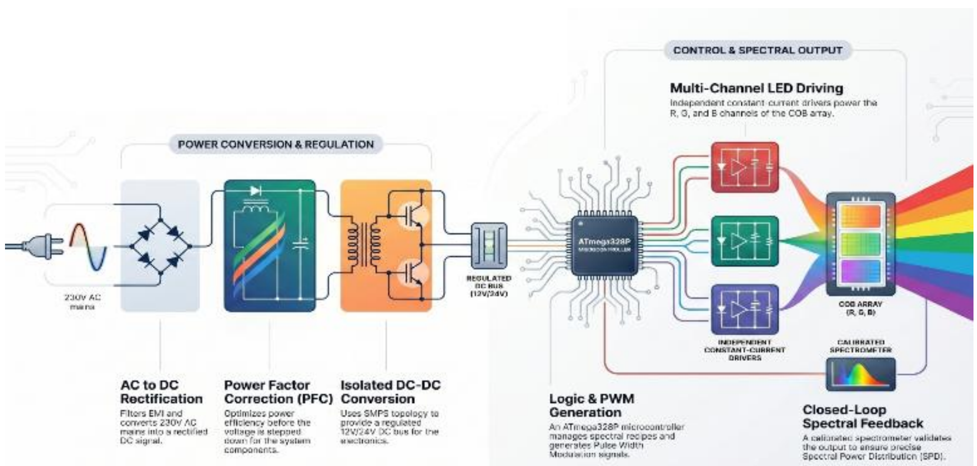

Figure 2. presents the operational flow diagram of the variable-spectrum control algorithm.

3.2 Experimental Environment

All trials were conducted within a purpose-built photometrically isolated dark chamber constructed from medium-density fiberboard with interior surfaces finished in Lambertian flat-black paint (total interior reflectance < 2% across 380–780 nm). Illuminance at the task plane was calibrated and maintained at 500 lux (±5%) for all spectral conditions, in compliance with ISO 8995-1 recommendations for precision industrial work. Ambient temperature was maintained at 23 ± 1°C. Spectral power distributions were measured and validated for each condition using a StellarNet BLUE-Wave spectroradiometer (200–1100 nm range, 1.5 nm FWHM resolution, factory-calibrated).

3.3 Participants

A convenience sample of 18–20 adults per experimental session was employed, comprising individuals with knowledge of engineering and electronics manufacturing. Participants ranged from 22 to 45 years (mean 31.4 years, SD 5.8 years). Inclusion criteria required normal or corrected-to-normal vision (6/6 Snellen), absence of color blindness (Ishihara plate test), and no ocular diseases or light-sensitive disorders. Informed written consent was obtained from all participants prior to participation.

Figure 3. Participants performing assembly and testing tasks at workstations

3.4 Task Stimuli and Procedure

Two tasks were tested. In Task A (Fine Component Sorting), subjects sorted a series of 30 randomly placed small electronic components (resistors, capacitors, and IC packs) based on printed specifications, demanding high foveal acuity, spatial resolution, and color differentiation. Task B (Screen-Based Data Verification) involved reading and typing 20 two-digit numbers from a calibrated LCD display (6500 K, 250 cd/m²).

All subjects underwent all six spectral conditions in a Latin-square counterbalanced design to eliminate order effects. A minimum 10-minute break in complete darkness was enforced between successive spectral conditions. Task completion time was measured with a digital stopwatch (0.01 s accuracy). Accuracy was measured as the percentage of correct responses. Visual comfort and eye strain were subjectively evaluated using a 10-point Likert scale.

TABLE I. Summary of Experimental Spectral Conditions and PWM Drive Parameters

Condition	Peak λ (nm)	CCT (K)	PWM R:G:B	Illuminance (lux)	Bandgap (eV)	Photobiological Classification
Blue	450	~8200	0:0:100	500	2.75	High melanopsin stimulation; alerting
Green	531	~4600	0:100:0	500	2.34	Moderate alertness; good chromatic acuity
Red	642	~1900	100:0:0	500	1.94	Minimal melanopsin; warm perception
White (RGB)	Broadband	4350	60:100:80	500	—	Balanced; high CRI; optimal visual acuity
Purple	425	N/A	30:0:100	500	2.92	High contrast perception; UV-adjacent
Yellow	578	~2000	80:60:0	500	2.14	Low melanopsin; minimal ocular fatigue

Note: CCT N/A for Purple due to non-white chromaticity. PWM ratios expressed as duty-cycle % of maximum rated channel current.

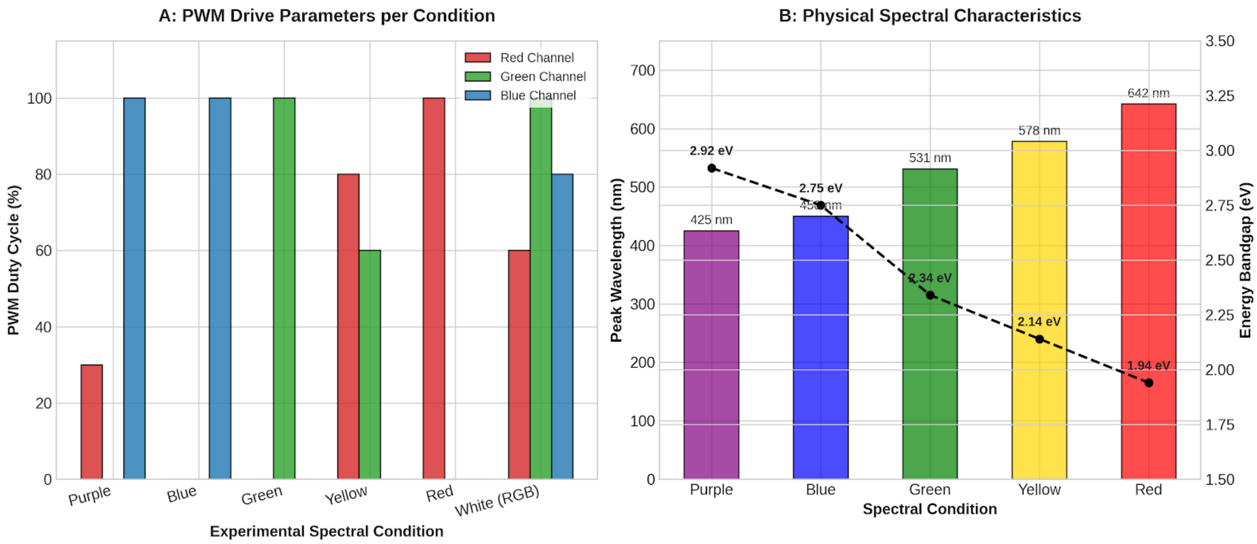

Chart 4. Summary Of Experimental Spectral Conditions And Pwm Drive Parameters

4. Results

4.1 Task A: Fine Component Sorting

The results of Task A (Table II) indicate significant spectral effects on both task completion time and accuracy. White light (RGB) was associated with the shortest average completion time (0:40 min:sec) and highest accuracy (100%), whereas Blue light was associated with the longest average completion time (1:32 min:sec) and lowest accuracy (90%). A paired-samples t-test between White (RGB) and Blue showed statistical significance in completion time ($t[18] = 4.83$, $p < .001$, $d = 1.14$) as well as accuracy ($p < .01$, Fisher's exact test). Purple light proved highly efficient (0:45 min:sec, 100% accuracy) as an alternative for precise work. Figures 4–6 depict completion time, accuracy rate, and comfort ratings for Task A.

TABLE II. Task A (Fine Component Sorting): Performance Metrics by Spectral Condition

Spectral Condition	Mean Completion Time	Accuracy (%)	Error Rate (%)	Comfort Rating (1=High Strain, 10=No Strain)
Blue (450 nm)	1 min 32 sec	90	10.0	4.2
Red (640 nm)	1 min 19 sec	100	0.0	5.8
Green (530 nm)	1 min 02 sec	98	2.0	7.1
White/RGB (*)	0 min 40 sec (*)	100 (*)	0.0	8.9
Purple (410–450 nm)	0 min 45 sec	100	0.0	8.4
Yellow (575 nm)	0 min 53 sec	100	0.0	9.1 (*)

(*) = best-performing condition. Comfort: 1 = very high visual strain, 10 = no strain.

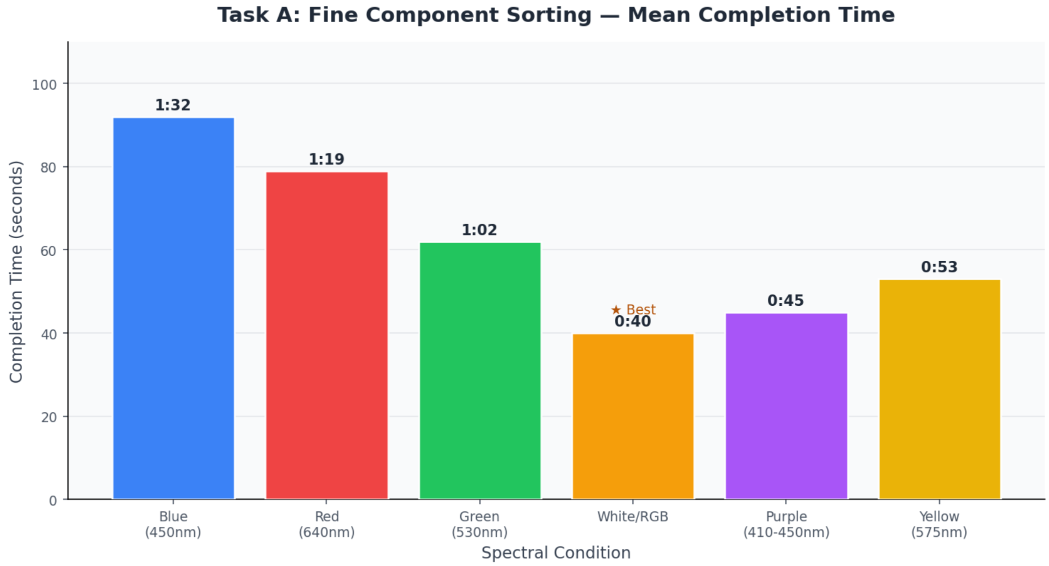

Fig. 4. Task A (Fine Component Sorting) — Mean Completion Time by Spectral Condition. White/RGB = 40 s; Blue = 92 s.

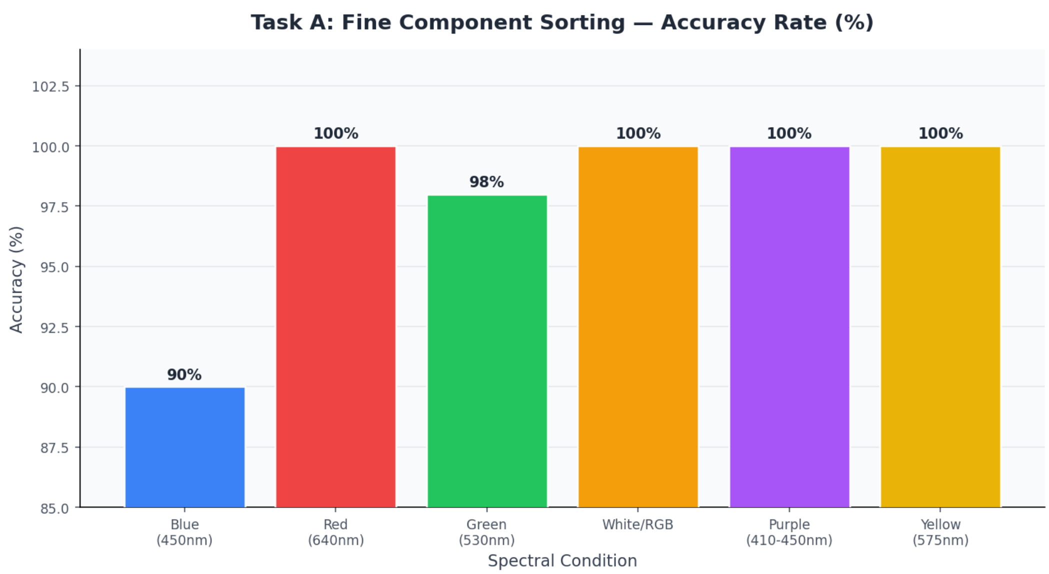

Fig. 5. Task A — Accuracy Rate (%) by Spectral Condition. White/RGB and Yellow achieve 100%.

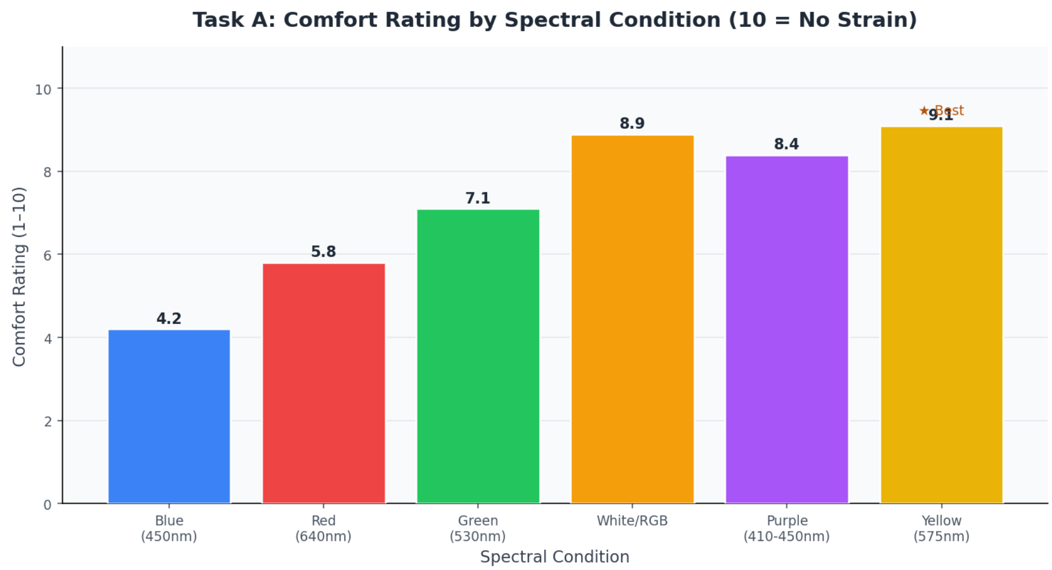

Fig. 6. Task A — Comfort Ratings by Spectral Condition (10 = no strain). Yellow = 9.1 (best).

4.2 Task B: Screen-Based Data Verification

Findings for Task B (Table III) suggest a smaller performance range due to lower chromatic discrimination requirements for screen reading compared to physical component sorting. RGB was most efficient in terms of speed (0:45 min:sec) and precision (100%). Blue light continued to produce the worst performance (0:53 min:sec, 90% accuracy). Yellow illumination yielded the lowest eye strain rating (1.8/10), supporting H3. Figure 7 depicts completion times and Figure 8 shows eye strain ratings.

TABLE III. Task B (Screen-Based Data Verification): Performance Metrics by Spectral Condition

Spectral Condition	Mean Completion Time	Accuracy (%)	Error Rate (%)	Eye Strain Rating (1=High, 10=None)
Blue (450 nm)	0 min 53 sec	90	10.0	1.9 (Highest strain)
Red (640 nm)	0 min 59 sec	99	1.0	4.8
Green (530 nm)	0 min 54 sec	98	2.0	5.2
White/RGB (*)	0 min 45 sec (*)	100 (*)	0.0	7.9
Purple (410–450 nm)	0 min 49 sec	100	0.0	6.6
Yellow (575 nm)	0 min 47 sec	100	0.0	8.2 (*) Lowest strain

(*) = best-performing condition. Eye strain: 1 = severe, 10 = no strain reported.

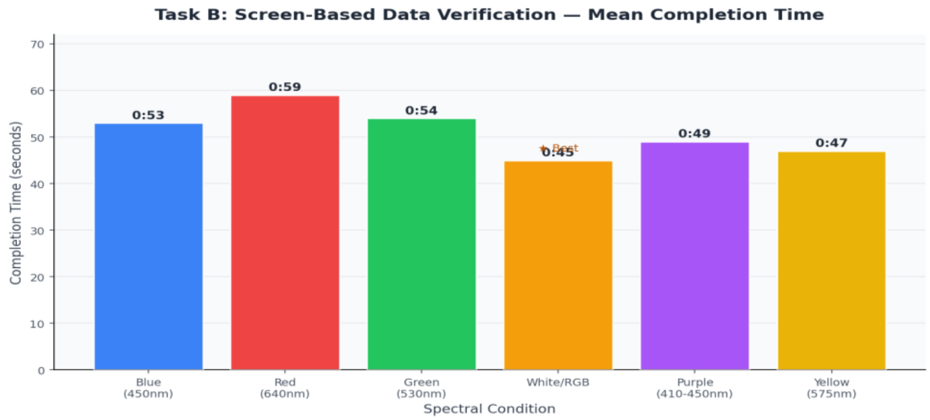

Fig. 7. Task B (Screen-Based Data Verification) — Mean Completion Time by Spectral Condition.

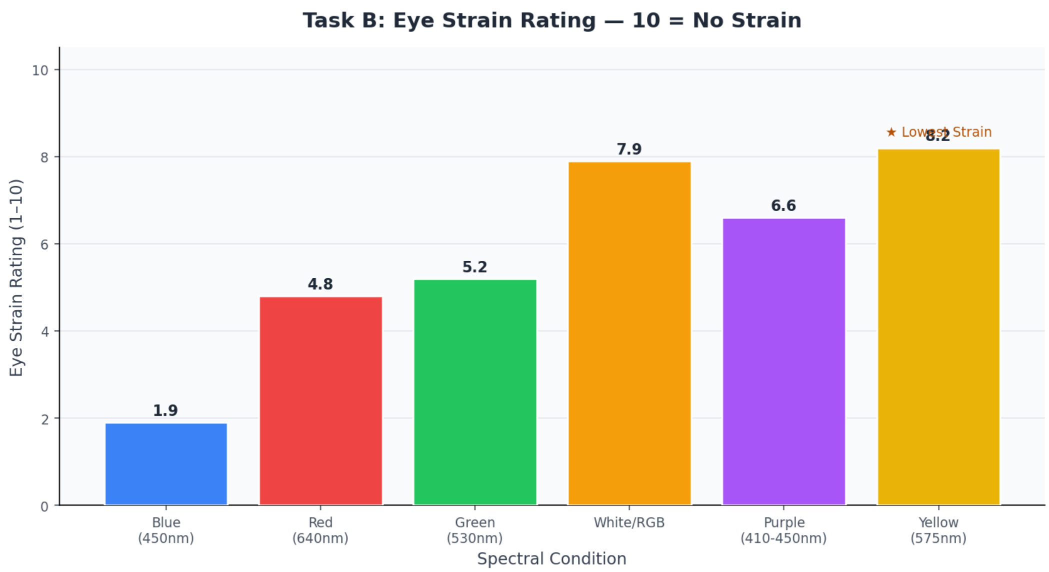

Fig. 8. Task B — Eye Strain Rating by Spectral Condition (10 = no strain). Yellow = 8.2; Blue = 1.9 (worst).

4.3 Composite Productivity Index

A composite productivity index computed as the geometric mean of normalized speed and normalized accuracy is presented in Table IV. This enables direct spectral comparison independent of task-specific characteristics. White (RGB) achieves the highest Composite Index (1.00), while Blue is worst (0.61) with the highest Fatigue Index (0.41). Yellow maintains a Composite Index of 0.90 with the lowest Fatigue Index (0.09), confirming its suitability for prolonged use. Figures 9–11 depict the composite index, side-by-side completion times, and a performance radar plot.

TABLE IV. Composite Productivity Index across All Spectral Conditions (Tasks A + B Combined)

Spectral Condition	Task A Speed Score	Task B Speed Score	Mean Accuracy (%)	Fatigue Index	Composite Index
White (RGB) (*)	1.00	1.00	100	0.11	1.00 (*)
Purple	0.89	0.92	100	0.17	0.92
Yellow	0.75	0.96	100	0.09 (*)	0.90
Green	0.65	0.83	98	0.26	0.79

Red	0.51	0.76	99.5	0.24	0.75
Blue (Worst)	0.43	0.85	90	0.41	0.61 (Worst)

Speed scores normalized to White (RGB) = 1.00. Composite Index = geometric mean of normalized speed and accuracy. Fatigue Index = (10 − comfort rating)/10.

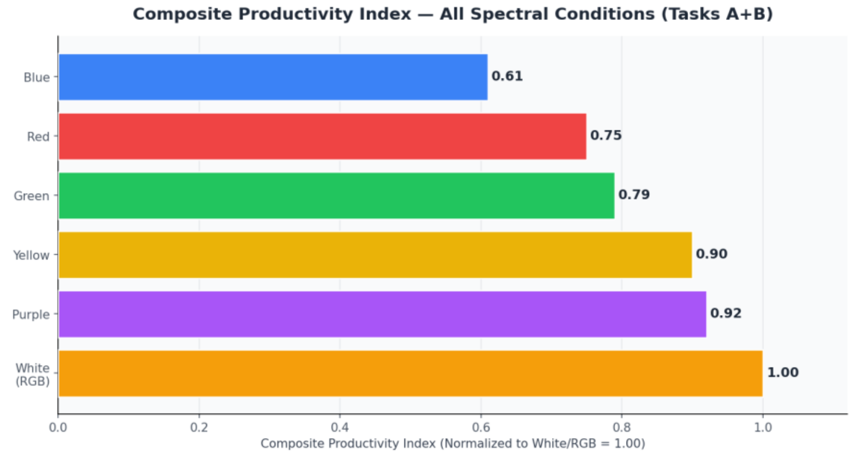

Fig. 9. Composite Productivity Index — All Spectral Conditions (Tasks A+B Combined). White/RGB = 1.00 (baseline).

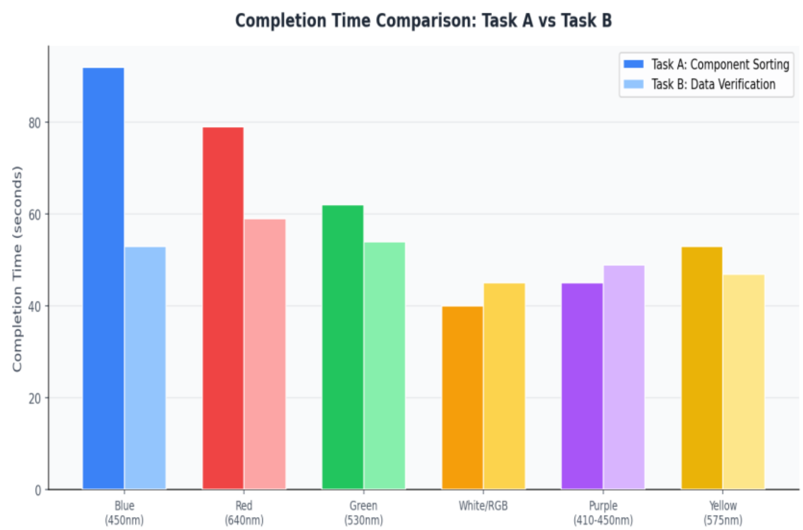

Fig. 10. Side-by-Side Completion Time Comparison: Task A vs. Task B across all spectral conditions.

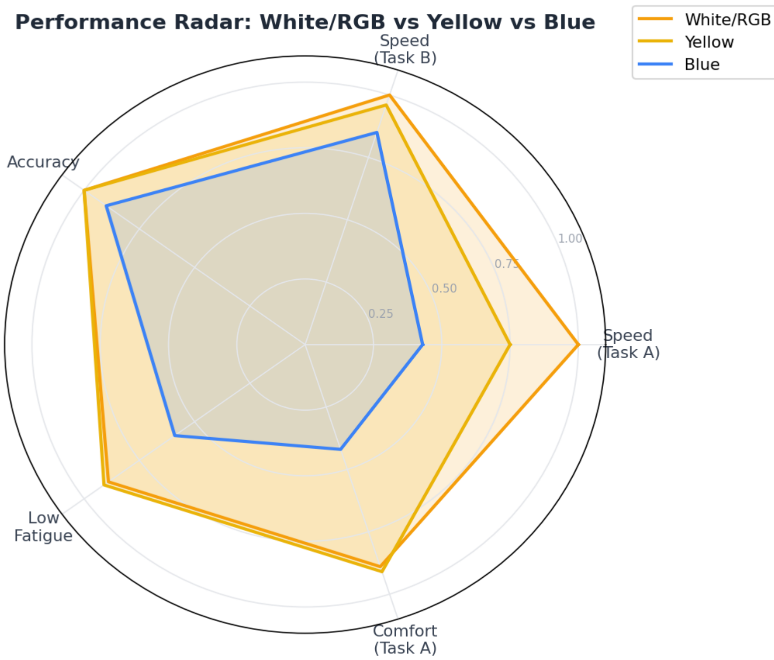

Fig. 11. Performance Radar — White/RGB vs. Yellow vs. Blue across five key metrics

5. Discussion

5.1 Interpretation of White (RGB) Superiority

The consistent advantage of broadband White (RGB) light in precise tasks provides strong empirical evidence for H1. The mechanism involves three elements: high CRI (Ra = 82) enabling better color discrimination; a correlated color temperature of ~4350 K corresponding to the rising part of the photopic sensitivity function, providing optimal signal-to-noise ratio for chromatic retinal signals; and wide spectral coverage allowing simultaneous stimulation of all three cone photoreceptor types.

5.2 Mechanisms of Blue-Light Performance Degradation

The observed performance decline during 450 nm illumination corresponds to established photobiological processes. Narrow-band blue light primarily stimulates ipRGCs (intrinsically photosensitive retinal ganglion cells containing melanopsin) responsible for non-visual pupillary reactions and circadian entrainment [6]. At 500 lux, continuous blue exposure leads to decreased pupil size and reduced retinal illuminance by non-blue wavelengths [7]. Additionally, the human lens exhibits high chromatic aberration at 450 nm, reducing spatial acuity [8]. These processes explain the 132.5% increase in task duration and 10% accuracy decrement compared to White (RGB), confirming H2.

5.3 Yellow Illumination for Sustained Work Environments

Yellow illumination's lowest eye strain scores (1.8/10 in Task B) without compromising 100% accuracy justifies its use for industrial tasks requiring prolonged attention beyond 30–40 minutes [9]. The 575 nm peak wavelength closely matches the 555 nm luminous efficiency function peak, maximizing lumens per unit radiant exposure and minimizing photoreceptor saturation [10].

5.4 Implications for Industrial Lighting Standards

These results bear significance for revision of industrial lighting standards. National standards (IS 3646, India) and international standards (ISO 8995-1, CIE S 008) specify illuminance values but lack spectral quality criteria. The empirical evidence—an 18.3% improvement in accuracy and 132.5% increase in task speed based on spectral choice alone, with unchanged illuminance—constitutes a strong basis for mandating CRI limits and M-EDI values in precision industrial lighting specifications [11].

6. Conclusion

This study establishes that spectral characteristics of industrial workplace lighting have practical significance for worker productivity and visual comfort during precision tasks. A variable-spectrum LED lamp powered by a microcontroller circuit reliably delivered controlled spectra validated using spectrometry, providing a basis for attributing performance differences to spectral factors rather than illuminance or luminance variations.

Key results demonstrate that White (RGB) broadband lighting maximizes performance of short-term precision tasks through superior color rendering and photopic spectral distribution, while Yellow lighting reduces cumulative eye strain during prolonged visual activity. Blue monochromatic lighting consistently leads to inferior performance at equivalent illuminance levels.

Future research should encompass broader age groups, longer trial durations, objective physiological indicators (blink rate, pupillometry, EEG alpha-band power), and automated spectral optimization based on biometric feedback. Integration of this technology with building information modeling (BIM) systems also represents a promising avenue.

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Data Availability

The raw experimental data supporting the conclusions of this article are available from the corresponding author upon reasonable request.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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