LUXREST:

A Crossover Trial Enhancing Sleep, Mood, and Productivity through Real-Time Personalized Feedback on Corneal plane Melanopic Equivalent Daylight Illuminance

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Introduction

Student: Ramyar Tajik
Current Position: Ph.D. Candidate in Architectural Engineering
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Advisor: Dr. Simi Hoque

Academic Background:

- B.Sc. in Architectural Engineering from University of Guilan (Rasht, Iran)
- M.Sc. in Building and Architectural Engineering from Politecnico di Milano (Milan, Italy)

Research Interest:

- Daylighting
- Enabling Technologies and Occupant Well-being
- Indoor Environmental Quality

Overview

- Introduction & Background
- Hypothesis & Aims
- Methods
- Analysis Overview
- Discussion Preview

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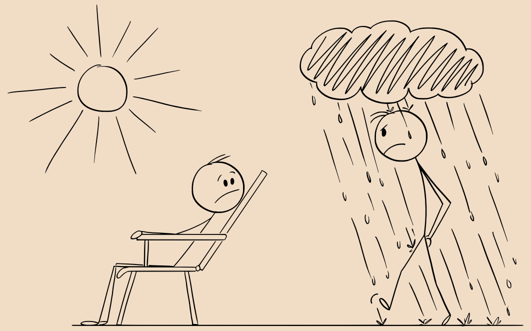
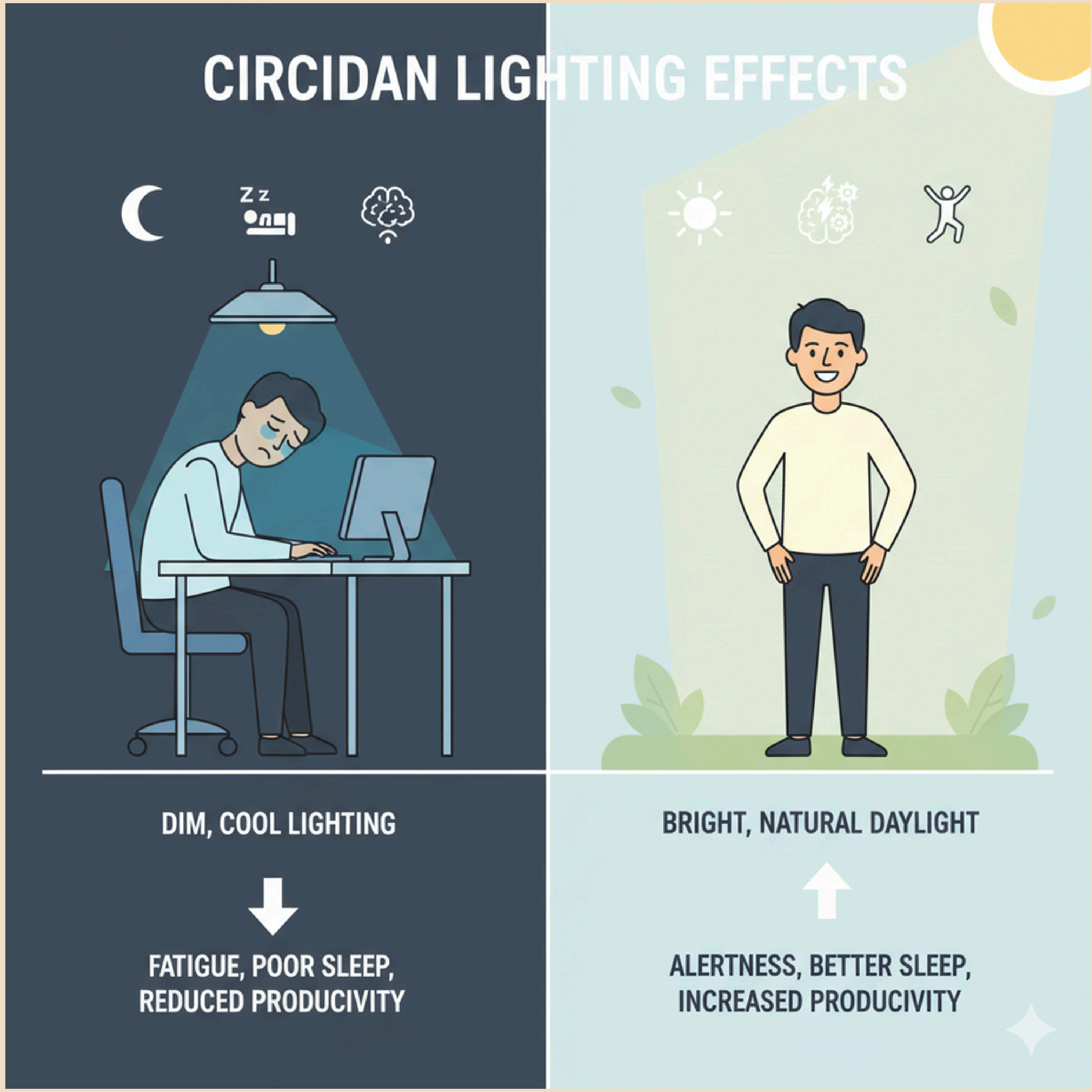
Circadian Lighting - General Picture

Circadian lighting = light designed for biological as well as visual effects

Impacts: sleep, alertness, mood, productivity, long-term health



Indoor environments often fail to deliver sufficient circadian-effective light

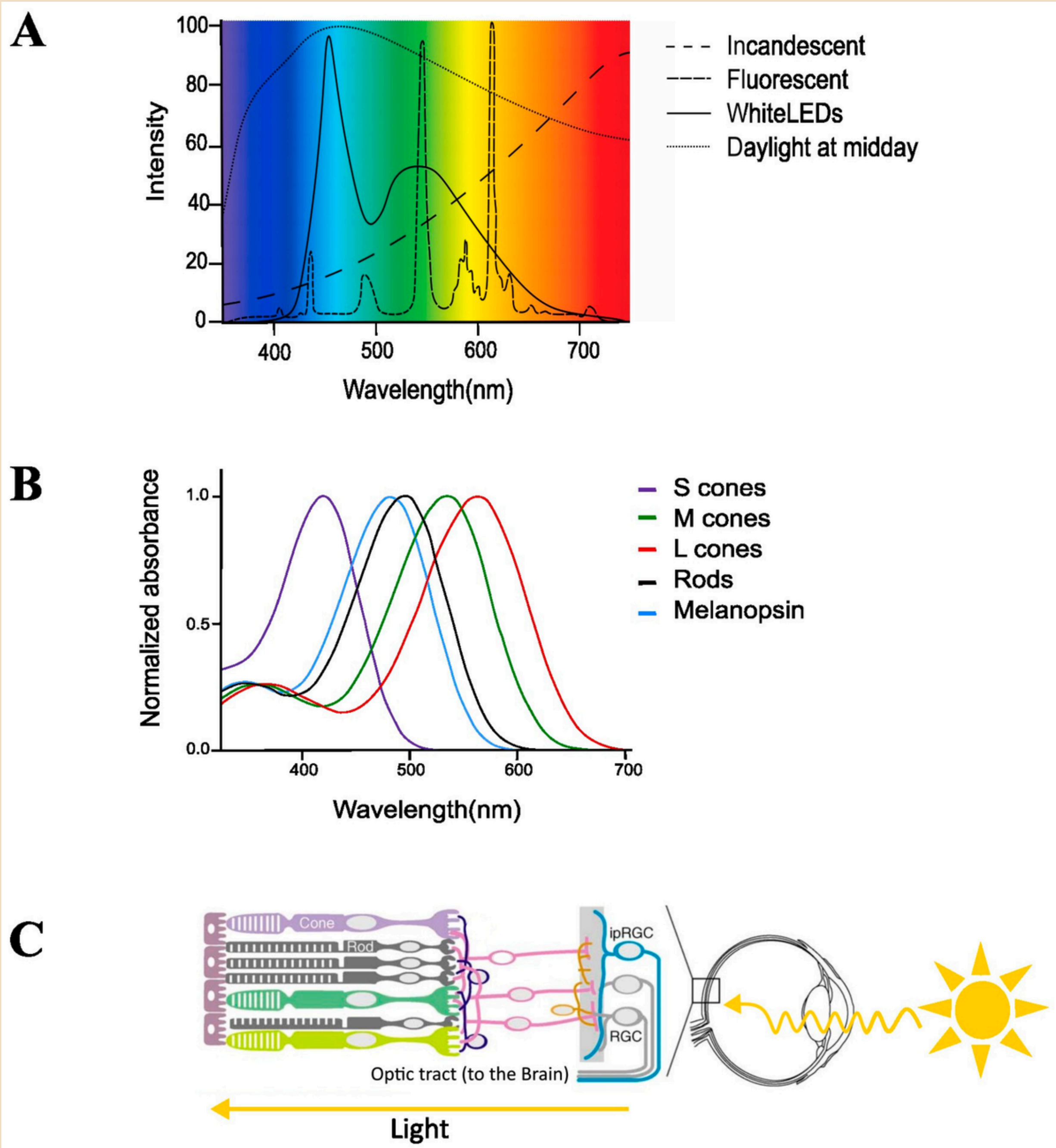


Spectral Sensitivity of the Human Visual and Circadian Systems

The human retina has multiple photoreceptor types:
S, M, L cones + rods (vision) + ipRGCs (non-visual).

Each has distinct peak sensitivities:
S-cones ~420 nm,
M-cones ~534 nm,
L-cones ~564 nm
Rods ~498 nm
Melanopsin (ipRGCs) ~480 nm

Light sources differ in spectral composition
same lux can mean very different circadian effects.



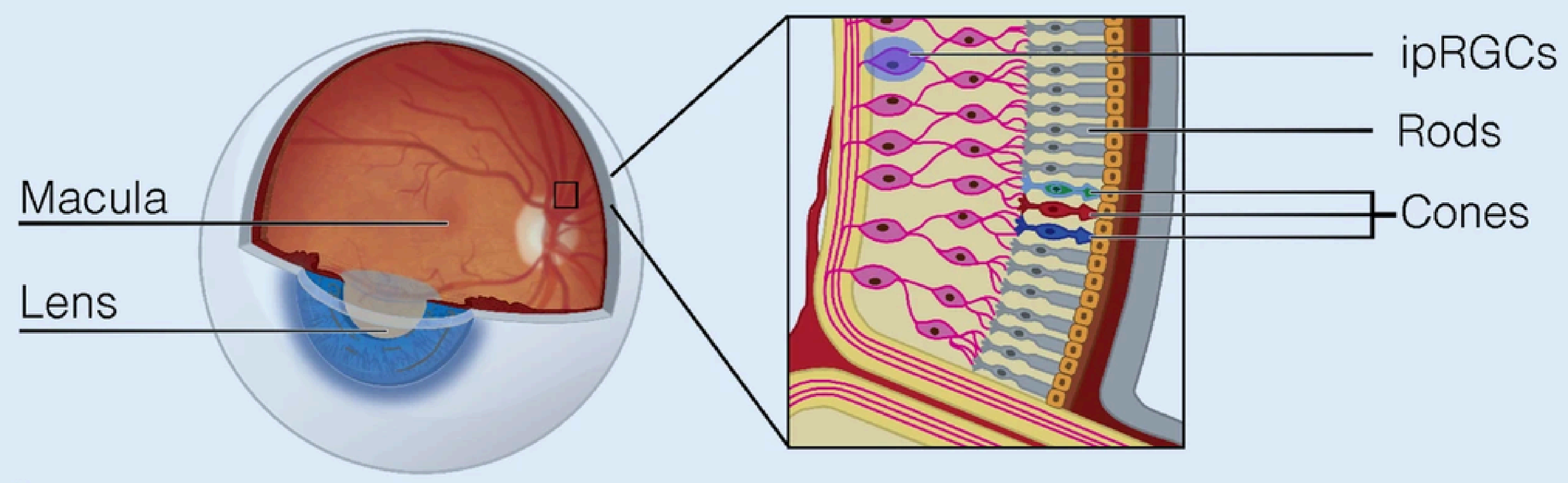
Source: Campbell I, Sharifpour R, Vandewalle G. Light as a modulator of non-image-forming brain functions—positive and negative impacts of increasing light availability. Clocks & Sleep. 2023 Mar 17;5(1):116-40.

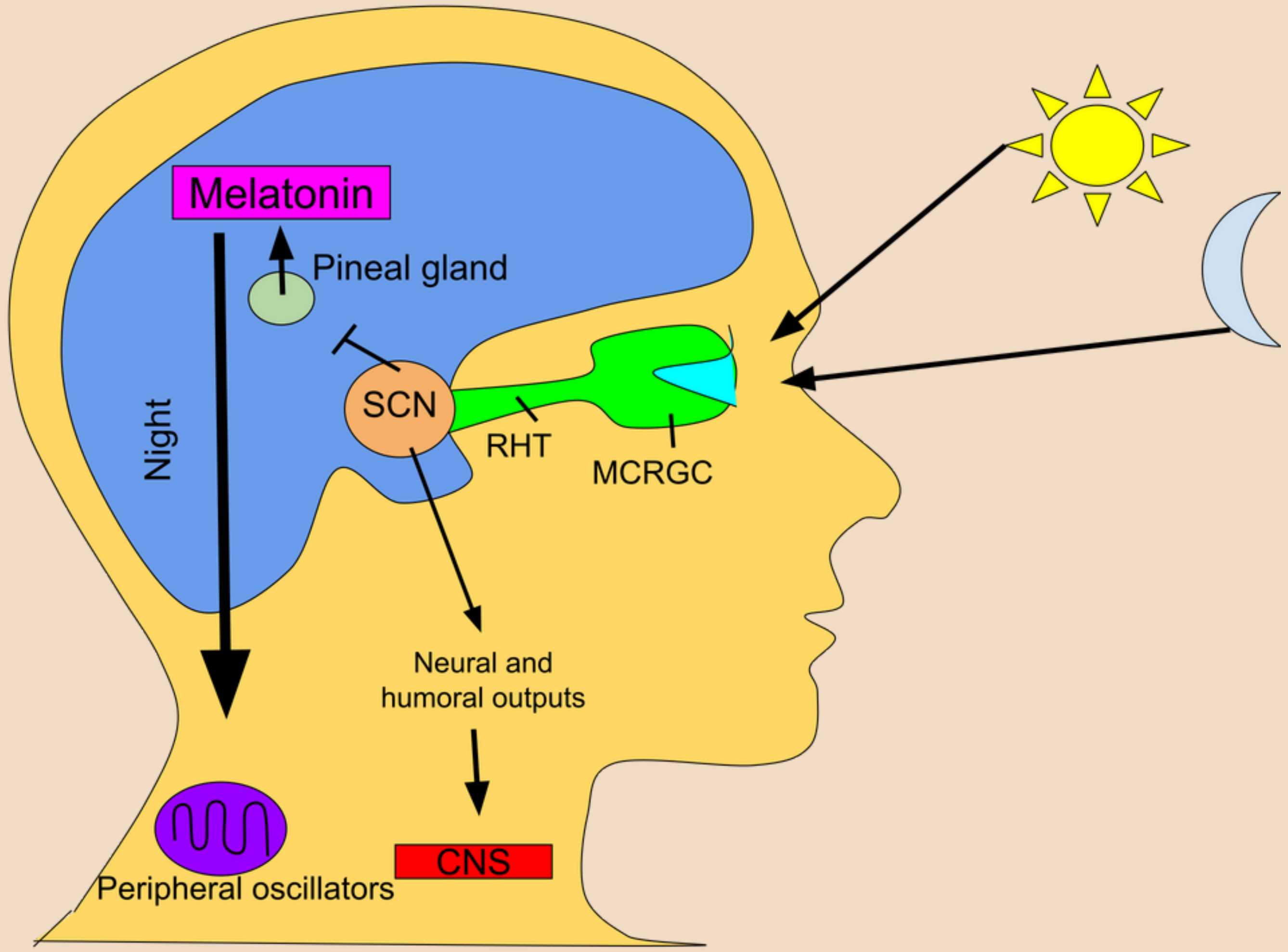
Photoreceptor sensitivities and light spectra. **(A)** Spectrum of white LED, fluorescent, and incandescent light sources and natural daylight. **(B)** Spectral sensitivities of retinal photoreceptors in primates. **(C)** Wiring and position of retinal photoreceptors.

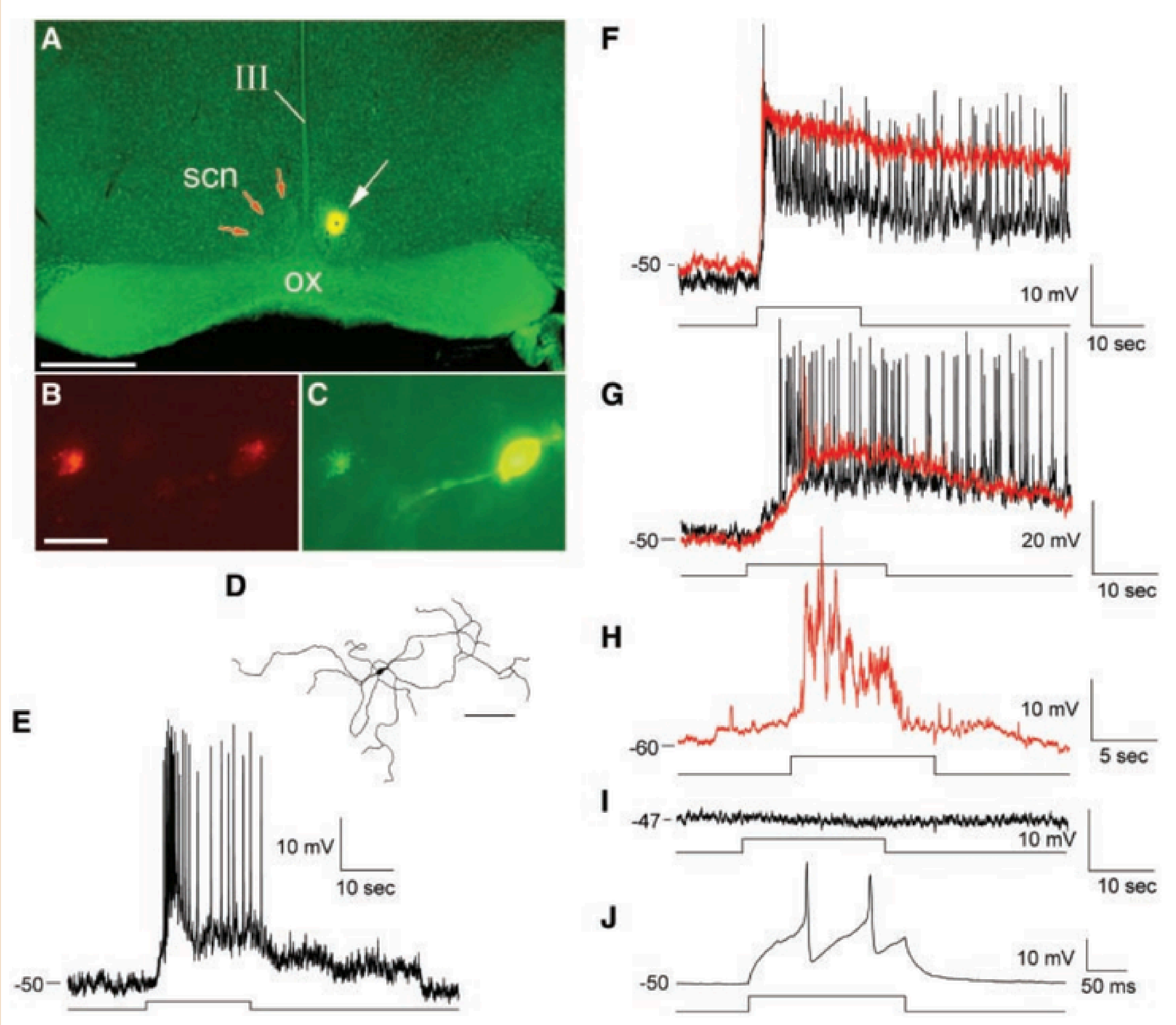
Biology of non-image-forming (NIF) light

Intrinsically photosensitive Retinal Ganglion Cells (ipRGCs):
intrinsic melanopsin photopigment.
Direct suprachiasmatic nucleus (SCN) projections via retinohypothalamic tract.

NIF pathways:
regulate circadian entrainment, melatonin suppression, pupil reflex, mood, etc.
Independent of rods/cones but integrate inputs from them.







source: Berson DM, Dunn FA, Takao M. Phototransduction by Retinal Ganglion Cells That Set the Circadian Clock. Science. 2002;295(5557):1070–1073.

Measuring Photopic vs. Circadian Light

Photopic Lux (visual system)

Visual illuminance: $$E_v = 683 \int_{380}^{780} SPD(\lambda)\, V(\lambda)\, d\lambda$$

Scotopic illuminance: $$E_s = 1700 \int_{380}^{780} SPD(\lambda)\, V'(\lambda)\, d\lambda$$

SPD(λ): spectral power distribution of light source
V(λ): photopic luminosity function, peak at 555 nm
V'(λ): scotopic luminosity function, peak at 498 nm

Circadian Sensitivity

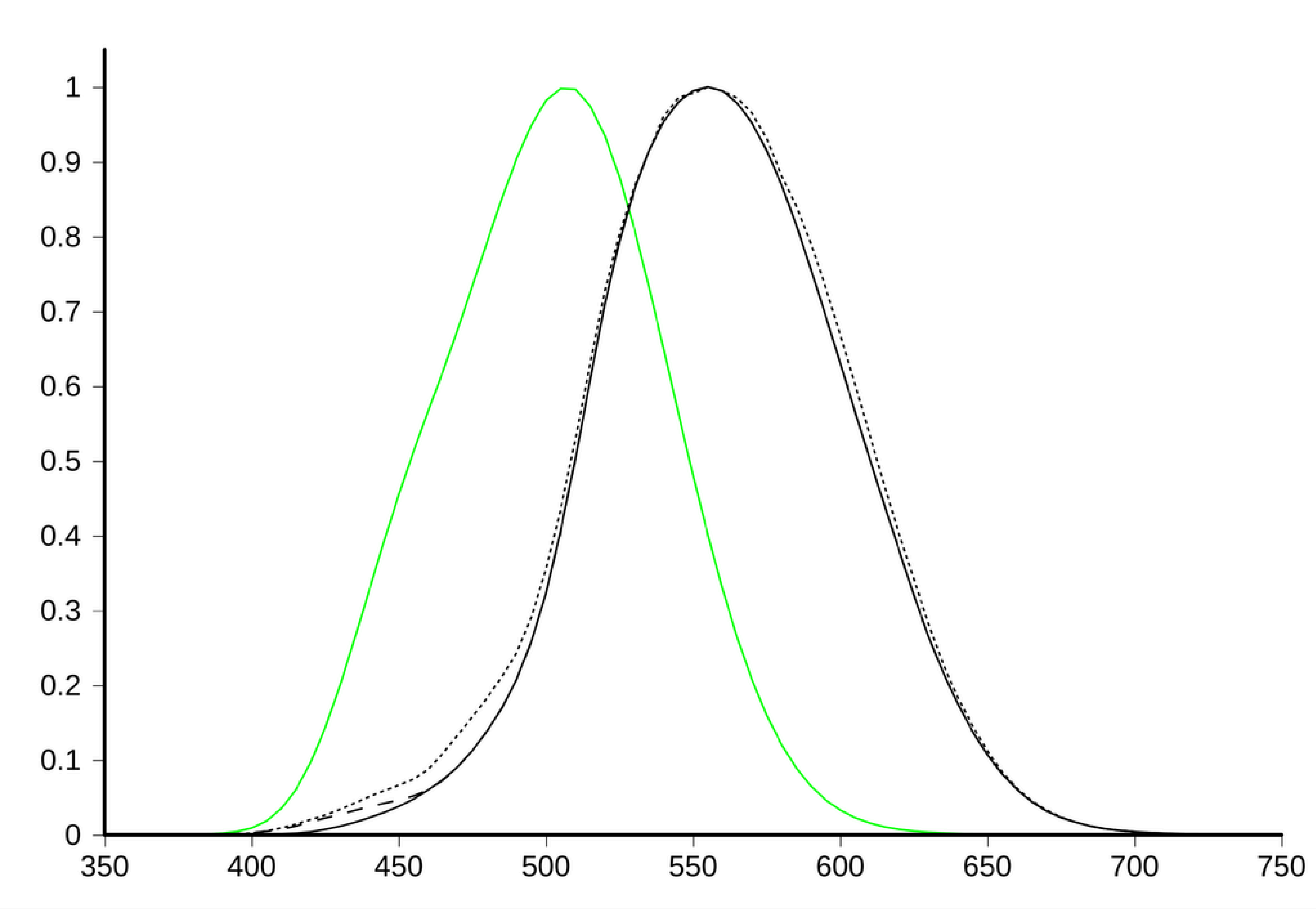
ipRGCs → melanopsin → peak sensitivity ≈ **480 nm**
Spectral sensitivity differs from **V(λ)**

Two lights with identical photopic lux can have very different circadian impacts

Key Problem

Relying on lux alone ignores **short-wavelength weighting** crucial for the circadian system

Necessitated the development of circadian metrics (CLA, CS, EML, later melanopic EDI)



Photopic **(black)** and scotopic **(green)** luminous efficiency functions. The photopic includes the CIE 1931 standard **(solid)**, the Judd–Vos 1978 modified data **(dashed)**, and the Sharpe, Stockman, Jagla & Jägle 2005 data **(dotted)**.

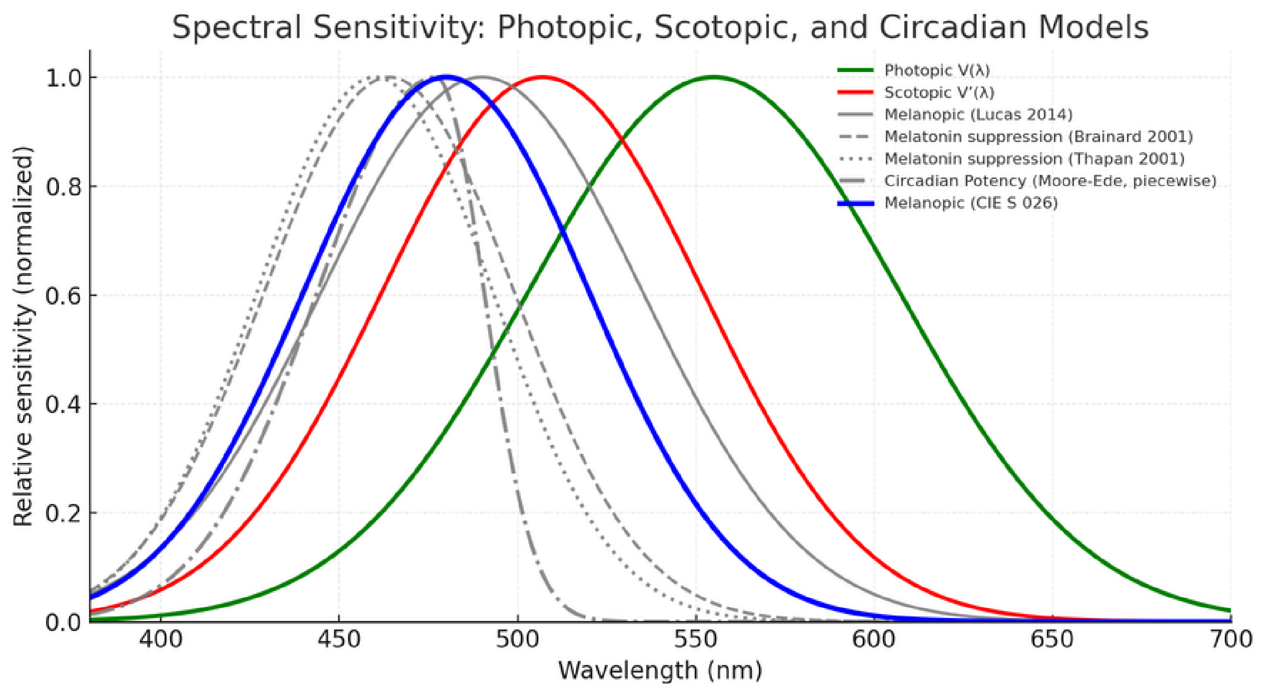
Circadian Light Metrics and Standards

Historical evolution of circadian light metrics

- Early models such as CLA (Circadian Light) and CS (Circadian Stimulus) combined weighted photoreceptor inputs to predict melatonin suppression.
- EML approach made it easier for architects and interior designers and adopted by WELL.
- The melanopic EDI approach normalized melanopic sensitivity to daylight (D65) and is now widely used in chronobiology.
- More recent models, such as Circadian Potency (Moore-Ede), introduced asymmetric sensitivity curves that may capture long-exposure responses with higher precision.

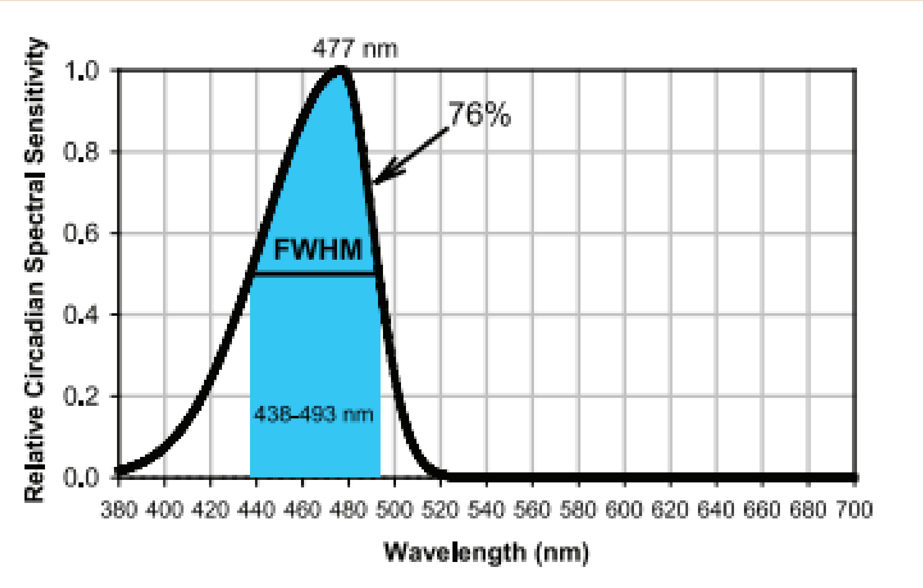
Why use melanopic EDI (CIE S 026, 2018):

- Provides standardized α-opic weighting functions for S-, M-, L-cones, rods, and melanopsin.
- Directly convertible to melanopic Equivalent Daylight Illuminance (melanopic EDI) in lux, enabling practical application.
- Adopted as the international standard for circadian lighting research, regulation, and clinical studies.
- Balances biological accuracy with reproducibility and comparability across studies.



Model	Meaning	Peak λ (nm)	Basis/Derivation	Formula	Primary Source
CLA	Circadian Light (weighted mixture)	blue-weighted	Weighted cone/rod/mel inputs	$CLA = \int SPD(\lambda)\, W_{CLA}(\lambda)\, d\lambda$	Rea et al. 2005
CS	Circadian Stimulus	—	Nonlinear mapping from CLA	$CS = f(CLA)(saturating 0–0.7)$	Rea et al. 2010
EML	Equivalent melanopic lux	≈480–490	Melanopsin-weighted lux, pre-CIE	$EML = E_v \times R$	Figueiro & Rea, 2016; & 2012
CIE S 026 Melanopic	ipRGC/melanopsin spectral sensitivity	≈480	α-opic sensitivity, standardized	$E_{mel} = \int SPD(\lambda)\, \bar{a}mel(\lambda)\, d\lambda;\; mEDI = Emel/k_{mel,D65}$	CIE S 026 (2018)
Circadian Potency	Asymmetric, 12-h exposure fit	477	Piecewise Gaussian	$P(\lambda) = e^{-(\lambda-\mu)^2/(2\sigma_L^2)}, \lambda \le \mu;\; e^{-(\lambda-\mu)^2/(2\sigma_R^2)}, \lambda > \mu$	Moore-Ede et al. 2021

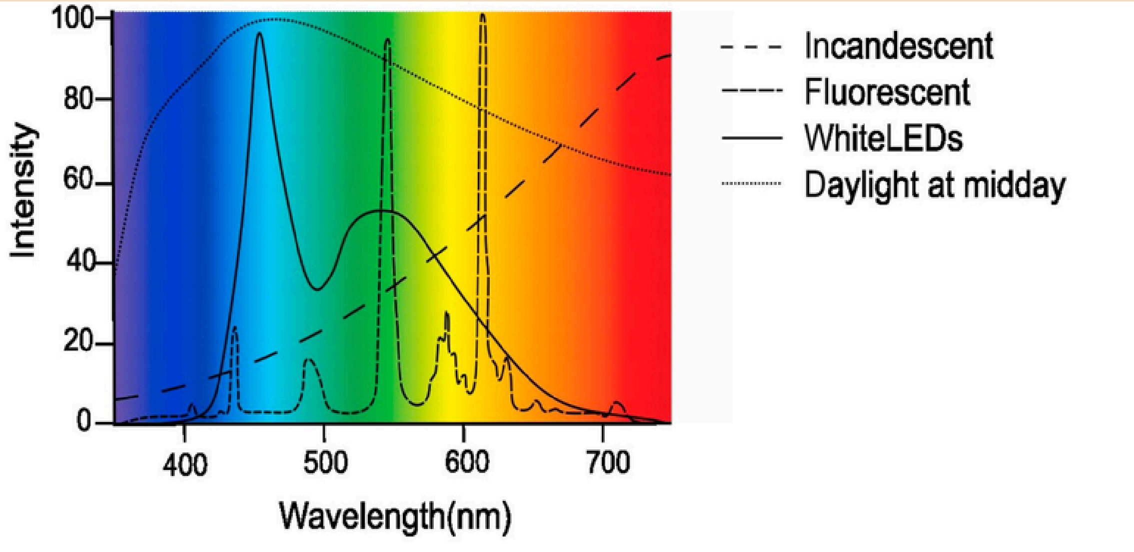
Optimized Circadian Potency spectral sensitivity curve with 76% of spectral sensitivity falling in the full-width half maximum 438- to 493-nm blue band depicted with the color of 477 nm blue.



Source: Moore-Ede M, Heitmann A, Guttkuhn R. Circadian potency spectrum with extended exposure to polychromatic white LED light under workplace conditions. Journal of biological rhythms. 2020 Aug;35(4):405-15.

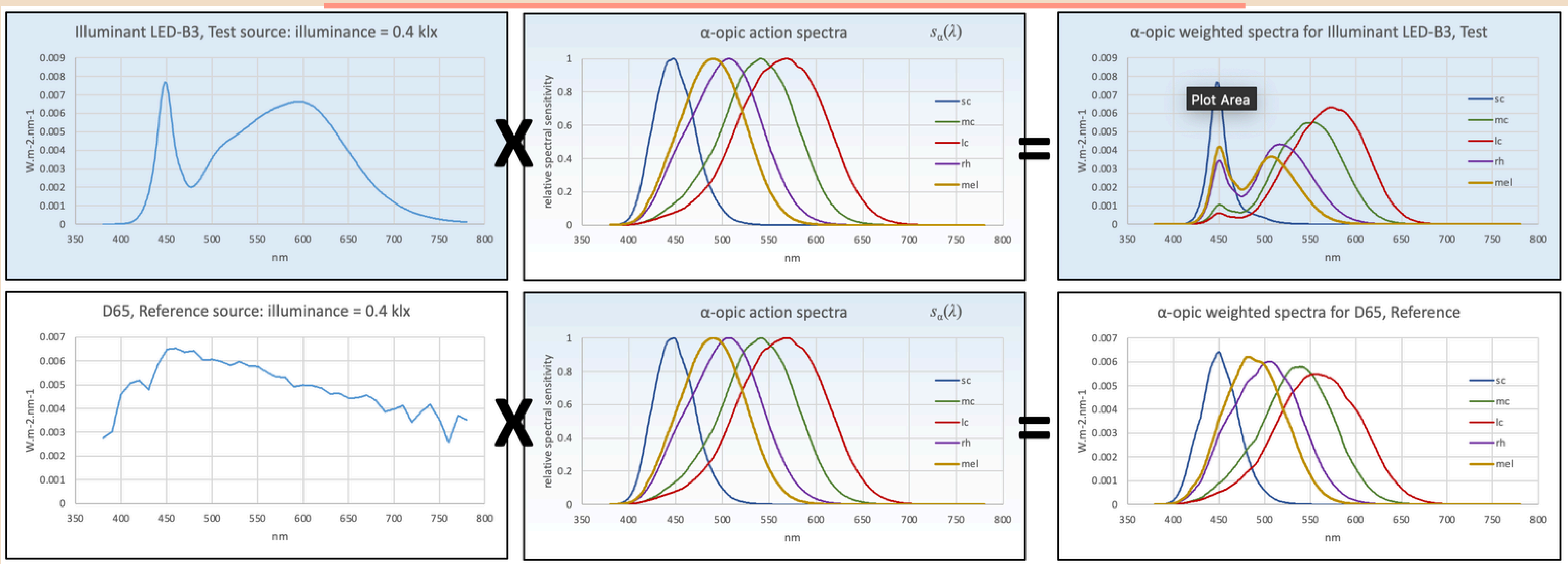
Melanopic Equivalent Daylight Illuminance

$$j\text{-EDI} = \frac{\int SPD(\lambda)\,\bar{a}^j(\lambda)\,d\lambda}{\int SPD_{D65}(\lambda)\,\bar{a}^j(\lambda)\,d\lambda} \times 1000\,\text{lx}$$



Where:
SPD(λ) = spectral power distribution of the light source
$\bar{\alpha}^j(\lambda)$ = CIE α-opic spectral sensitivity (for melanopsin, j = mel)
Denominator normalizes to D65 daylight per 1000 lux

- CIE S 026 (2018) defines α-opic irradiances for S, M, L cones, rods, and melanopsin.
- melanopic EDI converts melanopic irradiance into lux-equivalent values referenced to D65 daylight.
- Enables direct comparison of different spectra at the same photopic lux.
- Standardized measure for circadian-effective light exposure in research, design, and regulation.



α-opic weighted spectra for 400 photopic lux from different sources: typical Blue LED vs sunlight

Light Exposure Recommendations

Light Exposure Recommendations

Brown. et al.

- **Daytime:** ≥250 melanopic EDI lux at the eye during the daytime.
- **Evening:** <10 melanopic EDI lux in the 3 hours before habitual bedtime.
- **Night:** <1 melanopic EDI lux during sleep.

>250 lux day-time

<10 lux in the evening

<1 lux while sleeping

- Real-world workplaces often provide <100 lx for most of the day,
- Higher daytime levels (often much higher than 250 melanopic EDI) can enhance alertness/phase effects; exact targets depend on outcome and spectrum.Practical strategies: prioritize vertical eye-level light, use indirect or large-area luminaires, and maximize daylight when possible.

- Applies to **healthy adults** under everyday conditions.
- Uses **CIE S 026** melanopic EDI as the reference metric.
- Values are **minimum** effective thresholds, not optimal targets.
- **Sustained exposure** at the corneal plane is assumed.
- The **pattern of exposure** is as important as intensity.
- Not intended as therapeutic prescriptions (e.g., shift work, clinical populations).

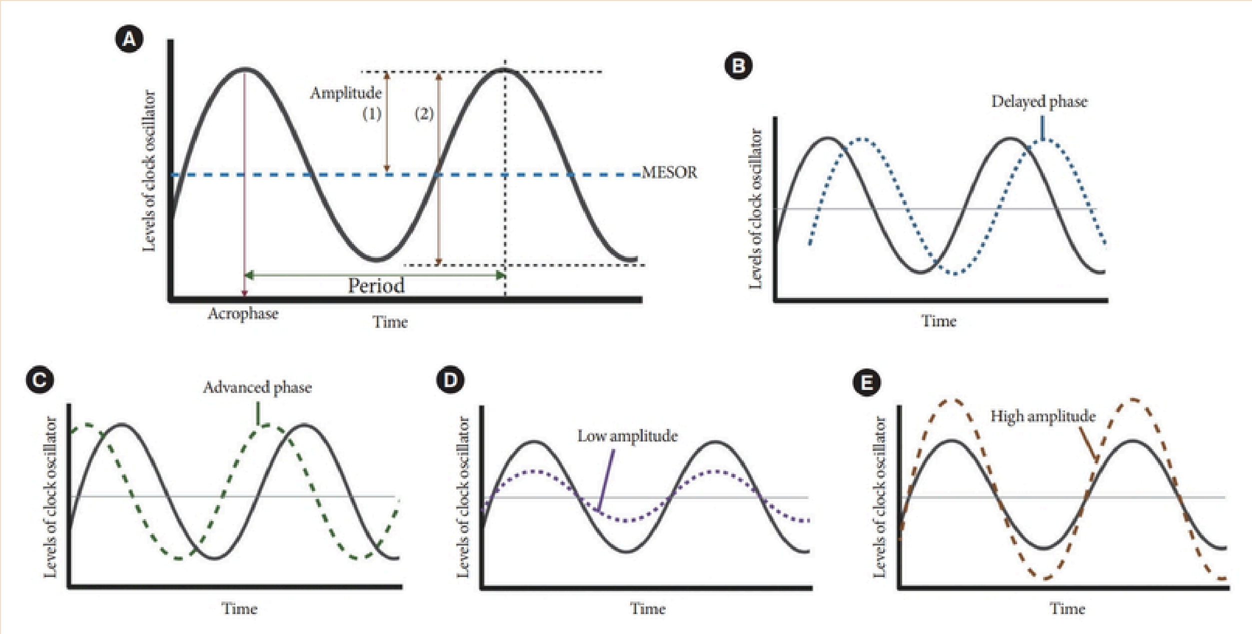
Time of Day	Target Melanopic EDI	What to Do
Sunrise to Sunset	**> 250 lux**	Go outside or near a window
Evening (3h before bed)	**< 10 lux**	Dim lights, avoid screens
Night (During sleep)	**< 1 lux**	Keep room dark

Wearables in Chronomedicine

Circadian Disruption Markers

- **Reduced amplitude**
- **Fragmentation (intradaily variability IV)**
- **Poor synchronization (interdaily stability IS)**
- **Phase shift**
- **Misalignment**
- **Social Jetlag (SJL)**
- **Light-based indices:**
  - **DDI** (Daylight Deficit Index) – insufficient daytime light.
  - **NEI** (Nocturnal Excess Index) – excessive nighttime light.

Cosine curve characteristics. (A) Parameters of circadian rhythmicity. Examples of delayed phase (B), advanced phase (C), low amplitude (D), and high amplitude (E) curves. MESOR, midline statistic of rhythm.



Source: Jung I, Park SY, Yu JH, Seo JA, Kim KJ, Kim NH, Yoo HJ, Kim SG, Choi KM, Baik SH, Kim NH. Attention to innate circadian rhythm and the impact of its disruption on diabetes. Diabetes & Metabolism Journal. 2024 Jan 3;48(1):37-52.

Wearables Commonly Used

- **Actigraphy-based devices** (e.g., Actiwatch, GENEActiv)
- **Consumer wearables** (e.g., Fitbit, Apple Watch, Oura Ring)
- **Specialized circadian sensors** (e.g., Daysimeter, Dimesimeter, LiDo)

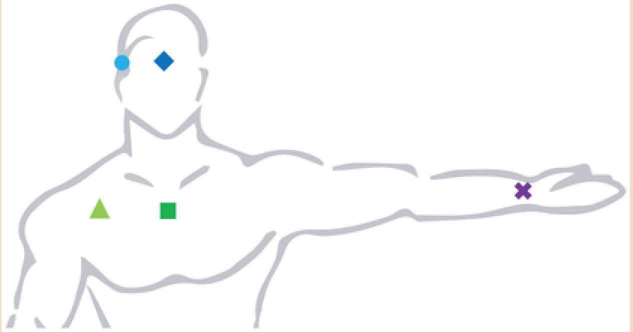
Specialized Circadian Sensors (LiDo):
- Near-Eye Dosimeter
- Passive Data Collection

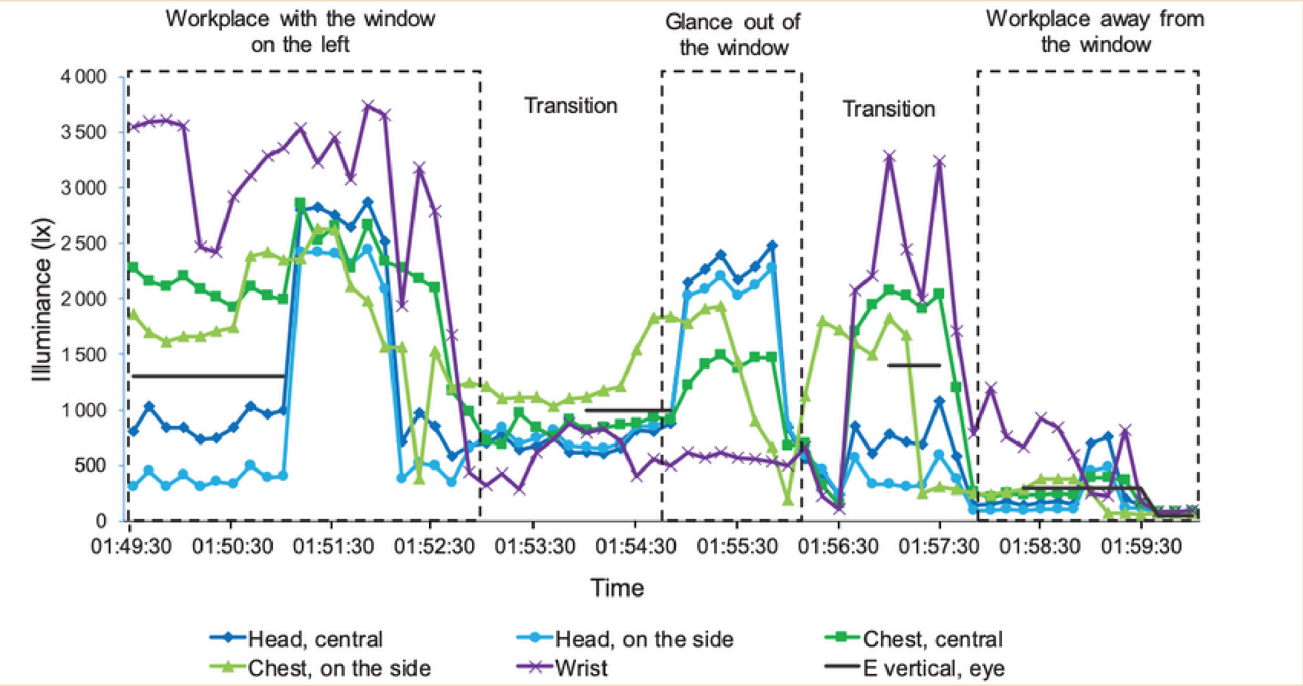
Actiwatches:
- Research Grade
- Passive activity, heart rate, and sleep patterns data.

Consumer Wearables:
- Accessible
- Proprietary Algorithms
- not research grade

Sensor Placement

- Closer to the Corneal Plane, Higher Accuracy
- Lower acceptance rate from the user

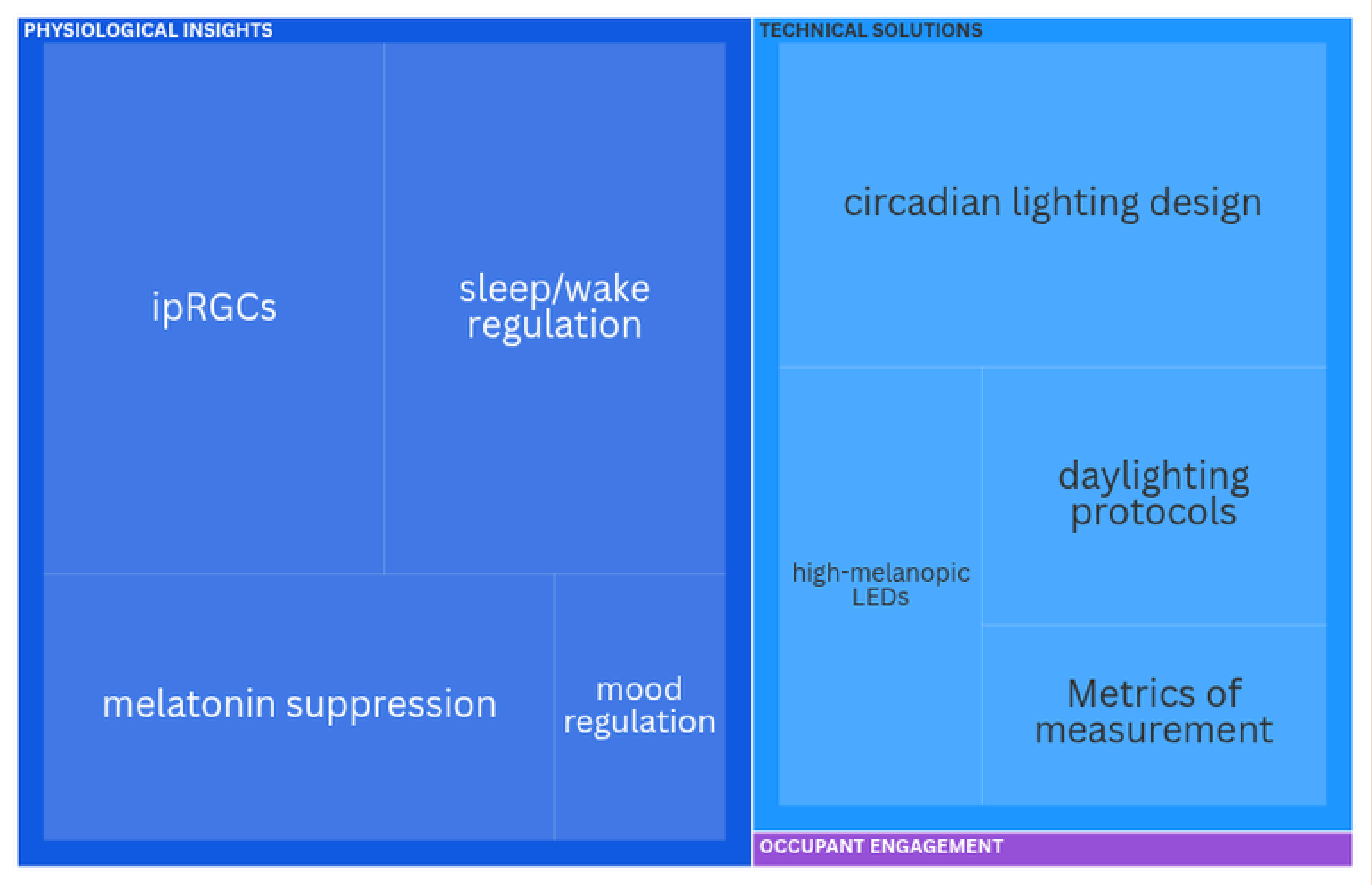




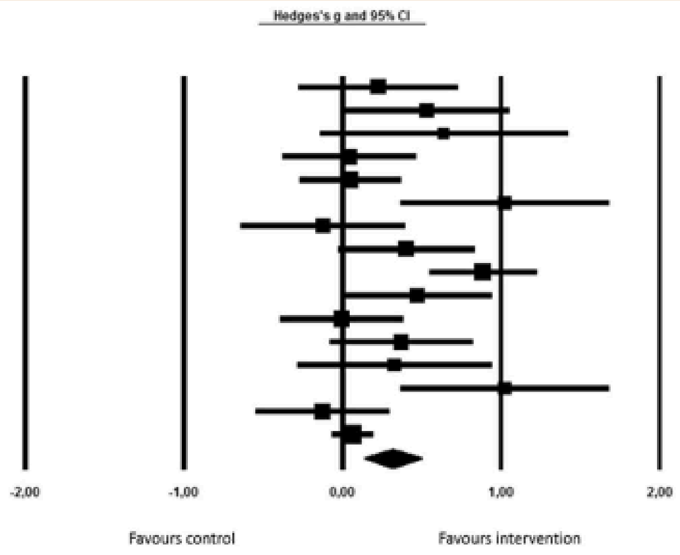
Source: Stampfli JR, Schrader B, Di Battista C, Häfliger R, Schälli O, Wichmann G, Zumbühl C, Blattner P, Cajochen C, Lazar R, Spitschan M. The Light-Dosimeter: A new device to help advance research on the non-visual responses to light. Lighting Research & Technology. 2023 Jun;55(4-5):474-86.

The Triad of Circadian Lighting Research

1. **Physiological Insight**
   Non-visual effects of light on circadian system, sleep, mood, cognition
2. **Technical Solutions**
   Metrics and Measurement, High-melanopic fixtures, daylighting protocols, integrative design
3. **Occupant Engagement**
   Education, Occupant in-loop control, feedback



Evidence from sedentary behavior research shows self-monitoring reduces inactivity; similar approaches may empower individuals to manage their own light exposure.



Study name	Sample size		Statistics for each study				
	Intervention	Control	Hedges's g	Standard error	Lower limit	Upper limit	p-Value
Adams, 2013	40	24	0,229	0,256	-0,273	0,730	0,371
Arrogi, 2017	31	27	0,536	0,264	0,018	1,054	0,043
Ashe, 2015	12	13	0,642	0,398	-0,137	1,422	0,106
Biddle, 2015	38	49	0,044	0,214	-0,376	0,464	0,837
Brakenridge, 2016	66	87	0,050	0,162	-0,269	0,368	0,759
Carr, 2013	23	17	1,026	0,334	0,372	1,681	0,002
De Cocker, 2016	35	23	-0,119	0,265	-0,639	0,400	0,653
De Greef, 2011	60	32	0,408	0,219	-0,022	0,838	0,063
Edwardson, 2018	77	69	0,890	0,173	0,551	1,229	0,000
Klaren, 2016	33	37	0,475	0,240	0,005	0,946	0,048
Lin, 2018	51	50	-0,000	0,198	-0,387	0,387	0,999
Lynch, 2019	37	40	0,374	0,228	-0,073	0,820	0,101
Lyons, 2017	20	20	0,332	0,312	-0,280	0,943	0,288
Smith, 2012	23	17	1,026	0,334	0,372	1,681	0,002
White, 2017	44	43	-0,121	0,213	-0,538	0,296	0,568
Wyke, 2019	464	471	0,065	0,065	-0,063	0,193	0,322
			0,320	0,090	0,142	0,497	0,000

Fig. 2 Forest plot for total sedentary behavior

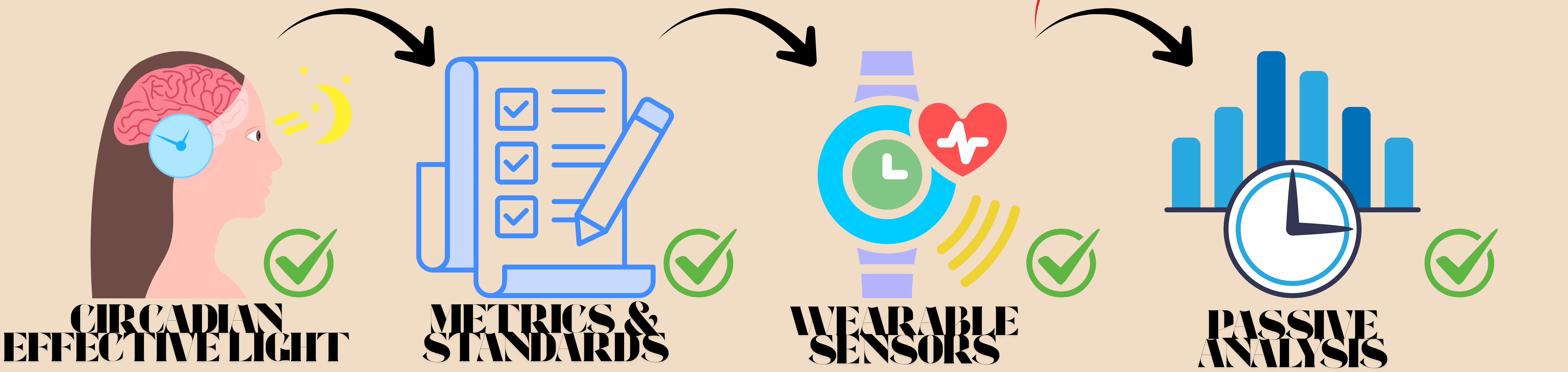
Source: Compernolle S, DeSmet A, Poppe L, Crombez G, De Bourdeaudhuij I, Cardon G, Van Der Ploeg HP, Van Dyck D. Effectiveness of interventions using self-monitoring to reduce sedentary behavior in adults: a systematic review and meta-analysis. International Journal of Behavioral Nutrition and Physical Activity. 2019 Aug 13;16(1):63.

The Gap

- Circadian-effective light exposure is well established as critical for sleep, mood, and health.
- Metrics exist (CIE S 026 melanopic EDI, CLA/CS, EML, etc.), and consensus recommendations (Brown et al. 2022) define thresholds.
- Wearables in chronomedicine widely used — but primarily for passive monitoring.

- **Current limitation:** Data are analyzed **retrospectively**; participants receive no guidance during exposure.

- **Unmet need: Real-time, personalized light feedback** that empowers individuals to actively manage circadian health.



Hypothesis

Research Hypothesis

We hypothesize that providing occupants with real-time, personalized feedback on corneal plane melanopic EDI exposure, using data collected from wearable devices, will encourage behavioral changes such as seeking healthier light environments by maximizing daytime and minimizing evening and nighttime melanopic light intake, leading to measurable improvements in sleep quality, mood, and productivity.

Primary Research Question

Does real-time, personalized feedback on corneal plane melanopic EDI exposure motivate occupants to change their behaviors enough to measurably improve their photic exposure patterns, sleep quality, mood, and productivity?

Secondary Research Questions

- Can a personalized visual and AI-assisted light exposure feedback system effectively guide individuals to optimize their daily light exposure?
- Is one week of light exposure feedback sufficient to produce statistically significant behavioral and physiological changes compared to a passive baseline phase?
- Do changes in light exposure behavior correlate with changes in self-reported sleep quality, energy levels, and daily performance?
- What is the usability and perceived value of real-time light feedback among participants?

Pilot Framing

Why a pilot?
First study to test real-time circadian light feedback using melanopic EDI.
Evaluate feasibility of data collection pipeline (sensor → backend → feedback → surveys).
Assess participant adherence to sensors, surveys, and feedback use.
Generate preliminary effect sizes for sleep, mood, and productivity outcomes.
Scope:
Small sample, fixed-order crossover design.
Focus on proof-of-concept and refining methods.
Next step:
Inform design of larger randomized trials.

Sample Size & Feasibility

Planned Sample Size: ~30 participants.

Rationale: Pilot framed to test feasibility, estimate effect sizes, and refine procedures.

Power not primary goal: Small N appropriate for pilot → outcomes are precision estimates, not hypothesis tests.

Primary Deliverable: Variance estimates and effect-size guidance for powering a larger trial.

Study Design

Design type: Fixed-order crossover trial.

Duration: 2 weeks per participant.

Phases:
Week 1 – Baseline: Sensor logging only (no feedback).
Week 2 – Intervention: Sensor logging + real-time LuxRest feedback
.
Participants: Healthy adults, similar age range, each serving as their own control.

Daily assessments:
Morning survey: Sleep diary + Stroop test.
Evening survey: Mood, productivity, stress, hydration, screen time.

Primary outcomes: Sleep duration, sleep quality, mood, productivity.
Secondary measures: Circadian disruption indices (DDI, NEI).

Hardware Development

LiDo sensors (Lucerne University of Applied Sciences & Arts, HSLU):

Near-eye wearable dosimeter for corneal-plane light exposure.
Records spectral data converted into melanopic EDI (CIE S 026).

Integration for LuxRest:

Paired with Raspberry Pi Zero W + Blues Notecard for wireless data transmission.
Custom power management for continuous daily use.

Reliability testing: Conducted pilot runs to confirm logging, battery life, and comfort for participants.
Collaboration: Hardware support from HSLU to adapt LiDo for intervention-based research.

Light-Dosimeter – Data sheet

The light-dosimeter (lido) is a mobile measurement device to investigate the non-visual responses to light. Attached to a pair of glasses, it records a person's light exposure in the near-corneal plane every 10 seconds. Thanks to a bespoke mounting it can be taken off during a recording, if required. The data can be analysed directly in the custom-made software Lido Studio or exported.
The lidos were developed by an interdisciplinary team from the Lucerne School of Engineering and Architecture and three project partners within the framework of a project funded by the Velux Stiftung (Project No. 1134).

VELUX STIFTUNG

Additional features

- An acceleration sensor, which tracks the tilt of the device
- A push-button, which can be used to mark events as pre-defined by the lead investigator
- An RGB LED, which indicates a device's battery status once activated

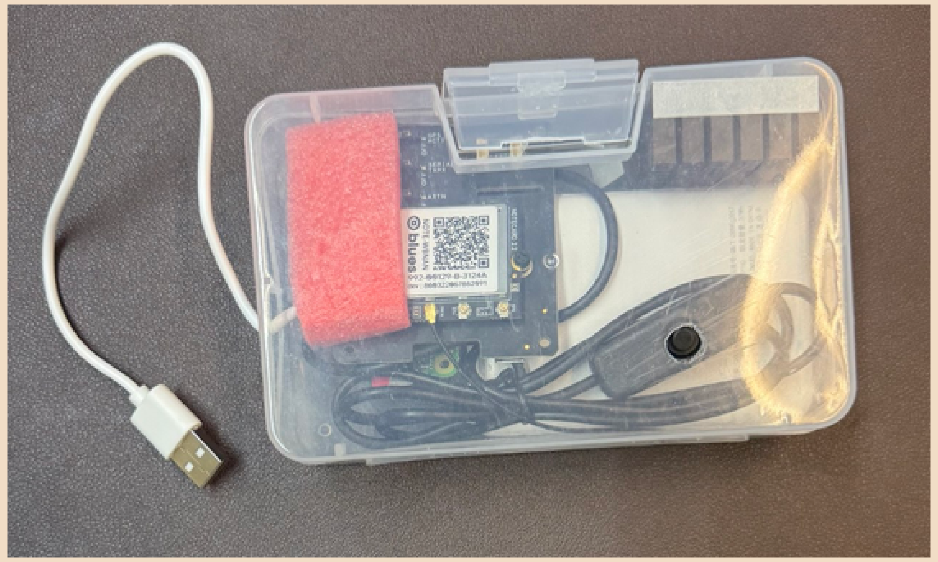
Project partners

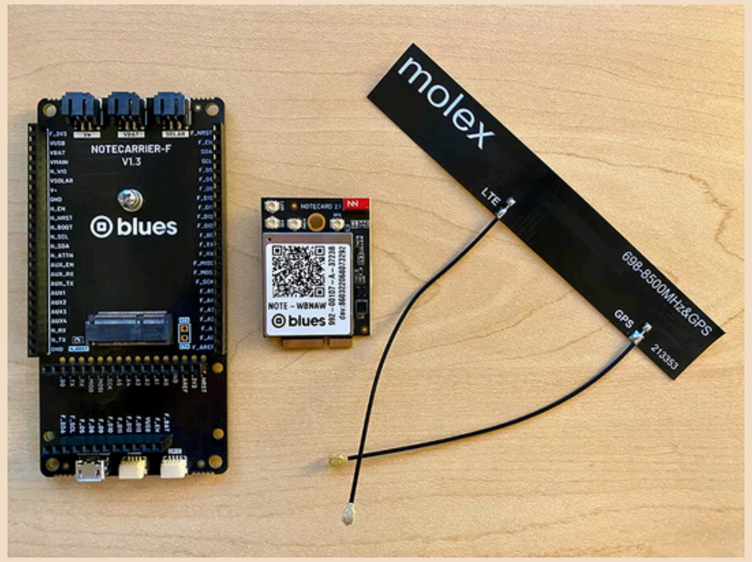
METAS UPK Universitäre Psychiatrische Kliniken Basel

Device specifications

Wavelength range	VIS 380 nm to 780 nm
Measurement range	~5 lx to >100'000 lx
Angular response	Close to cosine
Battery life	~7 days
Battery charging time	~2 hours
Memory size	~300 days
Dimensions of the casing	58 mm × 20,6 mm × 16 mm
Weight of the device	~27 g
Interface	Micro USB
Ingress Protection Code	IP20

36 LiDo (bottom) and LiDo Companion (top) connected together with a two-meter long USB to micro-USB cable.


Data Broker, consisting of a Raspberry Pi Zero W with a Notecard Pi hat, a power cable and power button, a 10000-mAh power bank and a heat sink



Blues NoteCard allows data transmission through cellular connection to the cloud from anywhere with a cell access.

Software Backend for Data Collection

Data pipeline:

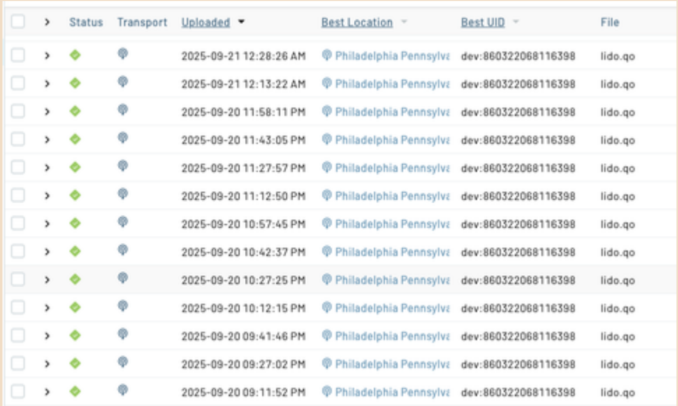
LiDo + Companion → Data Broker + NoteCard → Notehub → n8n → Collection & Feedback

Processing steps:

1. Data is transmitted through an MQTT protocol from the Companion to the Data Broker (Raspberry Pi Zero W) every 5 seconds
2. Transform data into single JSON packets and automatically upload data to the Notehub cloud every 15 minutes.
3. n8n Conversion of spectral data into melanopic EDI (CIE S 026 toolbox).
4. Processed per participant and sent to Google Sheets for collection
5. Data Processed per participant and sent to the AI agent to provide personalized feedback to participants.

Integration with surveys:
Qualtrics surveys are collected daily through automated notifications sent to participants via n8n.
All survey data are collected separately from Qualtrics.

Output: Clean datasets prepared for feedback system and later statistical analysis.



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		2025-09-20 11:58:11 PM	Philadelphia Pennsylva	dev:860322068116398	lido.qo
		2025-09-20 11:43:05 PM	Philadelphia Pennsylva	dev:860322068116398	lido.qo
		2025-09-20 11:27:57 PM	Philadelphia Pennsylva	dev:860322068116398	lido.qo
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		2025-09-20 10:27:25 PM	Philadelphia Pennsylva	dev:860322068116398	lido.qo
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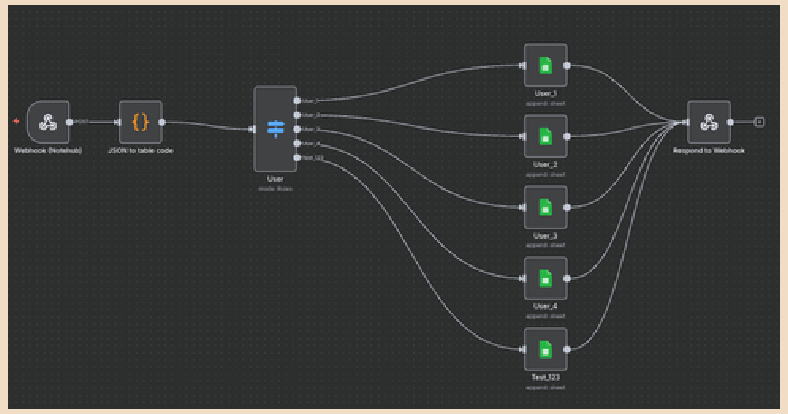
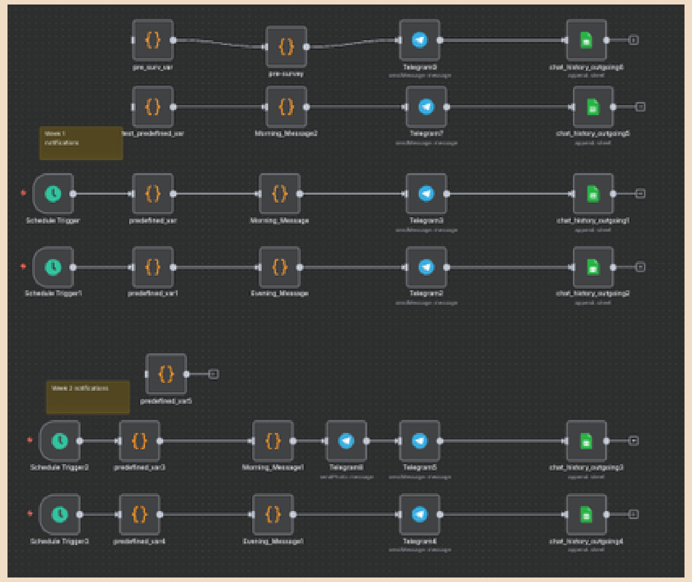
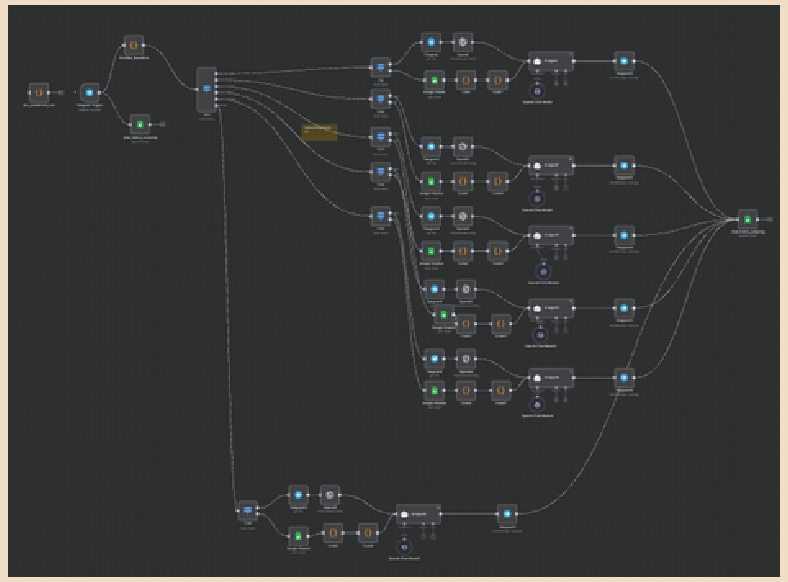




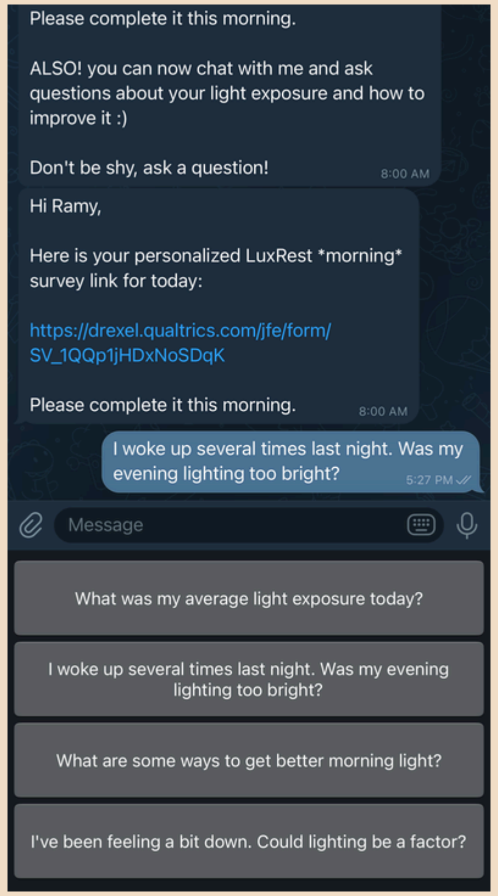


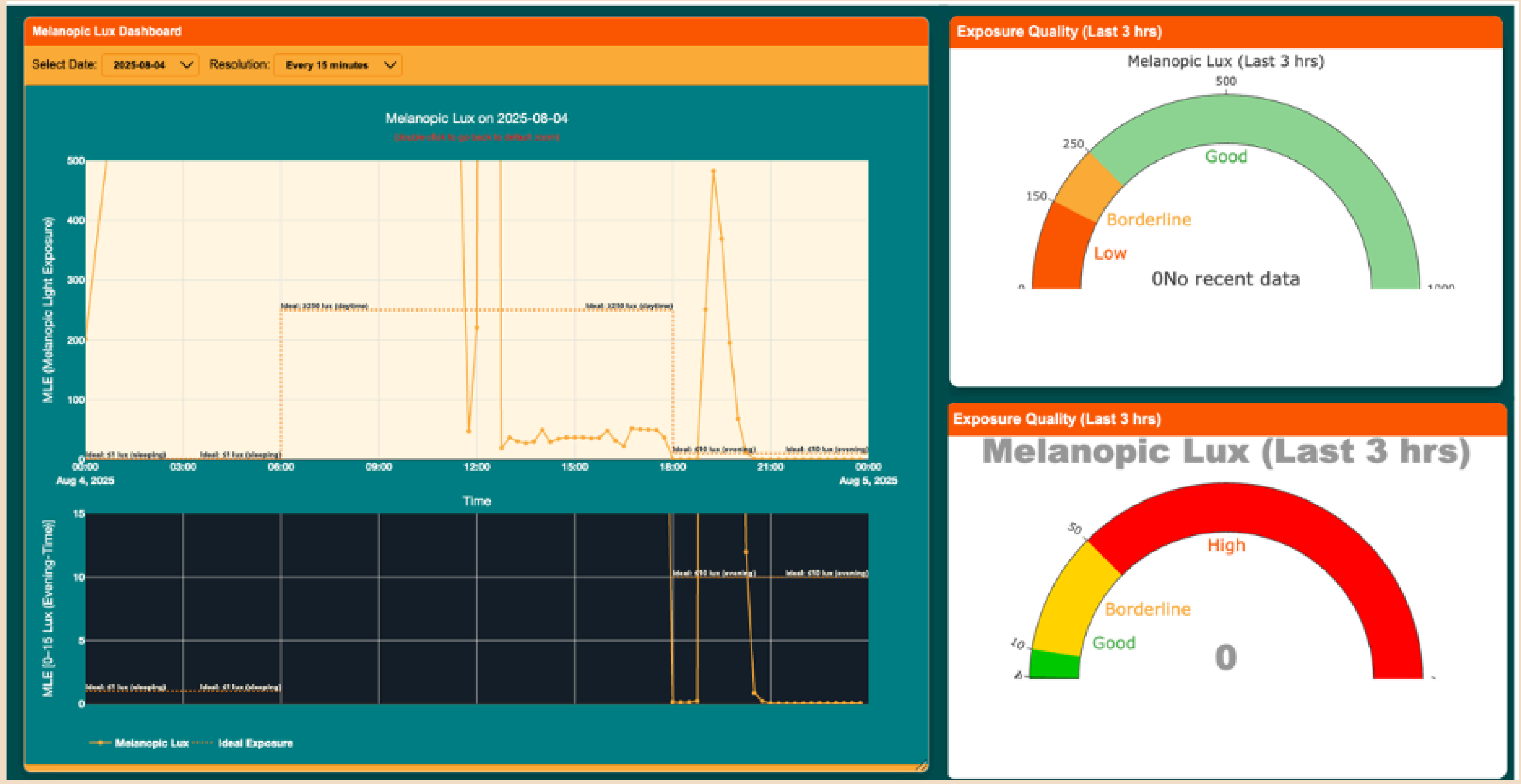
Intervention System (LuxRest Platform)

Dashboard: A web-based dashboard is created on GitHub. Participants view previous 3h exposure scores and historical daily trends.
Chatbot/Notifications: Automated personalized feedback delivered instantly (with up to 15 seconds latency) when prompted by participants in the Chatbot. The AI chatbot can answer any general or user-specific questions based on a pre-established source created from scientific consensus.
Visual cues: Traffic-light gauge (green = optimal, yellow/red = adjust light).

Feedback mechanism:
Data compared against thresholds (≥3 h ≥250 melanopic EDI daytime, <10 melanopic EDI evening, <1 melanopic EDI night).
Instant feedback: “Increase morning light” or “Reduce evening exposure.” through the gauge.

User experience:
Simple, low-burden interface.
Encourages proactive adjustments in daily light behaviors.





Surveys and Measures

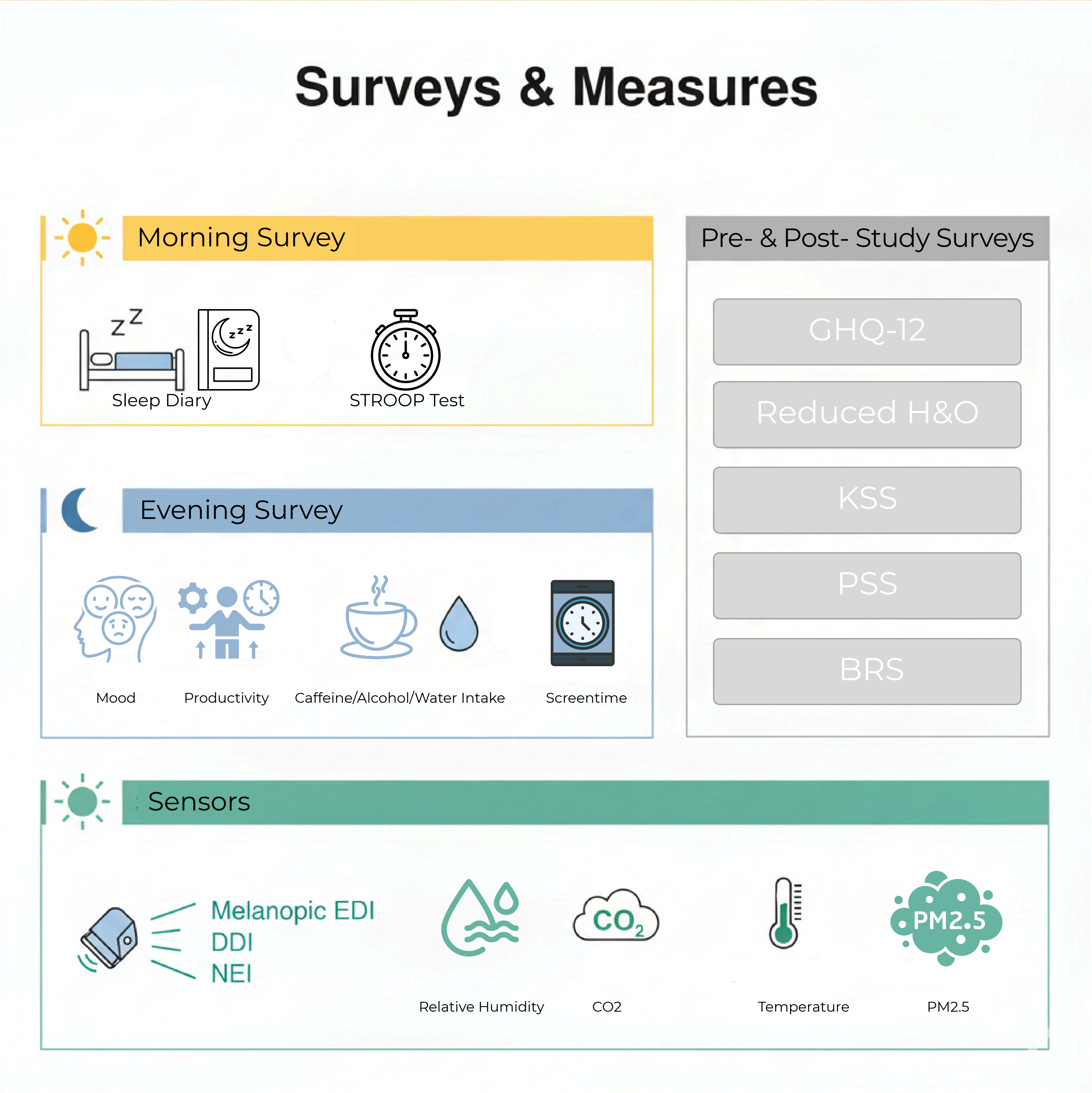
Morning survey
Sleep diary (bedtime, wake time, sleep duration, perceived quality).
Stroop test (reaction time, accuracy → cognitive performance).

Evening survey
Mood ratings (daily affect, stress).
Productivity and presenteeism/absenteeism items.
Lifestyle factors: hydration, caffeine, alcohol, and screentime.

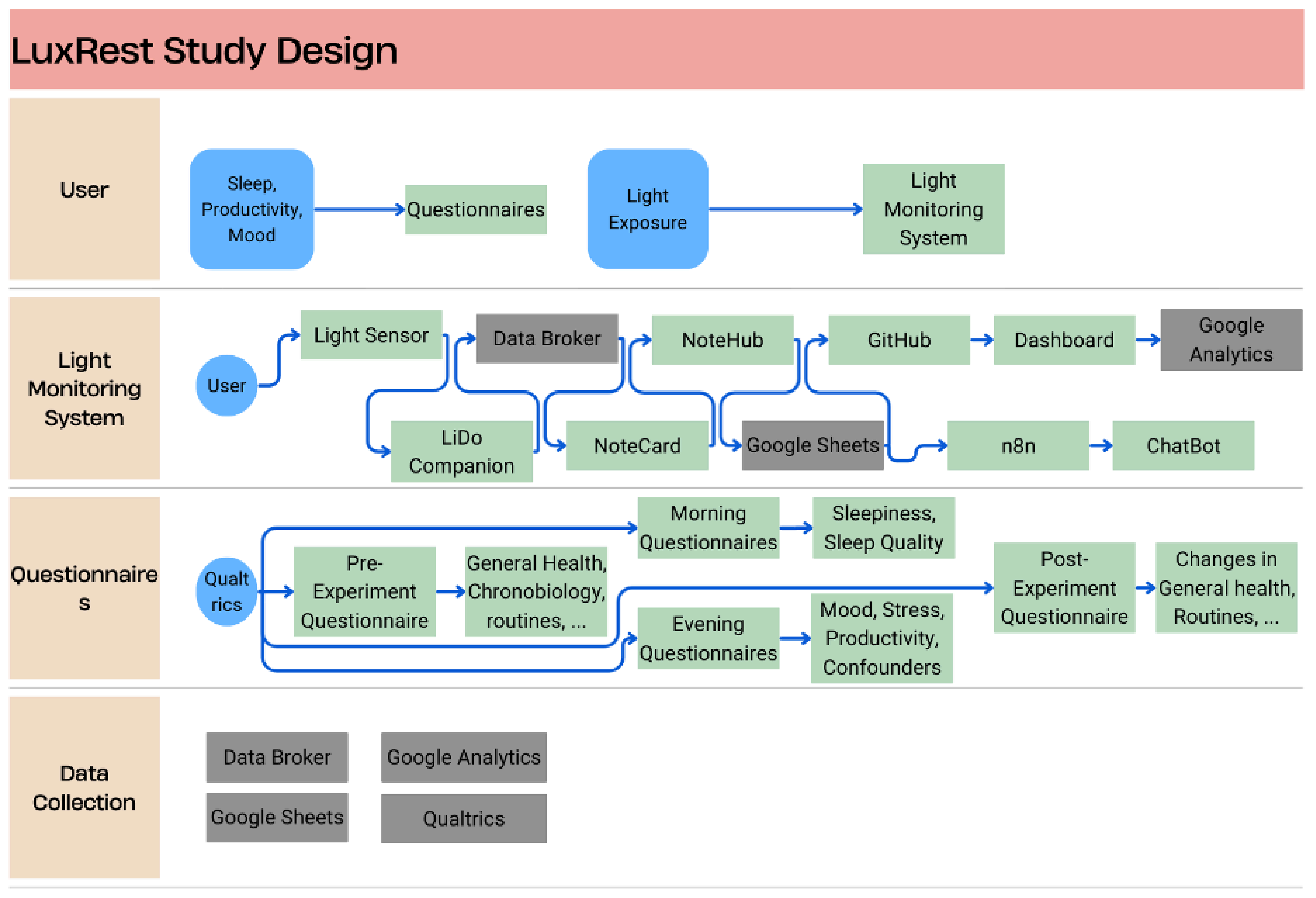
Pre- and Post-study questionnaires
GHQ-12 (general mental health).
Reduced Horne & Östberg (chronotype). (pre-study only)
Karolinska Sleepiness Scale (sleepiness).
Brief Resilience Scale and Perceived Stress Scale.

Sensor-derived measures
Light exposure (melanopic EDI, DDI, NEI, binning by wake/bedtime)

Environmental variables:
CO_2, temperature, humidity, and PM2.5



Study Design



Collected Data

Variable	Source	Type	Description	Units
Timestamp	Sensor	Continuous	Wall-clock time of measurement	datetime
Participant ID	Sensor	Identifier	Unique Participant Identifier	-
Illuminance_Melanopic, Illuminance_L-Cone, Illuminance_M-Cone, Illuminance_Rhodopic, Illuminance_S-Cone	Sensor	Continuous	α-opic equivalent daylight (D65) illuminance (Ev D ,α 65) according to CIE S 026/E:2018	lux
Irradiance_LC_D65, Irradiance_MC_D65, Irradiance_RH_D65, Irradiance_SC_D65	Sensor	Continuous	α-opic irradiance (Eα) according to CIE S 026/E:2018	W/m2
CCT	Sensor	Continuous	correlated color temperature	Kelvin
DUV	Sensor	Continuous	Distance to Planckian locus (chromaticity deviation)	unitless
Temperature	Sensor	Continuous	Sensor Temperature	Degree Celsius
WearFlag	Sensor	Binary	Detected wear vs non-wear	0/1
WakeTime_reported	Survey	Time	Participant self-reported wake-up time	HH:MM
BedTime_reported	Survey	Time	Participant self-reported attempted bedtime	HH:MM
SleepDuration	Survey	Continuous	Reported total sleep duration previous night	hours
SleepQuality	Survey	Ordinal	Reported sleep quality	1-10 scale
StroopAvgRT	Survey	Continuous	Stroop test mean reaction time	ms
StroopAccuracy	Survey	Proportion	Stroop test accuracy	% correct
Stress	Survey	Ordinal	EMA self-reported stress	Likert scale
Productivity	Survey	Ordinal	EMA self-reported productivity	Likert scale
Alertness	Survey	Ordinal	EMA alertness/energy level	Likert scale
Mood	Survey	Ordinal	EMA mood rating	Likert scale
Hydration	Survey	Continuous	Self-reported hydration	cups
Caffeine	Survey	Continuous	Caffeine consumption	mg or binary
Alcohol	Survey	Continuous	Alcohol consumption	drinks or binary
ScreenTimeEvening	Survey	Continuous	Evening screen time	minutes
Karolinska Sleepiness Scale	Survey	Ordinal	Standard KSS sleepiness score	1-9 Likert scale
Sensor Wear Time (self-reported)	Survey	Time	Reported sensor wear time	HH:MM
Time outdoor (self-reported)	Survey	Time	Reported outdoor time	HH:MM
Chronotype	Survey	Categorical	Self-reported chronotype (morning/evening)	categorical

Dependent Variables & Models

Primary Outcomes
Sleep Duration
Linear mixed-effects model (LMM, identity link).

$$\mathrm{SleepDuration}_{ij} = \beta_0 + \beta_1(\mathrm{Intervention}_{ij}) + \beta_2(\mathrm{Daytime\ mEDI}_{ij}) + \beta_3(\mathrm{Evening\ mEDI}_{ij}) + u_{0j} + \varepsilon_{ij}$$

Log-LMM used if residuals are skewed; coefficients interpreted as percentage change.

i = day (within participant)
j = participant

$\beta_0 = fixedintercept$

$\beta_{1..3} = fixedeffects(intervention + exposures)$

$u_{0j} = randominterceptforparticipantj$

$\varepsilon_{ij} = residualerror$

Sleep Quality
Cumulative logit mixed model (CLMM).
If proportional odds assumption fails → fallback to LMM.

Mood
Linear mixed-effects model.

Productivity
Linear mixed-effects model.

Model Features
- Random intercepts for participants; random slopes tested for intervention/time if justified.
- Fixed effects: intervention (baseline vs feedback), light exposure variables (melanopic EDI, DDI, NEI).
- Interaction terms: tested to evaluate whether intervention moderates the relationship between light exposure and outcomes.

Data preparation

Assumption Checks

- Normality of residuals (QQ-plots, Shapiro-Wilk).
- Linearity (predictors vs outcome).
- Homoscedasticity (residuals vs fitted values).
- Multicollinearity (Variance Inflation Factor, VIF).
- Proportional odds assumption for sleep quality (CLMM).

Derived Light Variables

- Time-binned melanopic EDI: wake → bedtime-3h; bedtime-3h → bedtime; bedtime → wake.
- Disruption indices: DDI (Daylight Deficit Index) and NEI (Nocturnal Excess Index).
- Adherence thresholds: ≥3 h ≥250 melanopic EDI daytime, <10 melanopic EDI 3h before bedtime, <1 melanopic EDI during sleep.

Adjustors & Confounders

- Environmental factors: CO_2, temperature, and humidity.
- Behavioral: caffeine, alcohol, hydration, screen time, stress.
- Chronobiological: chronotype (rH&O), social jetlag, sleep regularity.
- Engagement measures: dashboard visits and chatbot insights (Possibly Moderator).

Random Effects Candidates

- Random intercepts: Participant ID (accounts for within-subject correlation).
- Random slopes:
  - Time (study day) → individual trajectories.
  - Intervention → heterogeneity of response to feedback.
  - Light exposure bins (melanopic EDI, DDI, NEI) → variability in sensitivity to light across participants.

Assumptions

- normality
- residuals
- proportional odds

Confounders

- environmental
- behavioral
- chronobiological
- engagement

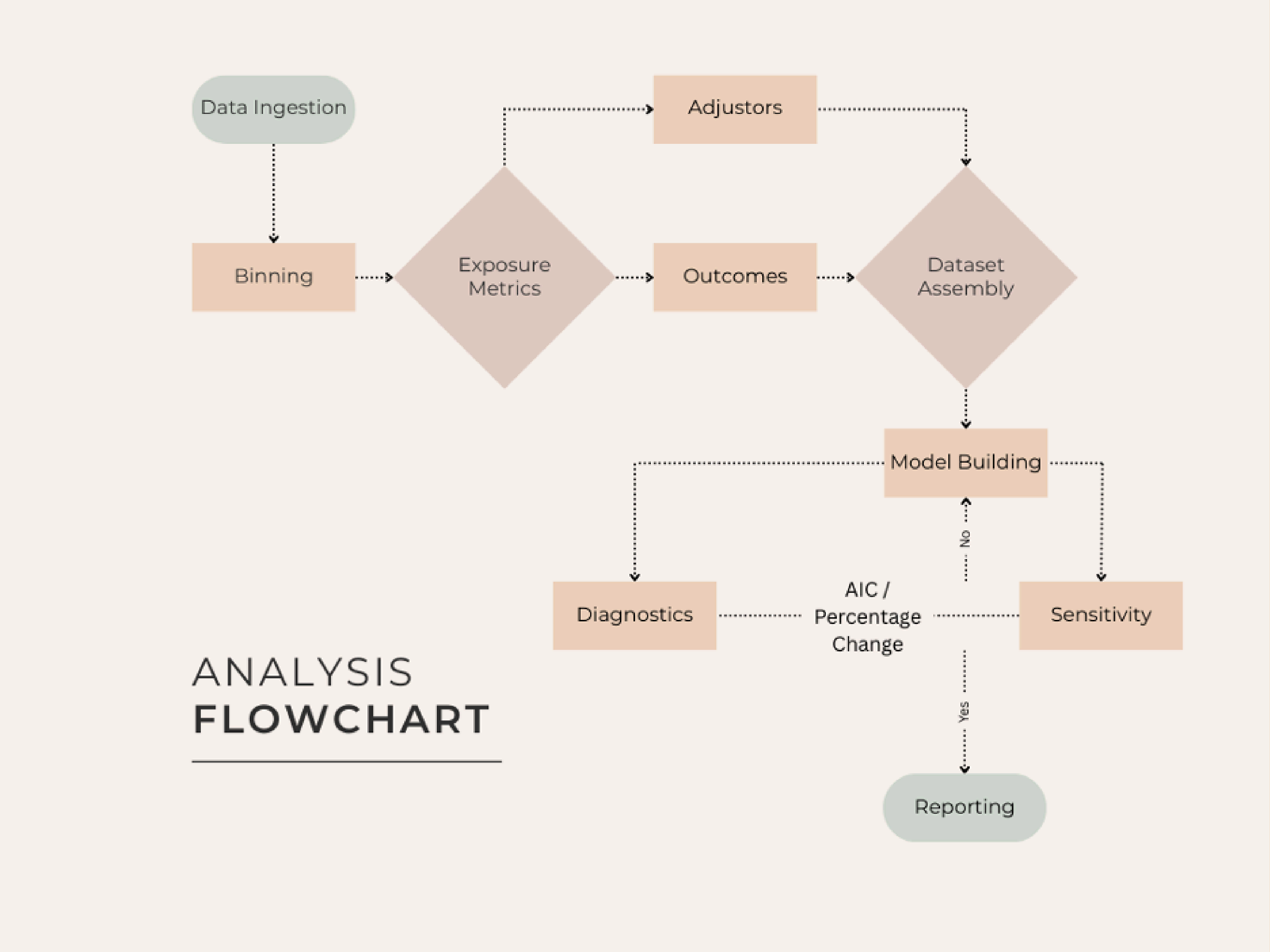
Random effects

- Time
- Intervention
- Light Exposure Bins (mEDI, DDI, NEI)

Stepwise Model-Building Path

Stepwise Model-Building Path

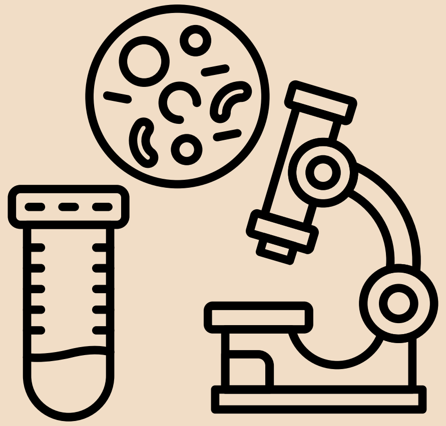
1. Baseline model: random intercept for participant.
2. + Light exposure variables: melanopic EDI (binned), DDI, NEI.
3. + Intervention: baseline vs feedback week.
4. + Behavioral & environmental covariates: caffeine, stress, CO_2, etc.
5. + Interaction terms: Intervention × Light exposure.
6. + Random slopes: time, intervention, light exposure bins (tested if justified).



Model Evaluation

- Likelihood Ratio Tests (nested models): check if added predictors significantly improve fit.
- AIC comparison: evaluate model precision and penalize overfitting.
- Percentage change in coefficients: quantify how covariate adjustment alters intervention effect estimates.
- Sensitivity analysis: exclude outliers, incomplete data days, or extreme wear-time non-adherence.

Expected Contributions



Scientific Contributions

- Demonstrates feasibility of real-time personalized circadian light feedback.
- Provides pilot evidence linking corneal-plane melanopic exposure (melanopic EDI) to sleep, mood, and productivity.
- Validates integration of disruption indices (DDI, NEI) into behavioral intervention research.

Methodological Contributions

- Combines sensor-based light measures with ecological momentary assessments (EMA).
- Applies advanced mixed-effects modeling with time-binned melanopic EDI and disruption metrics.
- Framework for combining subjective and objective measures in a crossover design.

Practical Contributions

- Prototype LuxRest platform integrating hardware, backend, and user feedback.
- Provides groundwork for larger real-world trials, especially in irregular light environments such as Space or Submarine environments.
- Potential to inform standards for light-based interventions in everyday settings.

Limitations and Challenges

Study Design

- Pilot framing: short 2-week crossover limits long-term inference.
- The small sample size may restrict statistical power.
- Participants act as their own control, but order effects cannot be excluded.
- Not measuring circadian rhythm objectively (actiwatches, saliva melatonin tests,...)

Data Quality

- Incomplete wear-time for sensors → coverage weighting or exclusions required.
- Self-reported surveys are subject to recall or compliance bias.
- Missing data may reduce the robustness of some outcome measures.

Technical

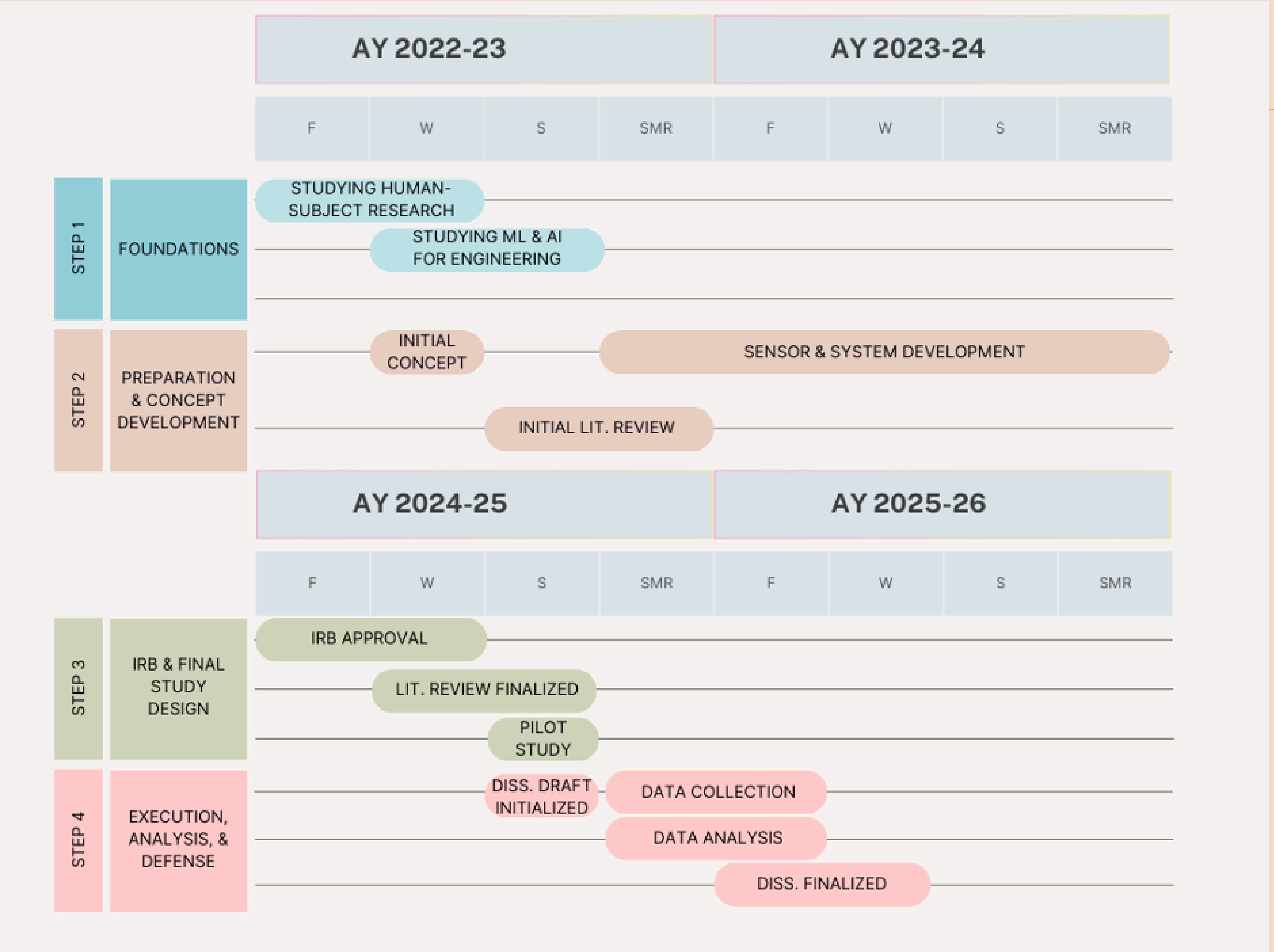
- Hardware is still in the prototype stage. Might cause difficulty wearing in public.
- LiDo sensors have a minimum lux limitation of 5 lux, which makes them less reliant for capturing night-time circadian light data.
- The feedback pipeline may have latency or user interface issues.
- The integration of multiple data streams (sensors, surveys, chatbots) poses complexity.

Analytical

- Mixed-effects models are sensitive to missingness and assumption violations.
- Potential difficulty in distinguishing direct light effects from behavioral confounders.
- Engagement variables complicate interpretation as moderators vs mediators.

Timeline

Deliverables:
1. Framework/Review Paper November 2025
2. Method and Results Paper February 2026
3. Dissertation April 2026



Ethics & Compliance

IRB Approval: Protocol reviewed and approved by Drexel University IRB.

Informed Consent: Participants provide verbal consent before enrollment.

Eligibility Criteria:
- Adults 18–65 years, enrolled students or staff at Drexel University.
- Exclude if diagnosed with major sleep disorders, severe psychiatric illness, or using light-based therapy.

Data Privacy & Security:
- De-identified datasets with participant codes.
- Secure cloud storage (HIPAA-compliant).
- Access restricted to research team only.

Questions

Thank you!

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Sensitivity Analysis

Data completeness:
Exclude days with <50% wear time.
Weight days with partial data by wear-time coverage.

Outlier handling:
Identify extreme melanopic EDI values (beyond ±3 SD).
Test models with and without outliers.

Adherence checks:
Compare participants with high vs low survey completion rates.
Assess whether intervention effects hold when restricted to adherent participants.

Alternative specifications:
Compare models using raw vs log-transformed variables.
Run analyses with and without random slopes to test stability.

Robustness across subgroups:
Chronotype groups (morning vs evening).
Season of data collection.

Circadian Light Metrics and Standards

Model/Function	Meaning	Peak λ (nm)	Basis/Derivation	Formula (compact)	Primary Source
Photopic V(λ)	Visual brightness sensitivity (cones)	555	Empirical luminous efficiency	$E_v = 683 \int SPD(\lambda)V(\lambda)\,d\lambda$	CIE 1931
Scotopic V′(λ)	Rod-mediated sensitivity	507	Empirical scotopic efficiency	$E_s = 1700 \int SPD(\lambda)V\prime(\lambda)\,d\lambda$	CIE 1951
CIE S 026 Melanopic (V_mel(λ))	ipRGC/melanopsin spectral sensitivity	≈480	α-opic sensitivity, standardized	$E_{mel} = \int SPD(\lambda)\,\bar{a}mel(\lambda)\,d\lambda;\ mEDI = Emel/k_{mel,D65}$	CIE S 026 (2018)
CIE S 026 S-cone	Short-wavelength cone	≈420	α-opic sensitivity	$E_S = \int SPD(\lambda)\,\bar{a}_S(\lambda)\,d\lambda$	CIE S 026 (2018)
CIE S 026 M-cone	Middle-wavelength cone	≈534	α-opic sensitivity	$E_M = \int SPD(\lambda)\,\bar{a}_M(\lambda)\,d\lambda$	CIE S 026 (2018)
CIE S 026 L-cone	Long-wavelength cone	≈564	α-opic sensitivity	$E_L = \int SPD(\lambda)\,\bar{a}_L(\lambda)\,d\lambda$	CIE S 026 (2018)
CIE S 026 Rod	Rod sensitivity	≈498	α-opic sensitivity	$E_{Rod} = \int SPD(\lambda)\,\bar{a}_{Rod}(\lambda)\,d\lambda$	CIE S 026 (2018)
EML (Lucas 2014)	Equivalent melanopic lux	≈480–490	Melanopsin-weighted lux, pre-CIE	$EML = \int SPD(\lambda)\,V_{mel,Lucas}(\lambda)\,d\lambda/k_{mel,Lucas,D65}$	Lucas et al. 2014
CLA (Rea 2005)	Circadian Light (weighted mixture)	blue-weighted	Weighted cone/rod/mel inputs	$CLA = \int SPD(\lambda)\,W_{CLA}(\lambda)\,d\lambda$	Rea et al. 2005
CS (Rea 2010)	Circadian Stimulus (melatonin suppression estimate)	–	Nonlinear mapping from CLA	$CS = f(CLA)(saturating 0–0.7)$	Rea et al. 2010
Circadian Potency (Moore-Ede)	Asymmetric, 12-h exposure fit	477	Piecewise Gaussian	$P(\lambda) = e^{-(\lambda-\mu)^2/(2\sigma_L^2)}, \lambda \le \mu;\ e^{-(\lambda-\mu)^2/(2\sigma_R^2)}, \lambda > \mu$	Moore-Ede et al. 2021