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Effects of light exposure on vagally-mediated heart rate variability: A systematic review

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ABSTRACT

Background: Light therapy is increasingly used to address disorders such as depression, anxiety, sleep disturbances, and seasonal affective disorder. Autonomic dysfunction, common in these conditions, may be modulated by light through its effects on cardiac vagal activity, indexed by vagally-mediated heart rate variability (vmHRV).
Objective: This systematic review synthesized evidence on the effects of ocular exposure to visible light (illuminance and color) on vmHRV in healthy and clinical populations.
Method: Following PRISMA guidelines, an electronic search of MEDLINE (via PubMed), Web of Science, Cochrane, and ProQuest was conducted in June 2024. Using the PICOS criteria, 24,673 records were screened, with 25 studies included. Risk of bias was assessed with the Cochrane Risk of Bias 2 tool.
Results: All included studies were rated as high risk of bias. High-illuminance blue light was generally associated with reduced vmHRV, likely due to its arousal-promoting effects. Conversely, lower-illuminance warm-colored light (e.g., red or dim white light) showed potential to increase vmHRV, indicating a calming effect. However, findings were inconsistent due to methodological heterogeneity, including variability in populations, exposure protocols, and control conditions.
Conclusion: While ocular light exposure shows promise for modulating vmHRV, the high risk of bias and variability across studies limit clinical application. Future research should adopt standardized protocols, account for confounding variables, and explore long-term interventions to better evaluate light's therapeutic potential for autonomic regulation.

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1. Introduction

1.1. The influence of light on autonomic function: implications for cardiac vagal activity

Light is an essential part of human life, influencing not only vision but also the endocrine system and regulating the endogenous circadian rhythm. Due to its impact on mental and physical states, light exposure can be purposefully used as an ergogenic aid (Cajochen et a106241l., 2005; Chellappa et al., 2011; Choi et al., 2011; Daneault et al., 2014). In clinical settings, light has been proposed to alleviate symptoms associated with various disorders, including depression (e.g., Martensson et al., 2015), anxiety (Baxendale et al., 2013), seasonal affective disorders (e.g., Strong et al., 2009), and insomnia (e.g., van Maanen et al., 2016). A common underlying factor in these conditions is autonomic dysfunction, often marked by reduced cardiac vagal activity (CVA). CVA can be assessed non-invasively through heart rate variability (HRV) measurements, specifically focusing on vagally-mediated heart rate variability (vmHRV) (Berntson et al., 1997; Malik, 1996). Previous research suggests that light exposure can influence vmHRV (Oldham and Ciraulo, 2014), with potential implications for emotional stability in individuals with mood disorders (Rechlin et al., 1995) and the regulation of rest-activity cycles through circadian synchronization (Ono et al., 2011). However, findings remain inconsistent, and no systematic review has yet synthesized this evidence. Therefore, a comprehensive overview of the association between ocular exposure to visible light (OEVL) and vmHRV is needed to clarify this relationship and its potential applications. Given the widespread use of light-based interventions, vmHRV may serve as a promising biomarker for assessing the autonomic effects of light exposure. A clearer understanding of how light modulates vmHRV could aid in standardizing study designs and refining light therapy protocols to enhance autonomic function. Accordingly, the present systematic review aims to synthesize existing evidence on the relationship between OEVL and vmHRV, providing insights into its physiological relevance and potential clinical implications.

HRV refers to the variation in the time intervals between successive heartbeats (Berntson et al., 1997; Laborde et al., 2017; Malik, 1996; Quigley et al., 2024). Various HRV parameters can be computed, which predominantly reflect the combined influence of the sympathetic and parasympathetic nervous systems, as well as other physiological systems, to cardiac functioning. Importantly, certain HRV parameters uniquely reflect the parasympathetic nervous system's contribution to cardiac functioning via the vagus nerve, thereby indexing CVA (i.e., vmHRV) (Berntson et al., 1997; Laborde et al., 2017; Malik, 1996). This review focuses on two key indexes: the root mean square of the successive differences (RMSSD) in the time-domain, and high-frequency HRV (HF-HRV) in the frequency-domain, when the breathing frequency is comprised between 9 and 24 cycles per minute (Berntson et al., 1997; Laborde et al., 2017).

1.2. The importance of vmHRV in clinical contexts

From a theoretical standpoint, focusing on vmHRV is crucial for understanding its connection with self-regulation processes in clinical settings (Heiss et al., 2021). Specifically, vmHRV is considered an outcome of the central autonomic network (Benarroch, 1997) and is thought to reflect the efficiency of self-regulatory mechanisms (Smith et al., 2017; Thayer et al., 2009). In clinical contexts, lower resting vmHRV has been associated with various psychiatric disorders, including depression and anxiety (Friedman, 2007; Hartmann et al., 2018; Heiss et al., 2021; Jung et al., 2019), making it a potential target for intervention. Notably, light has been proposed as a possible factor that could positively influence vmHRV, with bright light therapy emerging as a promising non-invasive approach to stimulate the vagus nerve (Oldham and Ciraulo, 2014). A systematic analysis of the light exposure-vmHRV connection could therefore strengthen light therapy as a valuable approach for clinical treatment targeting autonomic function, either as a standalone option or in combination with existing pharmacological and psychiatric interventions.

1.3. Key light parameters: illuminance and color

The primary parameters through which light is proposed to influence the parasympathetic nervous system are illuminance and color (Chellappa et al., 2017; Rossing and Chiaverina, 2019). Illuminance (sometimes referred to as brightness, luminance, or luminescence) describes the intensity of visible light, and is measured in lux, which is equal to one lumen per square meter. Illuminance is perceived by an individual as brightness ranging from dark to bright (Rossing and Chiaverina, 2019). Color (also sometimes referred to as hue) is typically defined by wavelength and occasionally by temperature (Canazei et al., 2017; Hayano et al., 2021; Kakitsuba, 2020). Color defined by wavelength refers to the spectral radiation distribution, the distance between successive wavelength crests measured in nanometers. The visible light spectrum ranges from about 400 nm to 750 nm, with each wavelength representing a different color (Rossing and Chiaverina, 2019). Monochromatic light is defined as having one wavelength only. However, as this is not possible in practice, light of monochromatic appearance always consists of a narrow bandwidth of wavelengths. It is therefore referred to as quasi-monochromatic light (Rossing and Chiaverina, 2019). Another way to refer to color is light's temperature. Temperature refers to a light sources' visible appearance measured in Kelvin (K; the unit of thermodynamic temperature). It is used to measure the color temperature of a light bulb. The higher the K rating, the shorter the light's wavelength, and the bluer (colder) the light will be (Rossing and Chiaverina, 2019).

1.4. Visual and non-visual pathways of light processing

Light can have both visual and non-visual effects. Visual effects are related to the processing of incident light by photoreceptor cells in the retina, cones, and rods (Curcio et al., 1990). The differential responsivity of the cones serves to quantify the color based on wavelength. Cones with sensitivity around 560 nm are sensitive to red, 530 nm to green, and 420 nm to blue (Gazzaniga et al., 2019). From these photoreceptors, the signals follow a path via the optic nerve up to the visual cortex passing by the lateral geniculate nucleus (Gazzaniga et al., 2019). The visual phototopic system, based on the functioning of rods and cones, does not seem to be the primary photoreceptor system mediating cardiovascular responses to light colors, as evidenced by studies involving different forms of visual blindness (Brainard et al., 2001; Lockley et al., 2006). Non-visual effects (i.e., absent image formatting) are related to different types of photoreceptors, specifically the intrinsically photosensitive retinal ganglion cells (ipRGCs) (Liu et al., 2023; Zaidi et al., 2007). These melanopsin-based photoreceptors detect environmental irradiance, contributing to perception of different levels of illuminance (Liu et al., 2023; Wong, 2012), and exhibit maximal sensitivity to short wavelength light (blue), with a peak sensitivity around 480 nm (Berson, 2003; Lockley et al., 2003).

IpRGCs are thought to have a central role in regulating processes related to circadian rhythm, sleep, and psychological states (Hattar et al., 2002; Hubbard et al., 2013; LeGates et al., 2014; Schmoll et al., 2011). In particular, ipRGCs might impact parasympathetic output to the heart via the retino-hypothalamic tract. This pathway goes from the retina to the suprachiasmatic nuclei (SCN), then to pre-autonomic neurons within the hypothalamus (specifically, the paraventricular nucleus of the hypothalamus), and finally projects onto the dorsal motor nucleus of the vagus nerve in the medulla. This pathway regulates parasympathetic output to the heart (Chellappa et al., 2017; Kalsbeek et al., 2011; Scheer et al., 2003, 2001). Another (SCN independent) pathway is through the effects of light modulating the homeostatic process of sleep, alertness, and emotion regulation (Maruani and

Geoffroy, 2022). Thus, preliminary findings indicate that light can contribute to influencing CVA. However, the role of specific light parameters (i.e., illuminance and color) remains unclear.

1.5. Rationale for the systematic review

In short, the autonomic nervous system, and the parasympathetic nervous system in particular, is central to maintaining health and managing disease (Sleight, 1997). There is evidence of a potential relationship between light and the parasympathetic nervous system (Chellappa et al., 2017), but a comprehensive review of how different light parameters, such as illuminance and color, impact vmHRV has not been undertaken. This limits our mechanistic understanding of the interplay between OEVL and autonomic function. Therefore, this systematic review aims to synthesize the existing evidence-base regarding the influence of light exposure on vmHRV (specifically RMSSD and HF-HRV). A review of this nature could have implications for treatment of healthy and clinical populations, and provide a foundation for future clinical practice and research into the utility of light therapy in treating disorders associated with autonomic dysfunction.

2. Method

2.1. Systematic review

This systematic review is reported using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses, PRISMA (Page et al., 2021). The PRISMA flow diagram can be found in Fig. 1, and the PRISMA checklist in the online supplementary file. The PICOS criteria (Population, Intervention, Comparator, Outcomes, and Study design) were followed for study selection and can also be found in the online supplementary file (Shamseer et al., 2015).

2.2. Eligibility criteria

Eligible studies were selected using the following PICOS criteria (see Table 1). Only studies in English and published or pre-registered for publication in peer-reviewed scientific journals were eligible for inclusion. No restrictions were made regarding the year of publication.

Table 1
PICOS criteria.

Criteria	Inclusion criteria	Exclusion criteria
Participants	Human beings (any health condition, age range, or gender)	Animal studies
Intervention	Empirical studies examining the acute effects of ocular light exposure on vmHRV (i.e., RMSSD and HF-HRV), either during light exposure, or right after light exposure; as well as the chronic effects following a multi-sessions intervention	Studies involving concomitant tasks (e.g. cognitive or emotional)
Comparator	No-light control condition (darkness), white light control condition, or comparison between two specified light conditions	
Outcomes	vmHRV (i.e., RMSSD and/or HF-HRV)	
Study design	Controlled mixed or within-subjects design	Non-peer-reviewed, no complete methods section, published abstracts, single-case studies, case series, no specification of light source (i.e. light parameters) or vmHRV (i.e. HF-HRV or RMSSD)

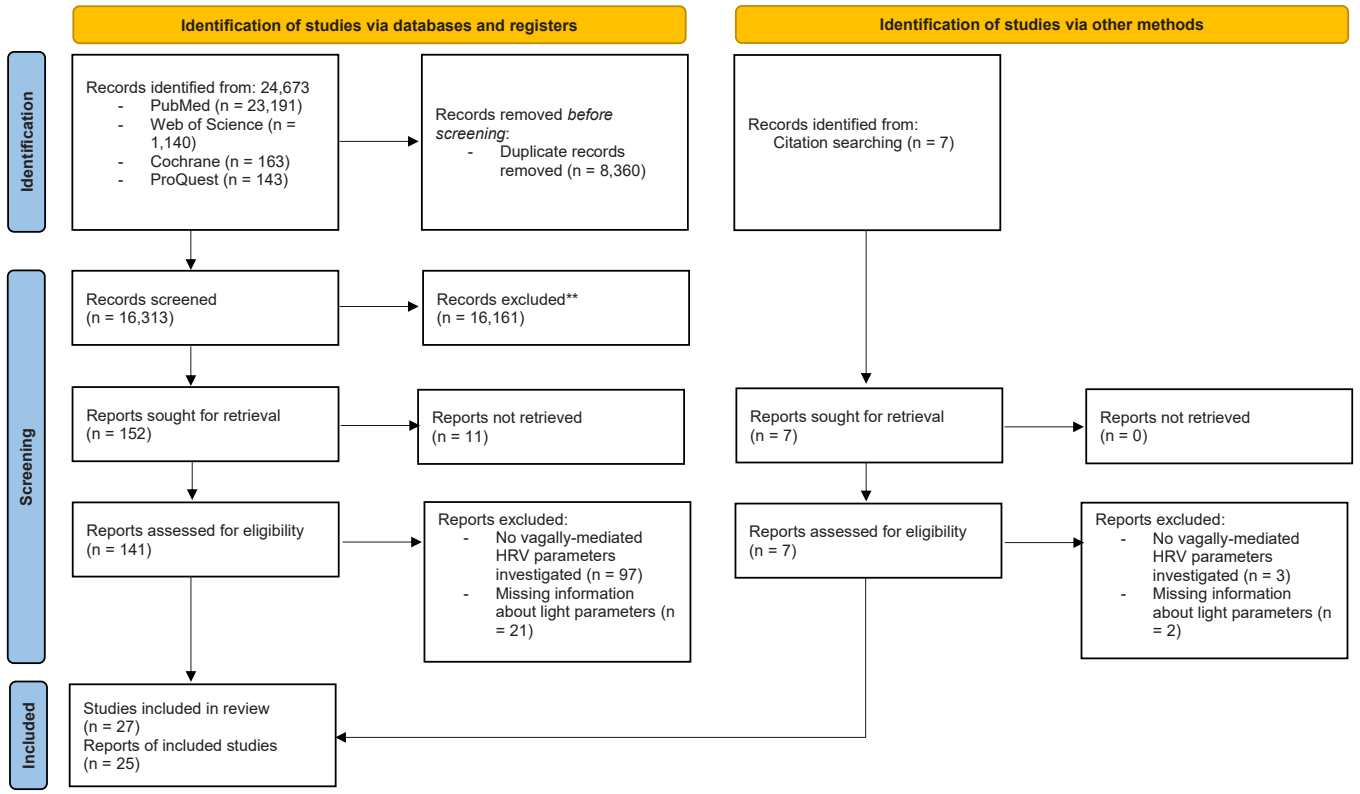

Fig. 1. PRISMA flow diagram.

2.3. Search strategy

A systematic search of databases was conducted using MEDLINE (via PubMed), Web of Science, Cochrane, and ProQuest. The search was conducted on June 7th, 2024. The search terms used were: (light OR illumination OR wavelength) AND (HRV OR "heart rate variability" OR parasympathetic OR vagal OR vagus OR RMSSD OR HF OR "high-frequency"). The terms "heart rate variability", "vagal", "RMSSD", "HF" and "high-frequency" were the concepts listed as MeSH terms.

2.4. Data management and selection process

All search results were extracted from the databases and imported into Zotero (Centre for History and New Media, 2009) for data management. The initial search yielded a total of 24,673 studies across the four databases (PubMed: 23,191; Web of Science: 1140; Cochrane: 163; ProQuest: 143). After the removal of duplicates, 16,313 unique studies remained.

The study selection process was conducted in two stages by two independent reviewers. First, titles and abstracts were screened together for relevance based on the predefined eligibility criteria, resulting in the exclusion of 16,161 studies. In the second stage, the full texts of the remaining studies were reviewed, leading to the exclusion of 118 studies that did not meet the inclusion criteria.

After the full-text screening, 23 studies were deemed eligible for inclusion. A backward and forward citation search of these remaining studies was then performed, leading to the identification of two additional relevant studies. Collectively, these studies comprised 27 experiments, as two studies reported two separate experiments. All included studies investigated the short-term effects of ocular light exposure on vmHRV.

2.5. Data extraction

The authors developed a data extraction sheet to record information related to the defined PICOS criteria, as well as information related to the following light parameters: illuminance and color (defined by wavelength or temperature). For each study, the following characteristics were extracted: year of publication, sample size, sample characteristics (healthy vs. unhealthy; age; gender); type of intervention with light characteristics (i.e., illuminance and color); study design (within- vs. between-subject design).

Two independent reviewers (VM & PL) assessed the risk of bias for each included study using the revised Cochrane Risk of Bias tool (RoB 2) for randomized trials (Sterne et al., 2019). The tool evaluates five domains: bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in the measurement of the outcome, and bias in the selection of reported results. Each study was categorized as having a low risk, some concerns, or high risk of bias based on the highest level of concern observed across domains.

3. Results

3.1. Study characteristics

The systematic review includes 25 studies exploring the effects of OEVL on vmHRV, with specific attention to light parameters such as illuminance and color. Study characteristics, including participant demographics and vmHRV outcomes, are summarized in Table 2. Most studies employed a within-subject design (n = 24), while only one utilized a between-subject design. Control conditions across studies varied widely, from complete darkness to neutral white light or dim light, reflecting the methodological diversity in this area. This heterogeneity, particularly in control conditions and exposure parameters, restricts the potential for a meta-analysis and complicates direct comparisons across studies, as discussed in further sections.

3.2. Participant characteristics

Across the 25 studies, a total of 669 participants were assessed, with an average age of 33.7 years (ranging from 18 to 84 years). The majority of studies (n = 20) focused on healthy participants, while five studies involved clinical or symptomatic populations. Notably, three studies included individuals with symptoms of anxiety (Sergeeva et al., 2023), depressive tendencies (Zhou et al., 2024), or a combination of both (Choi et al., 2011). In more clinical populations, one study investigated vmHRV responses in patients with major depression (Rechlin et al., 1995), and another studied patients post-oesophagectomy to assess circadian and autonomic regulation (Ono et al., 2011). The gender distribution slightly favored females (54 %), and most studies were conducted in controlled laboratory environments, predominantly in Asian countries, with nine studies conducted in Japan.

3.3. Risk of bias

Each study was evaluated for risk of bias, with all studies rated as having a high risk primarily due to limitations in blinding and issues with incomplete outcome data. Inter-rater reliability, measured using Cohen's kappa, demonstrated substantial agreement among reviewers ($\kappa = 0.86$). Discrepancies in assessment were resolved through discussion, and a third reviewer was consulted in cases where consensus could not be reached. Table 3 provides a detailed breakdown of the risk assessments for each study, highlighting areas where improvements in methodological rigor are needed to support more robust conclusions in future research.

3.4. Studies overview

The main findings from the reviewed studies are presented in Table 4, organized by light parameters (illuminance and color) and categorized into positive, neutral, or negative effects on vmHRV. Although findings across studies were mixed, certain patterns emerged, suggesting that the effects of OEVL on vmHRV may depend on the intensity, color, and individual characteristics of participants. High-illuminance blue light frequently corresponded with reductions in vmHRV, possibly due to its stimulating effects on alertness and circadian regulation. Conversely, lower-intensity blue or warm-colored light, including red and dim white light, more consistently supported increased vmHRV, hinting at a calming effect under specific conditions. However, these findings are tempered by inconsistencies, with many studies reporting non-significant changes in vmHRV, underscoring the complex and context-dependent nature of OEVL impact on autonomic functioning.

4. Discussion

This systematic review synthesized empirical research examining how OEVL parameters, specifically illuminance and color, affect vmHRV as measured by RMSSD and HF-HRV. While some studies provided evidence that OEVL can influence vmHRV, findings were highly variable, with many studies reporting null results. Despite this heterogeneity, certain trends appeared across subsets of studies; high illuminance, especially in blue light, often corresponded with reduced vmHRV, while lower illuminance in warm or blue-depleted light sometimes supported increases in vmHRV. However, these trends were inconsistently observed, with many studies reporting non-significant effects, underscoring a complex, context-dependent relationship between light exposure and vmHRV, as well as potential methodological limitations. These inconsistencies suggest that the impact of OEVL on vmHRV may depend on individual factors (e.g., age, psychological conditions) and contextual elements (e.g., timing and duration of exposure), warranting further

Table 2
All studies details.

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
Canazei et al. (2017)	N = 31 (healthy); 18 females; Mean age: 28.42 [19–56 years]; Austria	Testing the influence of light colours for optimising night-work	Colours compared to one another	RMSSD, HF	Within-subjects design (crossover)	Mean horizontal illuminance: 501 lx (SD = 15 lx), mean vertical illuminance: 149 lx (SD = 12 lx) at 120 cm height	High Light – Blue-enhanced (4667 K): Spectral peaks: First peak at approximately 450 nm (blue wavelength) and a second plateau peak spanning 550–600 nm. Moderate Light – moderate blue-enhanced (3366 K): Spectral peaks: Initial peak around 450 nm, with a prominent second peak near 620 nm. Low Light – Blue-depleted (2116 K): Spectral peak: Main peak centered around 620 nm	20 min	during	23:00–04:30 am	open	RMSSD was significantly higher under low light (2116 K, blue-depleted spectrum) compared to both moderate light (3366 K, blue-enhanced spectrum; effect size d = 3.48) and high light (4667 K, blue-enhanced spectrum; d = 3.44). Similarly, HF was significantly higher under low light relative to moderate light (d = 3.39) and high light conditions (d = 3.26), indicating enhanced vmHRV in lower illuminance and blue-depleted light settings.	not investigated
Choi et al. (2011)	N = 92 healthy (N = 23 with anxiety symptoms and N = 28 with depression symptoms); 36 females; Mean age: 26.4 years; South-Korea	Investigating the influence of light's colours in participants with symptoms of anxiety and depression	Darkness (0 lux)	RMSSD, lnHF	Within-subjects design	Blue: 0.04 lux / Red: 0.4 lux / White: 49.5 lux	Blue (380–495 nm, peak at 420 nm) Red (620–780 nm, peak at 765 nm White (approx. 380–750 nm)	5 min each colour	before and after	9–11 am or 14–16 pm	open	Red Light: significant decrease in both HF and RMSSD in participants with symptoms of anxiety or depression, compared to baseline ($p < .05$). White Light: significant increase in HF and RMSSD for the same symptomatic groups ($p < .05$). Blue Light: no significant changes in HF or	not investigated

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Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
												RMSSD across all participants, regardless of emotional status	
Edelhäuser et al. (2013)	N = 17 (healthy); 10 females; Mean age: 25.5 ± 6.2 years; Germany	Exposition to series of different coloured lights	Darkness (0 lux)	HF	Within-subjects design	Daylight: 30–100 lux Red light: ≈ . 50 lux Blue light: ≈ 50 lux	Red (approx. 640 nm) Blue (approx. 480 nm)	10 min each light, 50 min in total (Daylight - Red - Daylight - Blue - Daylight)	before and after	10 am−13 pm	open	HF decreased after exposure to red light (before/after difference: Before: 7.33 ln ms2 / After: 7.02 ln ms2 ($p < 0.05$)). No changes in HF were observed with blue light.	not investigated
Grote et al. (2013)	N = 16 (healthy); 7 females; Mean age: 52.1 ± 11.6 years; Austria	Investigating the influence of oscillating light's colours and white light	Not defined	HF	Within-subjects design	Oscillating between 3 lux and 42 lux	Oscillating red (600–780 nm), green (460–620 nm), blue (two peaks at 380–520 nm and at 680–780 nm)	21 min (oscillating in 10 s intervals for each colour)	Before, during, after,	8–11 am	open	HF increased after colour oscillating light exposure in comparison with white light exposure HF (Before - after) df = 4, F = 4.30, p = .004, η^2 = .22	not investigated
Hayano et al. (2021)	N = 10 (healthy); gender distribution not reported; Mean age not reported [young: 20–30 years vs. old: 65–80 years]; Japan	Comparing different light conditions in different tasks (sitting rest and psychomotor workout) in different age groups.	Darkness (0 lux)	HF, descriptive stats missing (only p values provided)	Within-subjects design	Not indicated	Condition 1 (high-low): Cold ambient light (12.000 K, peak at approx. 440–480 nm, second peak plateau at approx. 480–560 nm) and control stand light (5.000 K, peak at approx. 440–480 nm, second peak plateau at approx. 500–640 nm) Condition 2: Warm ambient light (low-low) (4.500 K, peak at approx. 440–480 nm,	5 min rest	Before, during, after	13–16:15 pm	open	Interaction effect of lighting type and age on HF HRV: HF-HRV was significantly reduced under high-intensity cold light (12,000 K) only in the elderly group (HF HRV (Before - during); $p < .001$	not investigated

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Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
							second peak plateau at approx. 600–640 nm) and control stand light (5.000 K, peak at approx. 440–480 nm, second peak plateau at approx. 500–640 nm)						
Kakitsuba (2020)	N = 16 (healthy); 8 females; Mean age not reported [20–22 years]; Japan	Investigating the differences in vmHRV between men and woman under different light conditions	Dim vs. bright light	HF	Within-subjects design	Condition 1: Dim light: 150–400 lux Bright light: 1500–5000 lux Condition 2: Dim light: 140–640 lux Bright light: 2000–5000 lux Condition 3: Dim light: 70–270 lux Bright light: 2500–7000 lux	Condition 1: 3000 K; first peak at approx. 460 nm, second peak plateau at approx. 420 nm. Condition 2: 4000 K; first peak at approx. 460 nm, second peak plateau at approx. 575–620 nm. Condition 3: 5000 K; first peak at approx. 450 nm, second peak plateau at approx. 550–610 nm.	not indicated	during	13–17 pm	open	Not investigated	No effect of light's illuminance on HF
Laufer et al. (2009)	N = 12 (healthy); gender distribution not reported; Mean 71 [66–84 years]; Hungary	Exploring the impact of different coloured lights on vmHRV	Colours compared to one another	HF	Within-subjects design	300 lux	Red (approx. 550–650 nm) Blue (approx. 400–500 nm)	8 min each colour	not reported, assume during	1–5 pm	not reported, assume open	No significant change in HF	not investigated
Luo et al. (2022)	N = 20 (healthy); 11 female; mean age 23.35 ± 2.3 years; China	The effects of different brightness of light	Dim vs. Bright light	RMSSD, HF (descriptive stat missing for HF)	Within-subject design	bright light: 1200 lux / dim light: 200 lux	6500 K	5 h	during	14–19 pm	both	not investigated	higher RMSSD under 200 lux than 1200 lux (200 lux: EMM = 49.14; SE = 6.0 VS 1200 lux: EMM = 44.24; SE = 6.01; p = .012) No significant impact on HF
Modi et al. (2019)	N = 77 (healthy); 27 females; Mean age: not reported	Exploring the effects of exposure to different light`s	Darkness (0 lux)	RMSSD, HF	Within-subjects design	not indicated	Red: 620–720 nm Blue: 455–492 nm	30 min each colour	Before, during after		Not indicated, assuming open	Colour has no effect on RMSSD HF increased after exposure to	not investigated

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Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
	[30–50 years]; India	colour (red, blue and white)					White: not indicated					white light (before/after effect, d = 0.38)	
Noguchi and Sakaguchi (1999)	N = 8 (healthy); 0 females; Mean age: 27.9 [25–30 years]; Japan	analysing the impact of different light illuminances	Two colour temperatures compared	HF, descriptive stats missing	Within-subjects design (crossover)	Condition 1: 30 lux, Condition 2: 150 lux, Condition 3: 30 lux, Condition 4: 150 lux	Condition 1: 3000 K, Condition 2: 5000 K, Condition 3: 3000 K, Condition 4: 5000 K	22 min	before and after	"afternoon time"	open	not investigated	no effect of illuminance on vmHRV (HF)
Petrowski et al., (2023)	Study 1: N = 29; healthy males; 24.6 years (SD = 4.8) Study 2: N = 24, healthy males, 24.5 years (SD = 4.8); Germany	Study 1: Comparison between dim light (< 2 lx) and bright white light (414 lx). Study 2: Comparison of red (235 lx, 635 nm), blue (201 lx, 470–480 nm), and green light (806 lx, 520 nm).	Study 1: Baseline measurements were taken in dim light conditions (< 2 lx) prior to comparing it with bright white light. Study 2: Baseline measurements were taken in a dim light setting before comparing the effects of red, blue, and green light.	RMSSD, LF, HF-HRV, LF/HF ratio		Study 1: Dim (< 2 lx) vs. Bright White (414 lx) Study 2: Red: 235 lx Blue: 201 lx, Green: 806 lx	Study 1: Bright white light, mix of blue, green and red light each one third of their corresponding setting Study 2: Red: 635 nm Blue: 470–480 nm Green: 520 nm	Studies 1 & 2: 60 min post-awakening.	HRV was measured during the 60 min, specifically at intervals of 5–10 min, 25–30 min, 35–40 min, and 55–60 min after light onset.	Light exposure started at 5:00 AM	Eyes open during exposure	Study 2: Red light increased RMSSD Blue light had no effect on vmHRV	Study 1: No significant difference on vmHRV parameters between dim and bright light conditions
Ono et al. (2011)	N = 22 (patients post-oesophagectomy); 0 females; Mean age; Study group 63.4 ± 9.7; Control Group 63.8 ± 7.8; Japan	Exposure to bright light; RR-interval was continuously measured until day 6 after surgery, 10:00 a.m.	Normal lighting based on weather, season, bed position	HF, ratio LF-HF	Between-subjects design	2500 lx 4000 lx 5000 lx alternating	not indicated	2 h for 4 days	during / constantly	07:30–09:30 a.m.	experimental: closed or watching tv; control: not reported, assume open	not investigated	no difference in HF between groups
Rechlin et al. (1995)	N = 30 (major depression); 25 females; Mean age: 45.2 [21–72 years]; N = 18 (healthy control), 13 females, Mean age: 43.6 [18–74 years] Germany	Investigating different illuminance of light to see their effect on vmHRV; 14 days of bright light exposure, followed by 5 days of dim light	Not defined	HF	Within-subjects design	> 2500 lux vs. < 200 lux	not indicated	90 min each light	vmHRV was measured before and after the 5th session of both bright light and dim light exposure conditions.	6–7:30 am	not reported, assume open	not investigated	Bright light therapy significantly increased HF-HRV in both the healthy controls and a subset of depressed patients who showed mood improvement, indicating an increase in

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Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
													vmHRV under bright light. (HF: (Before-after) Bright light exposure: 0.63–1.05 ($p < .025$))
Ross et al. (2013)	N = 117 (healthy); 89 females; Mean age: 43 [19–72 years]; USA & Canada	HF was measured under different light colours to see their impact on vmHRV	Darkness (0 lux)	HF	Within-subjects design	63 lux	Warm-colour range (Red, Orange, Yellow) Cool-colour range (Green, Blue, Indigo) Balanced (equal range of all colours) White	20 min in each colour	not indicated	not indicated	not indicated	No significant changes in HF for warm, cool, or white colors	not investigated
Sakakibara et al. (2000)	N = 12 (healthy); 12 females; Mean age not reported [20–21 years]; Japan	investigating the impact of illuminance in daily sessions	Darkness (0 lux)	HF, but descriptive stats missing	Within-subjects design (crossover)	5000 lux vs 0 lux	not indicated	2 h	during	6–8 pm	not reported, assuming open	not investigated	No effect of illuminance on HF
Schäfer & Kratky (2006)	N = 12 (healthy); gender distribution not reported; Mean age: 29.9 [24–37 years]; Austria	Effects of exposure to coloured light (Red, Green, Blue). Light phases were followed and preceded by 15 min of darkness	Darkness (0 lux)	RMSSD, HF	Within-subjects design	700 lux	red, green, blue	10 min each colour	before and after	November, December, starting from 9 pm	open	Blue light decreased HF in comparison with before light; no changes for green light or red light	not investigated
Scheer et al. (2004)	Study 1: N = 17 (healthy); 6 females Study 2: N = 10 (healthy); 0 females; The Netherlands	not indicated	Dim vs. bright light	RMSSD	Within-subjects design	Study 1: 0 lux vs. indoor lightning (illuminance not specified) Study 2: 100 und 800 lux	not indicated	Study 1: 5 × 10 min Study 2: 10 min 100 lux + 10 min 800 lux x 5	during	not indicated	not reported, assume open	not investigated	No effect of light illuminance on RMSSD
Scholkmann et al. (2017)	N = 14 (healthy); 5 females; Mean age: 33.4 [24–57 years]; Switzerland	Exploring the influence of a series of 15 alternating light-on/light-off with coloured light	Darkness (0 lux)	HF	Within-subjects design (crossover)	20 lux	Red: 682 nm Green: 515 nm Blue: 465 nm	10 min [15 alternating light-on (20 s) and light-off (20 s) periods]	Before, during, after	the mean time of measurement was 12:24 SD 2.36 h.	not reported, assume open	HF increased under red light (comparison before/after)	not investigated
Sergeeva et al. (2023)	N = 17 (anxiety symptoms), all females, age 18–20 years - Russia	Exposure to monochromatic blue light right after cognitive task	No light (resting baseline)	HF	Within-subjects design	765 lux	Blue light (480 ± 5 nm)	20 min	During	12:00–16:00	not reported, assume open	HF significantly decreased during the first 5 min of blue light exposure ($p < .05$) but returned to	not investigated

(*continued on next page*)

Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
												baseline by 15–20 min ($p > .05$).	
Tsunoda et al. (2001)	N = 10 (healthy); 2 females; Mean age: 21.9 years; Japan	Effects of a 30 min exposure to different light illuminance	Darkness (0 lux)	HF	Within-subjects design	< 0.01 lux, 100 lux, 2500 lux, 10000 lux	not indicated	30 min each light	before, during, after	14 pm	not reported, assume open	not investigated	No effect of illuminance on HF
Yuda et al. (2016)	Study 1: N = 12 (healthy); 2 females; Mean age: 23 years; Japan Study 2: N = 4 (healthy); 2 females; Mean age not reported [25–39 years]; Japan	Study 1: Effects of a 6 min-exposure to 3 coloured lights Study 2: Effects of 6 min-exposure to 3 different illuminance of blue light	Darkness (0 lux)	HF	Within-subjects design	Study 2: 10 lux VS 5 lux VS 2 lux	Study 1: Red (peak at 600–700 nm) Green (peak at 500–600 nm) Blue (peak at 450–500 nm) Study 2: Blue (peak at 450–500 nm)	Study 1: 6 min each colour Study 2: 6 min	before, during, after	8:30 am−13 pm	open	study 1: HF Main effect for colour (before and during lighting), HF decreased compared to darkness for all colours; F= 4.62, $p = .03$ Decrease was greater under blue light than under red and green (Post-hoc comparison) blue - red: $p = .007$, blue - green: $p = .010$	study 2: HF decrease under 10 lux, blue light (during: $p = .006$, after: $p = .001$)
Yuda et al. (2017a)	N = 10 (healthy); 4 females; Mean age: 26 [20–40 years] - Japan	Effects of a 10 min-exposure to different coloured lights	Colours compared to one another	HF	Within-subjects design	Blue: 13 lux / Green: 91 / lux White: 158 lux	Blue: Mean 483 nm (peak at approx. 450 nm, total range: approx. 430–540 nm) Green: Mean 555 nm (peak at approx. 520 nm, total range: approx. 480–660 nm) White: Mean 594 nm (first peak at approx. 560 nm, second peak at approx. 620 nm, total range: approx. 480–660 nm)	Five consecutive 10 min sessions for each light	before, during, after	9:30am−14pm	open	HF increased more under blue light than under green and white light HF (Before - during) $F2126 = 13.16$, $p < .0001$ Hf Post-hoc comparison Blue - green: $t126 = -3.56$, $p = .001$ Blue - white: $t126 = -4.9$, $p < .0001$	not investigated
Yuda et al. (2017b)	N = 8 (healthy); 2 females; Mean age: 27 [21–39 years]; Japan	Exploring the effects of different light colours	Colours compared to one another	HF	Within-subjects design	not indicated	Blue Orange	30 min each colour	before, during, after	"after lunch"	open	HF was lower under blue light than under orange light $p = .003$	not investigated

(*continued on next page*)

Table 2 (*continued*)

Study	Participants	Intervention	Baseline / Comparison	Outcomes (vmHRV)	Study design	Light's illuminance	Light's colour	Light's exposure time	Measurement time (during/ after)	Time of the day	Eyes closed/ opened	Effect colour on vmHRV (nm/K)	Effect illuminance on vmHRV
Zhang et al. (2020)	N = 12 (healthy); 4 females; Mean age not reported [range: 22–26 years]; China	Investigating the influence of different light conditions	Darkness (0 lux) AND colours compared to one another	HF, but descriptive stats missing	Within-subjects design	White light blue-enriched: 227 lux White light blue-less: 232 lux	White light blue-enriched (6395 K, peak at 430–480 nm, total range: 400–700 nm, second peak at approx. 530 nm) White light blue-less (2850 K, major peak at 580–630 nm, second peak at approx. 440 nm)	50 min each colour	before and after	2–4:30 pm	open	No effect of color on HF	No effect of illuminance on HF
Zhou et al., (2024)	N = 10 (with depressive tendencies); 8 males, 2 females; Mean age: 23.20 ± 2.35 years; China	Testing the effects of different light conditions on individuals with depressive tendencies	Darkness (0 lux)	HF	Within-subjects design	50 lx, 300 lx, 1500 lx	White: 6500 K, Red: 633 nm, Blue: 460 nm	3 min dark adaptation, then 20 min exposure	During	9:00–11:20 am	Open	HF values with white light (6500 K) higher than with colored lights red (633 nm) and blue (460 nm) ($p < .05$)	HF values higher with 1500 lux in comparison to both 300 lux and 50 lux ($p < .05$)

Table 3
Risk of bias.

	Risk of bias arising from the randomization process		Risk of bias due to deviations from the intended interventions (effect of adhering to intervention)		Risk of bias due to missing outcome data		Risk of bias in measurement of the outcome		Risk of bias in selection of the reported result		Overall risk-of-bias judgement	
	Rater P	Rater V	Rater P	Rater V	Rater P	Rater V	Rater P	Rater V	Rater P	Rater V	Rater P	Rater V
Canazei et al. (2017)	Some concerns	Some concerns	Some concerns	Some concerns	High risk	High risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Choi et al. (2011)	Some concerns	Some concerns	Some concerns	Some concerns	High risk	High risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Edelhauser et al. (2013)	High risk	High risk	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	High risk	High risk	High risk	High risk
Grote et al. (2013)	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Some concerns	High risk	High risk	High risk
Hayano et al. (2021)	Some concerns	High risk	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	High risk	High risk	High risk	High risk
Kakitsuba et al. (2020)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	Some concerns	High risk	High risk	High risk
Laufer et al. (2009)	High risk	High risk	Some concerns	Some concerns	High risk	High risk	High risk	High risk	Some concerns	High risk	High risk	High risk
Luo et al. (2022)	Some concerns	High risk	Some concerns	Some concerns	Low risk	Low risk	Low risk	Some concerns	Some concerns	Some concerns	High risk	High risk
Modi et al. (2019)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Some concerns	Some concerns	Some concerns	Some concerns	High risk	High risk
Noguchi and Sakaguchi (1999)	High risk	High risk	Some concerns	Some concerns	High risk	High risk	Low risk	Some concerns	High risk	High risk	High risk	High risk
Ono et al. (2011)	Some concerns	Some concerns	Some concerns	High risk	High risk	High risk	High risk	High risk	Low risk	Low risk	High risk	High risk
Petrowski et al. (2023)	High risk	High risk	High risk	High risk	Low risk	Low risk	Low risk	Some concerns	High risk	High risk	High risk	High risk
Rechlin et al. (1995)	High risk	High risk	High risk	High risk	High risk	High risk	Low risk	Low risk	High risk	High risk	High risk	High risk
Ross et al. (2013)	Some concerns	Some concerns	Low risk	Low risk	Low risk	Some concerns	Low risk	Low risk	Some concerns	High risk	High risk	High risk
Sakakibara et al. (2000)	High risk	High risk	Some concerns	Some concerns	Some concerns	High risk	High risk	High risk	High risk	High risk	High risk	High risk
Sergeeva et al. (2023)	High risk	High risk	High risk	High risk	Low risk	Low risk	High risk	High risk	High risk	High risk	High risk	High risk
Schäfer and Kratky (2006)	Some concerns	High risk	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Scheer et al. (2004)	High risk	High risk	High risk	High risk	Low risk	Low risk	High risk	High risk	Some concerns	High risk	High risk	High risk
Scholkmann et al. (2017)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	High risk	High risk	High risk	High risk
Tsunoda et al. (2001)	High risk	High risk	Low risk	Low risk	Low risk	Low risk	High risk	High risk	Some concerns	Some concerns	High risk	High risk
Yuda et al. (2016)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Yuda et al. (2017a)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Yuda et al. (2017b)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	Some concerns	Some concerns	High risk	High risk
Zhang et al. (2020)	Some concerns	Some concerns	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	High risk	High risk	High risk	High risk
Zhou et al. (2024)	High risk	High risk	Some concerns	Some concerns	Low risk	Low risk	Low risk	Low risk	High risk	High risk	High risk	High risk

research to refine our understanding of these moderating variables.

4.1. *Effects of illuminance on vmHRV*

Illuminance appears to be an influential factor in modulating vmHRV, particularly in the context of blue or cool-colored light, although findings were inconsistent across studies. Preliminary indications suggest that high illuminance may reduce vmHRV (decreased HF-HRV and RMSSD) under certain conditions, though these findings varied by timing, exposure duration, and other conditions.

The timing of measurements influenced observed responses. Studies assessing vmHRV during high illuminance exposure often reported immediate reductions in vmHRV, suggesting potential transient autonomic adjustments to light intensity. However, many studies did not observe a significant immediate effect, pointing to the possibility that other factors, such as individual differences or specific light characteristics, may moderate these responses. For instance, Hayano et al. (2021) noted reduced HF-HRV during high-illuminance cold light exposure in older adults, potentially due to age-related sensitivity to both illuminance and color. Such immediate effects may represent temporary adaptations rather than lasting impacts on vmHRV.

When measuring the impact of OEVL after light exposure, studies measuring vmHRV pre- and post-exposure found lingering reductions in vmHRV after high illuminance exposure, suggesting a residual impact

Table 4
Main findings summarized.

Illuminance Effects			
Outcome Summary	**Studies (k)**		**Studies (References and vmHRV outcomes)**
Positive	k = 2		(Rechlin et al., 1995) - both healthy participants and a subset of depressed patients who showed mood improvement experienced increased HF, measured pre- and post-session on the 5th day of either bright (> 2500 lux) or dim (< 500 lux) light exposure (Zhou et al., 2024) - HF higher with 1500 lux vs. 300 & 50 lux ($p < .05$); participants with depressive tendencies
Negative	k = 2		(Luo et al., 2022) - RMSSD higher at 200 lux than 1200 lux, no change in HF (Yuda et al., 2016) - HF decreased under 10 lux vs. 0 lux
Null	k = 9		(Kakitsuba, 2020) - no difference in HF between dim (70–640 lux) and bright (1550–7000 lux) light (Noguchi and Sakaguchi, 1999) - no difference in HF between 30 vs. 150 lux (Petrowski et al., 2023, Study 1) - no differences (RMSSD & HF) between dim & bright light (Ono et al., 2011) - no difference in HF, 2500–5000 lux vs. normal lighting, patients post-oesophagectomy, between-subject design (Scheer et al., 2004, Study 1) - no difference in HF between 0 lux and indoor lightning (Scheer et al., 2004, Study 2) - no difference in HF between 100 and 800 lux (Sakakibara et al., 2000) - no difference in HF between 0 lux and 5000 lux (Tsunoda et al., 2001) - no differences in HF between < 0.01 lux, 100 lux, 2500 lux, 10000 lux (Zhang et al., 2020) - no difference in HF between 0 lux vs. 227–232 lux
Color Effects			
Color	**Outcome Summary**	**Studies (k)**	**Studies (References and vmHRV outcomes)**
Blue	Positive	k = 1	(Yuda et al., 2017a) - HF higher under blue vs. green/white (potential confounder: lowest illuminance under blue light)
	Negative	k = 4	(Canazei et al., 2017) - HF and RMSSD lower in blue-depleted light in comparison to blue-enhanced light (Sergeeva et al., 2023) - acute HF decrease, then return to baseline by 15–20 min (Schäfer & Kratky, 2006) - decreased HF under blue compared to pre-light (Yuda et al., 2016, Study 1) - HF decrease compared to darkness, and more than with exposure to green and red light (Yuda et al., 2017b) - HF lower compared to orange light (Zhou et al., 2024) - HF lower compared to white light, participants with depressive tendencies
	Null	k = 5	(Choi et al., 2011) - all participants, no effect on HF and RMSSD, compared to darkness (Edelhäuser et al., 2013) - no effect on HF, before/after exposure (Laufer et al., 2009) - no effect on HF compared to red (Modi et al., 2019) - no effect on RMSSD (Petrowski et al., 2023, Study 2) - no effect on RMSSD/HF"
Red	Positive	k = 2	(Petrowski et al., 2023, Study 2) - RMSSD increased with red, compared to darkness (Scholkmann et al., 2017) - HF increase under red
	Negative	k = 3	(Choi et al., 2011) - significant decrease under red, for anxiety/depression participants (no change for healthy participants) (Edelhäuser et al., 2013) - HF decrease after red light exposure (Yuda et al., 2016, Study 1) - HF decreased compared to darkness, but less than with exposure to blue light (Zhou et al., 2024) - HF lower compared to white light, participants with depressive tendencies
	Null	k = 4	(Choi et al., 2011) - significant decrease under red, for anxiety/depression participants (no change for healthy participants) (Laufer et al., 2009) - no significant change in HF compared to blue (Modi et al., 2019) - no effect on RMSSD (Schäfer & Kratky, 2006) - no effect on RMSSD/HF
Green	Null	k = 3	(Schäfer & Kratky, 2006) - no effect on RMSSD/HF (Yuda et al., 2016, Study 1) - HF decrease compared to darkness, but less than with exposure to blue light (Zhou et al., 2024) - no effect of green light on HF
White	Positive	k = 3	(Choi et al., 2011) - significant increase in both RMSSD & for patients with anxiety/depression symptoms (no change for healthy participants) (Modi et al., 2019) - HF increase compared to darkness (Zhou et al., 2024) - HF increased compared to colored lights red and blue, participants with depressive tendencies
	Null	k = 1	(Zhang et al., 2020) - no difference in HF vs. darkness
Orange	Positive	k = 1	(Yuda et al., 2017b) - HF higher compared to blue light
Warm-colored white	Null	k = 1	(Ross et al., 2013) - no effect on HF
Cold-colored light	Negative	k = 1	(Hayano et al., 2021) - decrease in HF only in the elderly group
	Null	k = 1	(Hayano et al., 2021) - no change in HF the younger adult group (Ross et al., 2013) - no effect on HF
Color (blue, green, red)	Positive	k = 1	(Grote et al., 2013) - HF increased under oscillating colors compared to white

beyond the exposure period. For example, Kratky (2006) found that HF-HRV was lower following blue light exposure than baseline, indicating sustained autonomic effects even after exposure had ceased. These observations underline the need for studies to differentiate between immediate and residual autonomic effects of high illuminance to clarify the mechanisms involved.

In contrast to high illuminance, lower illuminance—particularly under warm or blue-depleted lighting—was often linked to increased vmHRV. Canazei et al. (2017) observed that lower illuminance in blue-depleted conditions significantly increased HF-HRV and RMSSD, suggesting that reduced intensity, especially in specific color spectrums, may support autonomic relaxation (Chellappa et al., 2011). While these findings indicate potential for illuminance modulation in promoting autonomic relaxation, they remain preliminary and appear highly context-dependent, requiring further confirmation under standardized conditions.

A notable distinction between single and repeated exposures emerged in Rechlin et al. (1995), where multiple days of bright light exposure led to a significant increase in HF-HRV (measured as the difference between pre- and post-exposure) on the fifth day of high-illuminance exposure in a subset of patients with depression who showed mood improvement. Similar cumulative effects were observed in healthy controls, suggesting that ongoing light exposure may promote gradual autonomic adaptation—a potentially valuable area for therapeutic intervention. However, as this is the only study in this systematic review with repeated stimulations over multiple days, further systematic research is needed to confirm and expand upon these findings.

Mechanistically, it is hypothesized that high-illuminance light, particularly in the blue spectrum, may activate ipRGCs through melanopsin, a photopigment responsive to blue light. This ipRGC activation could contribute to physiological arousal, increasing alertness and possibly influencing CVA in ways that reduce vmHRV by decreasing parasympathetic activity. This mechanism aligns with prior findings that ipRGCs may influence non-visual pathways, relaying light information to brain areas involved in circadian and autonomic functions, such as the hypothalamus and brainstem. However, it is important to note that alternative pathways, such as cortical or emotional processing of light, might also mediate vmHRV responses to illuminance and merit

consideration in future studies (Brainard et al., 2001; Cajochen et al., 2005).

4.2. Color

4.2.1. Blue light

Previous research has reported mixed effects of blue light on vmHRV, with outcomes often influenced by illuminance. High-illuminance blue light has been shown to suppress melatonin and increase alertness (Cajochen et al., 2005; Munch et al., 2006), potentially leading to reduced vmHRV. In line with these findings, the current review found preliminary trends suggesting that higher-illuminance blue light may have neutral or negative effects on vmHRV under certain conditions. For instance, in Sergeeva et al. (2023) and Kratky (2006), decreases in HF-HRV values were observed. However, results were inconsistent, with other studies showing no significant change, indicating that the effects of blue light on vmHRV may vary considerably based on individual, environmental, and contextual factors. In contrast, lower-intensity blue light appeared to yield some favorable vmHRV outcomes, though these findings may be influenced by differences in illuminance. For example, Yuda et al. (2017a) reported increases in HF-HRV under lower-illuminance blue light compared to green and white light, but this effect may be confounded by the lower illuminance level used for blue light. Furthermore, another study by Yuda et al. (2017b) found that lower-intensity blue light was associated with reduced vmHRV relative to orange light, suggesting that even at lower intensities, the effects of blue light on vmHRV may vary based on specific conditions. These findings imply that while blue light might support CVA more effectively at lower intensities, illuminance levels need to be carefully controlled in future studies to clarify these effects, particularly in environments like night shifts where blue light is commonly used to enhance alertness.

4.2.2. White light

White light, particularly at moderate to high illuminance levels, has shown positive effects on vmHRV in some studies. For instance, moderate-intensity white light exposure has been associated with improved vmHRV in individuals with mood disturbances such as anxiety and depression (Choi et al., 2011; Zhou et al., 2024). Additionally, Rechlin et al. (1995) observed a significant improvement in HF-HRV following repeated exposure to bright white light, suggesting that cumulative high-illuminance exposure may foster autonomic adaptation over time. The broad spectrum of white light, which includes wavelengths similar to red, appears to support a balanced autonomic response, especially at moderate illuminance levels. However, while these findings are promising, some studies report no significant changes in vmHRV under white light, indicating that its effects may vary based on individual and contextual factors, such as exposure duration or participant characteristics. These inconsistencies underscore the need for further controlled studies to elucidate the conditions under which white light can reliably enhance vmHRV.

4.2.3. Other colors

In contrast to white light, colored lights—particularly red, green, and other warm colors—demonstrate more variable effects on vmHRV. Red light, which likely exerts minimal influence on melanopsin activation, seems to have a limited impact on alertness, illustrated by little influence on vmHRV (Rahman et al., 2014). Studies such as Petrowski et al. (2023) and Scholkmann et al. (2017) found that red light exposure was associated with increases in HF-HRV and RMSSD, indicating potential benefits for enhancing CVA.

However, findings are less consistent for other warm colors, such as orange and green light. While green light, studies reviewed here, such as those by Kratky (2006) and Yuda et al. (2016), showed minimal vmHRV modulation, suggesting that it may not sufficiently engage autonomic pathways to influence CVA. Similarly, warm-colored lights, including orange, showed limited vmHRV modulation, as observed by Ross et al. (2013), where no significant changes in HF-HRV were reported. These findings suggest that while red light may hold some promise for supporting vmHRV, other warm-colored lights and green light may have restricted utility for autonomic modulation, particularly when vmHRV enhancement is the primary goal. Further research is needed to clarify the potential of each color and identify contextual factors that may moderate these effects.

4.2.4. Oscillating and dynamic light exposure

An emerging area of interest is dynamic or oscillating light exposure and its potential to modulate vmHRV. Grote et al. (2013) observed that oscillating colored light (alternating blue, green, and red) improved HF-HRV compared to static white light exposure, suggesting that dynamic changes in color and illuminance might enhance CVA. Intermittent exposure to light may invoke stronger physiological responses due to the novelty and possible reduction in adaptation over continuous exposure (Cajochen et al., 2005). This area holds promise for future investigations, though preliminary evidence is limited, and further research is needed to determine its feasibility and consistency of effects. Oscillating light might provide an innovative approach to personalized interventions tailored to individual autonomic responses to light variability.

4.3. Interaction of illuminance and color on vmHRV

The interaction between illuminance and color in modulating vmHRV remains largely unexplored. Anecdotal evidence suggests that bright, cool-toned light (e.g., blue sky) is stimulating, while low, warm-toned light (e.g., candlelight) promotes relaxation (Noguchi and Sakaguchi, 1999). Only two studies in this review directly examined this interaction, with Noguchi and Sakaguchi (1999) finding no significant effect and Kakitsuba (2020) reporting inconclusive results due to methodological limitations.

Some studies suggest that color effects on vmHRV may depend on reaching certain illuminance thresholds. For example, Yuda et al. (2016) found that 10-lux blue light led to a greater decrease in HF-HRV than higher illuminance red and green lights, suggesting that blue light's impact may intensify at specific illuminance levels (Cajochen et al., 2005). This interaction implies that certain illuminance-color combinations might enhance vmHRV modulation, whether for relaxation or alertness. Future research should further investigate these combinations to clarify optimal settings for autonomic regulation.

4.4. Limitations

This systematic review reveals several limitations, largely due to methodological variability and physiological measurement concerns, both of which likely contributed to the observed inconsistencies across studies. A key methodological limitation was the diversity in study designs, including differences in timing, duration, and conditions of light exposure. For instance, some studies assessed vmHRV during exposure, while others measured effects before and after exposure, complicating direct comparisons and highlighting a need for standardized protocols. Inconsistent control conditions, such as variations in baseline lighting or darkness protocols, further hindered comparability and emphasized the importance of standardized control settings. Additionally, many studies manipulated simultaneously illuminance and color, limiting the ability to attribute specific effects to each parameter independently. The exclusion of studies that lacked vmHRV-specific data also narrowed the range of included research, potentially limiting the comprehensiveness of this review. Furthermore, regarding the selection of RMSSD and HF-HRV as indices of vmHRV, it is important to note that these metrics reflect a specific facet of CVA—namely, phasic, respiratory-gated modulation of sinoatrial node function. They do not fully capture other components of cardiac vagal control, such as baroreflex-mediated influences or tonic, non-respiratory cardiac parasympathetic regulation

(Hayano and Yuda, 2019; Quigley et al., 2024; Reyes del Paso et al., 2013). This interpretive nuance should be taken into account when evaluating the present findings.

Physiological measurement concerns were another significant source of variability. Few studies controlled for respiratory rate—a crucial factor for interpreting HF-HRV as an indicator of CVA, especially given that HF-HRV sensitivity varies within a specific respiratory range (9–24 cycles per minute) (Laborde et al., 2017). Diurnal variations in light sensitivity, which can affect autonomic responses depending on the time of day, were also rarely accounted for in the studies. Furthermore, the prolonged response of ipRGCs necessitates adequate intervals between exposures to prevent carryover effects, a factor often overlooked. Moreover, a high risk of bias was common across the included studies, underscoring the need for rigorous, controlled methodologies to improve reliability and consistency in future findings.

Beyond these methodological and physiological concerns, we acknowledge that this review focused specifically on the physiological impact of non-image-forming light pathways on vmHRV, excluding the potential influence of light-dependent image-forming visual processes on autonomic function. While this is an important topic, addressing it thoroughly would require a significantly broader scope, given that CVA may respond differently depending on the emotional or cognitive salience of visual stimuli. Future research should explore this connection to further elucidate the complex interplay between image-forming and non-image-forming light pathways in autonomic regulation.

4.5. Future research directions

This systematic review underscores critical gaps in understanding how OEVL —specifically illuminance and color—affects vmHRV. To advance the field, future research should prioritize three main areas:

1) Standardization of control conditions and study designs: The most pressing need is for consistent, well-controlled study designs that allow for comparability across studies. Standardizing control conditions (e.g., baseline light types, darkness protocols) and light exposure parameters (timing, duration) would reduce methodological variability and provide a clearer foundation for future findings. Employing established guidelines like the ENLIGHT checklist (Spitschan et al., 2023) can also ensure comprehensive and reliable reporting on light characteristics and control over confounding variables like respiratory rate and participant health status (Laborde et al., 2017). Morover, integrating the 3Rs framework of cardiac vagal activity functioning (Laborde et al., 2018) REF—resting, reactivity, and recovery phases— into OEVL protocols would enhance methodological rigor by capturing dynamic changes in CVA over time.
2) Isolation of light parameters in controlled experiments: Future studies should focus on isolating the effects of illuminance and color by manipulating one parameter at a time while keeping the other constant. Controlled, single-parameter designs will allow for more precise insights into the unique impact of each factor on vmHRV, providing a clearer basis for developing evidence-based applications.
3) Use of longitudinal and varied-duration studies: Longitudinal designs and studies with varied exposure durations are essential to understand both immediate and cumulative effects of light exposure on vmHRV. Differentiating between short-term and long-term autonomic responses will help determine if observed changes are transient or reflect lasting autonomic adaptations. Incorporating circadian timing could also help clarify how diurnal variations may influence vmHRV responses (Schäfer et al., 2009).

By prioritizing these areas, future research can systematically address the limitations noted in this review and contribute toward establishing evidence-based protocols for light exposure in both clinical and non-clinical contexts.

4.6. Clinical relevance

This systematic review indicates that tailored light exposure may have exploratory potential for modulating vmHRV across various clinical conditions, pointing to a promising – although still preliminary - area for therapeutic applications. Given the role of the autonomic nervous system in managing stress and health outcomes (Jung et al., 2019; Sleight, 1997), targeted light exposure could provide an adjunctive strategy for autonomic support in clinically vulnerable populations.

4.6.1. Targeted light exposure may enhance emotional stability in individuals with mood disorders

Evidence suggests that specific light characteristics may benefit vmHRV in patients experiencing mood-related symptoms. In cases of major depression, Rechlin et al. (1995) observed significant increases in vmHRV following repeated exposure to bright white light in a subset of participants experiencing mood improvement, suggesting that high-illuminance therapy may support cumulative autonomic adaptation over time. The study, however, noted that concurrent medication could independently affect vmHRV, underlining the importance of accounting for medication use in light-based interventions (Rechlin et al., 1994). Similarly, Zhou et al. (2024) found that moderate-intensity white light (1500 lux) improved autonomic regulation and emotional responses in individuals with depressive symptoms, indicating that well-calibrated illuminance levels may benefit autonomic and emotional regulation in clinical populations.

4.6.2. Optimizing light therapy for anxiety: the role of color and intensity

Patients with anxiety may exhibit varying responses to light exposure depending on the color and illuminance level, emphasizing the need for tailored approaches in clinical applications. Sergeeva et al. (2023) reported that high-illuminance blue light exposure led to an initial reduction in HF-HRV among female students with high anxiety, with levels normalizing after 20 min. This transient suppression of CVA suggests that blue light at high intensities may temporarily heighten autonomic reactivity in anxious individuals, though the effect may lessen with continued exposure. Additionally, Choi et al. (2011) found that red light exposure decreased vmHRV in participants with anxiety or depressive symptoms, likely due to red's association with psychological arousal or stress (Elliot et al., 2011). In contrast, dim blue light had a neutral effect on vmHRV, indicating it may be a gentler option for individuals sensitive to stress. These findings underscore that in anxiety-prone populations, lower-intensity blue light may help stabilize autonomic reactivity without excessive arousal, whereas red light could inadvertently increase stress responses, underscoring the importance of selecting appropriate light settings to support vmHRV effectively in this group.

4.6.3. ***Bright light therapy for circadian alignment and autonomic regulation***

Furthermore, studies investigating clinical populations outside of psychiatric settings reveal intriguing possibilities for light exposure. For instance, Ono et al. (2011) examined postoperative patients following esophagectomy and found that bright light exposure helped to entrain circadian rhythms and potentially improved rest-activity cycles, although it did not produce significant differences in HF-HRV between the study and control groups. This lack of differentiation underscores the complexity of ANS modulation in clinical populations with surgical interventions, where vagal function may already be compromised.

4.6.4. vmHRV as a physiological marker for light therapy efficacy

A key challenge in advancing light therapy is establishing objective physiological markers to quantify its effects. vmHRV presents a promising candidate, offering real-time insights into autonomic function and stress regulation. By tracking vmHRV responses to different light parameters (e.g., illuminance, color, exposure duration), clinicians and

researchers may develop more personalized light therapy protocols tailored to individual autonomic profiles. Future research should explore how vmHRV fluctuations correlate with therapeutic outcomes, particularly in populations with autonomic dysfunction.

4.6.5. *In sum: exploring the feasibility of vmHRV-guided light therapy*

In sum, these exploratory findings suggest that tailored light exposure holds potential for symptom-targeted autonomic support across diverse clinical conditions, yet these insights remain preliminary. Future studies should confirm these effects under rigorously standardized conditions to establish optimal parameters for clinical application. Should subsequent research substantiate these initial findings, light exposure might emerge as a non-invasive adjunctive intervention for enhancing vmHRV across a range of health conditions. Until such evidence is firmly established, clinical applications should proceed with caution, focusing on personalized approaches and carefully monitored interventions to ensure both safety and efficacy.

5. Conclusion

To conclude, studying the impact of OEVL on vmHRV provides valuable insights into fundamental autonomic reactivity processes, which may subsequently inform clinical applications. While light therapy traditionally utilizes full-spectrum or daylight white light, it is essential to clarify the individual and combined effects of illuminance and color on vmHRV. Findings from this review indicate a potential for OEVL to influence vmHRV markers, such as HF-HRV and RMSSD. However, the methodological heterogeneity across studies prevents definitive conclusions regarding the precise effects of illuminance and color. Current light research lacks consistent evidence distinguishing the specific impacts of these parameters on vmHRV.

Enhancing vmHRV remains a priority in HRV research, as it is a desirable intervention outcome across clinical and non-clinical domains (Ackermann et al., 2023; Heiss et al., 2021; Laborde et al., 2022, 2023a, 2023b; Mosley and Laborde, 2022; Schmaußer et al., 2022). OEVL presents a promising tool in this context, yet further research is needed to isolate the effects of different light parameters (illuminance and color) and to assess how factors like exposure duration and intervention frequency (acute vs. repeated exposures) impact vmHRV. Additionally, light exposure may confer benefits beyond vmHRV, impacting other physiological pathways relevant to overall well-being (Chellappa et al., 2017; Oldham and Ciraulo, 2014). Given the methodological variability and preliminary nature of these findings, future research must confirm these effects before considering clinical applications of light exposure for autonomic modulation.

CRediT authorship contribution statement

VM and SL realized the systematic review and wrote the first draft, VM and PL performed the risk-of-bias supervised by SL. Tables were realized by VM, PL, MJ, and SL. MA, UB, MJ, FJ, PL, EM provided critical feedback on the first manuscript draft, and helped shape the final version of this manuscript.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT by OpenAI to improve the English language and readability of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of Competing Interest

The authors have no competing interests to disclose.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.neubiorev.2025.106241.

Data availability

The data extracted to perform this systematic review is fully available as supplementary material.

References

Ackermann, S.P., Raab, M., Backschat, S., Smith, D.J.C., Javelle, F., Laborde, S., 2023. The diving response and cardiac vagal activity: a systematic review and meta-analysis. Psychophysiology 60 (3), e14183. https://doi.org/10.1111/psyp.14183.

Baxendale, S., O'Sullivan, J., Heaney, D., 2013. Bright light therapy for symptoms of anxiety and depression in focal epilepsy: randomised controlled trial. Br. J. Psychiatry 202 (5), 352–356. https://doi.org/10.1192/bjp.bp.112.122119.

Benarroch, E.E., 1997. The central autonomic network. In: Low, P.A. (Ed.), Clinical Autonomic Disorders. Lippincott-Raven, pp. 17–23.

Berntson, G.G., Bigger Jr., J.T., Eckberg, D.L., Grossman, P., Kaufmann, P.G., Malik, M., Nagaraja, H.N., Porges, S.W., Saul, J.P., Stone, P.H., van der Molen, M.W., 1997. Heart rate variability: origins, methods, and interpretive caveats. Psychophysiology 34 (6), 623–648. https://doi.org/10.1111/j.1469-8986.1997.tb02140.x.

Berson, D.M., 2003. Strange vision: ganglion cells as circadian photoreceptors. Trends Neurosci. 26 (6), 314–320. https://doi.org/10.1016/S0166-2236(03)00130-9.

Brainard, G.C., Hanifin, J.P., Greeson, J.M., Byrne, B., Glickman, G., Gerner, E., Rollag, M.D., 2001. Action spectrum for melatonin regulation in humans: evidence for a novel circadian photoreceptor. J. Neurosci. 21 (16), 6405–6412. https://doi.org/10.1523/JNEUROSCI.21-16-06405.2001.

Cajochen, C., Munch, M., Kobialka, S., Krauchi, K., Steiner, R., Oelhafen, P., Orgul, S., Wirz-Justice, A., 2005. High sensitivity of human melatonin, alertness, thermoregulation, and heart rate to short wavelength light. J. Clin. Endocrinol. Metab. 90 (3), 1311–1316. https://doi.org/10.1210/jc.2004-0957.

Canazei, M., Pohl, W., Bliem, H.R., Weiss, E.M., 2017. Acute effects of different light spectra on simulated night-shift work without circadian alignment. Chronobiol. Int. 34 (3), 303–317. https://doi.org/10.1080/07420528.2016.1222414.

Chellappa, S.L., Lasauskaite, R., Cajochen, C., 2017. In a heartbeat: light and cardiovascular physiology. Front. Neurol. 8, 541. https://doi.org/10.3389/fneur.2017.00541.

Chellappa, S.L., Steiner, R., Blattner, P., Oelhafen, P., Gotz, T., Cajochen, C., 2011. Non-visual effects of light on melatonin, alertness and cognitive performance: can blue-enriched light keep us alert? PLoS ONE 6 (1), e16429. https://doi.org/10.1371/journal.pone.0016429.

Choi, C.J., Kim, K.S., Kim, C.M., Kim, S.H., Choi, W.S., 2011. Reactivity of heart rate variability after exposure to colored lights in healthy adults with symptoms of anxiety and depression. Int. J. Psychophysiol. 79 (2), 83–88. https://doi.org/10.1016/j.ijpsycho.2010.09.011.

Curcio, C.A., Sloan, K.R., Kalina, R.E., Hendrickson, A.E., 1990. Human photoreceptor topography. J. Comp. Neurol. 292 (4), 497–523. https://doi.org/10.1002/cne.902920402.

Daneault, V., Hebert, M., Albouy, G., Doyon, J., Dumont, M., Carrier, J., Vandewalle, G., 2014. Aging reduces the stimulating effect of blue light on cognitive brain functions. Sleep 37 (1), 85–96. https://doi.org/10.5665/sleep.3314.

Edelhauser, F., Hak, F., Kleinrath, U., Luhr, B., Matthiessen, P.F., Weinzirl, J., Cysarz, D., 2013. Impact of colored light on cardiorespiratory coordination. Evid.-Based Complement. Altern. Med. 2013, 810876. https://doi.org/10.1155/2013/810876.

Elliot, A.J., Payen, V., Brisswalter, J., Cury, F., Thayer, J.F., 2011. A subtle threat cue, heart rate variability, and cognitive performance. Psychophysiology 48, 1340–1345. https://doi.org/10.1111/j.1469-8986.2011.01216.x.

Friedman, B.H., 2007. An autonomic flexibility-neurovisceral integration model of anxiety and cardiac vagal tone. Biol. Psychol. 74, 185–199. https://doi.org/10.1016/j.biopsycho.2005.08.009.

Gazzaniga, M., Ivry, R.B., Mangun, G.R., 2019. Sensation and perception. In: Gazzaniga, M., Ivry, R.B., Mangun, G.R. (Eds.), Cognitive Neuroscience: The Biology of the Mind (5th ed.). WW Norton & Co..

Grote, V., Kelz, C., Goswami, N., Stossier, H., Tafeit, E., Moser, M., 2013. Cardio-autonomic control and wellbeing due to oscillating color light exposure. Physiol. Behav. 114-115, 55–64. https://doi.org/10.1016/j.physbeh.2013.03.007.

Hartmann, R., Schmidt, F.M., Sander, C., Hegerl, U., 2018. Heart rate variability as indicator of clinical state in depression. Front. Psychiatry 9, 735. https://doi.org/10.3389/fpsyt.2018.00735.
Hattar, S., Liao, H.W., Takao, M., Berson, D.M., Yau, K.W., 2002. Melanopsin-containing retinal. Ganglion cells: architecture, projections, and intrinsic photosensitivity. Science 295 (5557), 1065–1070. https://doi.org/10.1126/science.1069609.
Hayano, J., Ueda, N., Kisohara, M., Yoshida, Y., Yuda, E., 2021. Ambient-task combined lighting to regulate autonomic and psychomotor arousal levels without compromising subjective comfort to lighting. J. Physiol. Anthropol. 40 (1), 8. https://doi.org/10.1186/s40101-021-00258-w.
Hayano, J., Yuda, E., 2019. Pitfalls of assessment of autonomic function by heart rate variability. J. Physiol. Anthr. 38 (1), 3. https://doi.org/10.1186/s40101-019-0193-2.
Heiss, S., Vaschillo, B., Vaschillo, E.G., Timko, C.A., Hormes, J.M., 2021. Heart rate variability as a biobehavioral marker of diverse psychopathologies: a review and argument for an "ideal range". Neurosci. Biobehav. Rev. 121, 144–155. https://doi.org/10.1016/j.neubiorev.2020.12.004.
Hubbard, J., Ruppert, E., Gropp, C.M., Bourgin, P., 2013. Non-circadian direct effects of light on sleep and alertness: lessons from transgenic mouse models. Sleep. Med. Rev. 17 (6), 445–452. https://doi.org/10.1016/j.smrv.2012.12.004.
Jung, W., Jang, K.I., Lee, S.H., 2019. Heart and brain interaction of psychiatric illness: a review focused on heart rate variability, cognitive function, and quantitative electroencephalography. Clin. Psychopharmacol. Neurosci. 17 (4), 459–474. https://doi.org/10.9758/cpn.2019.17.4.459.
Kakitsuba, N., 2020. Comfortable indoor lighting conditions for LEDlights evaluated from psychological and physiological responses. Appl. Ergon. 82, 102941. https://doi.org/10.1016/j.apergo.2019.102941.
Kalsbeek, A., Scheer, F.A., Perreau-Lenz, S., La Fleur, S.E., Yi, C.X., Fliers, E., Buijs, R.M., 2011. Circadian disruption and SCN control of energy metabolism. FEBS Lett. 585 (10), 1412–1426. https://doi.org/10.1016/j.febslet.2011.03.021.
Laborde, S., Ackermann, S., Borges, U., D'Agostini, M., Giraudier, M., Iskra, M., Mosley, E., Ottaviani, C., Salvotti, C., Schmaußer, M., Szeska, C., Van Diest, I., Ventura-Bort, C., Voigt, L., Wendt, J., Weymar, M., 2023. Leveraging vagally-mediated heart rate variability as an actionable, noninvasive biomarker for self-regulation: Assessment, Intervention, and Evaluation. Policy Insights Behav. Brain Sci. 10 (2), 212–220. https://doi.org/10.1177/23727322231196789.
Laborde, S., Allen, M.S., Borges, U., Dosseville, F., Hosang, T.J., Iskra, M., Mosley, E., Salvotti, C., Spolverato, L., Zammit, N., Javelle, F., 2022. Effects of voluntary slow breathing on heart rate and heart rate variability: a systematic review and a meta-analysis. Neurosci. Biobehav. Rev. 138, 104711. https://doi.org/10.1016/j.neubiorev.2022.104711.
Laborde, S., Mosley, E., Mertgen, A., 2018. Vagal Tank Theory: The Three Rs of Cardiac Vagal Control Functioning – Resting, Reactivity, and Recovery. Front. Neurosci. 12. https://doi.org/10.3389/fnins.2018.00458.
Laborde, S., Mosley, E., Thayer, J.F., 2017. Heart rate variability and cardiac vagal tone in psychophysiological research - recommendations for experiment planning, data analysis, and data reporting. Front. Physiol. 8, 213. https://doi.org/10.3389/fpsyg.2017.00213.
Laborde, S., Wanders, J., Mosley, E., Javelle, F., 2023. Influence of physical post-exercise recovery techniques on vagally-mediated heart rate variability: a systematic review and meta-analysis. Clin Physiol Funct Imaging. https://doi.org/10.1111/cpf.12855.
Laufer, L., Láng, E., Izsó, L., Németh, E., 2009. Psychophysiological effects of coloured lighting on older adults. Light. Res. Technol. 41 (4), 371–378. https://doi.org/10.1177/1477153509336803.
LeGates, T.A., Fernandez, D.C., Hattar, S., 2014. Light as a central modulator of circadian rhythms, sleep and affect. Nat. Rev. Neurosci. 15 (7), 443–454. https://doi.org/10.1038/nrn3743.
Liu, A., Milner, E.S., Peng, Y.R., Blume, H.A., Brown, M.C., Bryman, G.S., Emanuel, A.J., Morquette, P., Viet, N.M., Sanes, J.R., Gamlin, P.D., Do, M.T.H., 2023. Encoding of environmental illumination by primate melanopsin neurons. Science 379 (6630), 376–381. https://doi.org/10.1126/science.ade2024.
Lockley, S.W., Brainard, G.C., Czeisler, C.A., 2003. High sensitivity of the human circadian melatonin rhythm to resetting by short wavelength light. J. Clin. Endocrinol. Metab. 88 (9), 4502–4505. https://doi.org/10.1210/jc.2003-030570.
Lockley, S.W., Evans, E.E., Scheer, F.A., Brainard, G.C., Czeisler, C.A., Aeschbach, D., 2006. Short-wavelength sensitivity for the direct effects of light on alertness, vigilance, and the waking electroencephalogram in humans. Sleep 29 (2), 161–168.
Luo, X., Ru, T., Chen, Q., Li, Y., Chen, Y., Zhou, G., 2022. Influence of daytime blue-enriched bright light on heart rate variability in healthy subjects. Chronobiol. Int. 39 (6), 826–835. https://doi.org/10.1080/07420528.2022.2040526.
Malik, M., 1996. Heart rate variability. Standards of measurement, physiological interpretation, and clinical use. Task. Force Eur. Soc. Cardiol. North Am. Soc. Pacing Electrophysiol. Eur. Heart J. 17, 354–381.
Martensson, B., Pettersson, A., Berglund, L., Ekselius, L., 2015. Bright White light therapy in depression: a critical review of the evidence. J. Affect. Disord. 182, 1–7. https://doi.org/10.1016/j.jad.2015.04.013.
Maruani, J., Geoffroy, P.A., 2022. Multi-Level processes and Retina-Brain pathways of photic regulation of mood. J. Clin. Med. 11 (2). https://doi.org/10.3390/jcm11020448.
Modi, P., Jha, K., Kumar, Y., Kumar, T., Singh, R., Mishra, A., 2019. The effect of short-term exposure to red and blue light on the autonomic tone of the individuals with newly diagnosed essential hypertension. J. Fam. Med. Prim. Care 8 (1), 14–21. https://doi.org/10.4103/jfmpc.jfmpc_375_18.
Mosley, E., Laborde, S., 2022. A scoping review of heart rate variability in sport and exercise psychology. Int. Rev. Sport Exerc. Psychol. 1–75. https://doi.org/10.1080/1750984x.2022.2092884.
Munch, M., Kobialka, S., Steiner, R., Oelhafen, P., Wirz-Justice, A., Cajochen, C., 2006. Wavelength-dependent effects of evening light exposure on sleep architecture and sleep EEG power density in men [Article]. Am. J. Physiol. Regul. Integr. Comp. Physiol. 290 (5), R1421–R1428. https://doi.org/10.1152/ajpregu.00478.2005.
Noguchi, H., Sakaguchi, T., 1999. Effect of illuminance and color temperature on lowering of physiological activity. Applied human science journal physiological anthropology 18 (4), 117–123. https://doi.org/10.2114/jpa.18.117.
Oldham, M.A., Ciraulo, D.A., 2014. Bright light therapy for depression: a review of its effects on chronobiology and the autonomic nervous system. Chronobiol. Int. 31 (3), 305–319. https://doi.org/10.3109/07420528.2013.833935.
Ono, H., Taguchi, T., Kido, Y., Fujino, Y., Doki, Y., 2011. The usefulness of bright light therapy for patients after oesophagectomy. Intensive Crit. Care Nurs. 27 (3), 158–166. https://doi.org/10.1016/j.iccn.2011.03.003.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hrobjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., Moher, D., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Bmj 372, n71. https://doi.org/10.1136/bmj.n71.
Petrowski, K., Mekschrat, L., Buhrer, S., Siepmann, M., Albus, C., Schmalbach, B., 2023. Effects of Post-awakening light exposure on heart rate variability in healthy Male individuals. Appl. Psychophysiol. Biofeedback 48 (3), 311–321. https://doi.org/10.1007/s10484-023-09581-7.
Quigley, K.S., Gianaros, P.J., Norman, G.J., Jennings, J.R., Berntson, G.G., de Geus, E.J. C., 2024. Publication guidelines for human heart rate and heart rate variability studies in psychophysiology-Part 1: physiological underpinnings and foundations of measurement. Psychophysiology, e14604. https://doi.org/10.1111/psyp.14604.
Rahman, S.A., Flynn-Evans, E.E., Aeschbach, D., Brainard, G.C., Czeisler, C.A., Lockley, S.W., 2014. Diurnal spectral sensitivity of the acute alerting effects of light. Sleep 37 (2), 271–281. https://doi.org/10.5665/sleep.3396.
Rechlin, T., Weis, M., Claus, D., 1994. Heart rate variability in depressed patients and differential effects of paroxetine and amitriptyline on cardiovascular autonomic functions [Clinical Trial; Journal Article; Randomized Controlled Trial; Research Support, Non-U.S. Gov't]. Pharmacopsychiatry 27 (3), 124–128. https://doi.org/10.1055/s-2007-1014291.
Rechlin, T., Weis, M., Schneider, K., Zimmermann, U., Kaschka, W.P., 1995. Does bright-light therapy influence autonomic heart-rate parameters? J. Affect. Disord. 34 (2), 131–137.
Reyes del Paso, G.A., Langewitz, W., Mulder, L.J., van Roon, A., Duschek, S., 2013. The utility of low frequency heart rate variability as an index of sympathetic cardiac tone: a review with emphasis on a reanalysis of previous studies. Psychophysiology 50 (5), 477–487. https://doi.org/10.1111/psyp.12027.
Ross, M.J., Guthrie, P., Dumont, J.C., 2013. The impact of modulated, colored light on the autonomic nervous system. Adv. Mind Body Med 27 (4), 7–16.
Rossing, T.D., Chiaverina, C.J., 2019. Light science. Springer-Verlag.
Sakakibara, S., Honma, H., Kohsaka, M., Fukuda, N., Kawai, I., Kobayashi, R., Koyama, T., 2000. Autonomic nervous function after evening bright light therapy: spectral analysis of heart rate variability. Psychiatry Clin. Neurosci. 54 (3), 363–364. https://doi.org/10.1046/j.1440-1819.2000.00716.x.
Schafer, A., Kratky, K.W., 2006. The effect of colored illumination on heart rate variability. Forsch. Komplement. ärmedizin (Res. Complement. Med.) 13 (3), 167–173. https://doi.org/10.1159/000092644.
Schäfer, A., Kratky, K.W., Schulmeister, K., 2009. The effect of colored illumination on breathing rate and cardiorespiratory dynamics. *journal of alternative medicine. Research* 1 (3), 359–367.
Scheer, F.A., Kalsbeek, A., Buijs, R.M., 2003. Cardiovascular control by the suprachiasmatic nucleus: neural and neuroendocrine mechanisms in human and rat. Biol. Chem. 384 (5), 697–709. https://doi.org/10.1515/bc.2003.078.
Scheer, F.A., Ter Horst, G.J., van Der Vliet, J., Buijs, R.M., 2001. Physiological and anatomic evidence for regulation of the heart by suprachiasmatic nucleus in rats. Am. J. Physiol. Heart Circ. Physiol. 280 (3), H1391–H1399. https://doi.org/10.1152/ajpheart.2001.280.3.H1391.
Scheer, F.A., Van Doornen, L.J., Buijs, R.M., 2004. Light and diurnal cycle affect autonomic cardiac balance in human; possible role for the biological clock. Auton. Neurosci.: Basic Clin. 110 (1), 44–48. https://doi.org/10.1016/j.autneu.2003.03.001.
Schmaußer, M., Hoffmann, S., Raab, M., Laborde, S., 2022. The effects of noninvasive brain stimulation on heart rate and heart rate variability: a systematic review and meta-analysis. J. Neurosci. Res. 100 (9), 1664–1694. https://doi.org/10.1002/jnr.25062.
Schmoll, C., Lascaratos, G., Dhillon, B., Skene, D., Riha, R.L., 2011. The role of retinal regulation of sleep in health and disease. Sleep. Med. Rev. 15 (2), 107–113. https://doi.org/10.1016/j.smrv.2010.06.001.
Scholkmann, F., Hafner, T., Metz, A.J., Wolf, M., Wolf, U., 2017. Effect of short-term colored-light exposure on cerebral hemodynamics and oxygenation, and systemic physiological activity. Neurophotonics 4 (4), 045005. https://doi.org/10.1117/1.NPh.4.4.045005.
Sergeeva, M., Borisova, O., Romanchuk, N., Videnin, A., Pyatin, V., Shusharina, N., Zakharov, A.V., Kolsanov, A., 2023. The effect of circadian photoreceptors stimulation on the stress response of subjects with high anxiety: a pilot study. Appl. Sci. 13 (11). https://doi.org/10.3390/app13116679.
Shamseer, L., Moher, D., Clarke, M., Ghersi, D., Liberati, A., Petticrew, M., Shekelle, P., Stewart, L.A., Group, P.-P., 2015. Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015: elaboration and explanation. Bmj 350, g7647. https://doi.org/10.1136/bmj.g7647.

Sleight, P., 1997. The importance of the autonomic nervous system in health and disease. Aust. N. Z. J. Med. 27 (4), 467–473. https://doi.org/10.1111/j.1445-5994.1997.tb02220.x.

Smith, R., Thayer, J.F., Khalsa, S.S., Lane, R.D., 2017. The hierarchical basis of neurovisceral integration. Neurosci. Biobehav. Rev. 75, 274–296. https://doi.org/10.1016/j.neubiorev.2017.02.003.

Spitschan, M., Kervezee, L., Lok, R., McGlashan, E., Najjar, R.P., Consortium, E., 2023. ENLIGHT: a consensus checklist for reporting laboratory-based studies on the non-visual effects of light in humans. EBioMedicine 98, 104889. https://doi.org/10.1016/j.ebiom.2023.104889.

Sterne, J.A.C., Savovic, J., Page, M.J., Elbers, R.G., Blencowe, N.S., Boutron, I., Cates, C. J., Cheng, H.Y., Corbett, M.S., Eldridge, S.M., Emberson, J.R., Hernan, M.A., Hopewell, S., Hrobjartsson, A., Junqueira, D.R., Juni, P., Kirkham, J.J., Lasserson, T., Li, T., Higgins, J.P., 2019. RoB 2: a revised tool for assessing risk of bias in randomised trials. Bmj 366, l4898. https://doi.org/10.1136/bmj.l4898.

Strong, R.E., Marchant, B.K., Reimherr, F.W., Williams, E., Soni, P., Mestas, R., 2009. Narrow-band blue-light treatment of seasonal affective disorder in adults and the influence of additional nonseasonal symptoms. Depress Anxiety 26 (3), 273–278. https://doi.org/10.1002/da.20538.

Thayer, J.F., Hansen, A.L., Saus-Rose, E., Johnsen, B.H., 2009. Heart rate variability, prefrontal neural function, and cognitive performance: the neurovisceral integration perspective on self-regulation, adaptation, and health. Ann. Behav. Med. 37, 141–153. https://doi.org/10.1007/s12160-009-9101-z.

Tsunoda, M., Endo, T., Hashimoto, S., Honma, S., Honma, K.I., 2001. Effects of light and sleep stages on heart rate variability in humans. Psychiatry clin. neurosci. 55 (3), 285–286. https://doi.org/10.1046/j.1440-1819.2001.00862.x.

van Maanen, A., Meijer, A.M., van der Heijden, K.B., Oort, F.J., 2016. The effects of light therapy on sleep problems: a systematic review and meta-analysis. Sleep. Med. Rev. 29, 52–62. https://doi.org/10.1016/j.smrv.2015.08.009.

Wong, K.Y., 2012. A retinal ganglion cell that can signal irradiance continuously for 10 h. J. Neurosci. 32 (33), 11478–11485. https://doi.org/10.1523/JNEUROSCI.1423-12.2012.

Yuda, E., Ogasawara, H., Yoshida, Y., Hayano, J., 2016. Suppression of vagal cardiac modulation by blue light in healthy subjects. J. Physiol. Anthropol. 35 (1), 24. https://doi.org/10.1186/s40101-016-0110-x.

Yuda, E., Ogasawara, H., Yoshida, Y., Hayano, J., 2017a. Enhancement of autonomic and psychomotor arousal by exposures to blue wavelength light: importance of both absolute and relative contents of melanopic component. J. Physiol. Anthropol. 36 (1), 13. https://doi.org/10.1186/s40101-017-0126-x.

Yuda, E., Ogasawara, H., Yoshida, Y., Hayano, J., 2017b. Exposure to blue light during lunch break: effects on autonomic arousal and behavioral alertness. J. Physiol. Anthropol. 36 (1), 30. https://doi.org/10.1186/s40101-017-0148-4.

Zaidi, F.H., Hull, J.T., Peirson, S.N., Wulff, K., Aeschbach, D., Gooley, J.J., Brainard, G. C., Gregory-Evans, K., Rizzo, J.F., 3rd, Czeisler, C.A., Foster, R.G., Moseley, M.J., Lockley, S.W., 2007. Short-wavelength light sensitivity of circadian, pupillary, and visual awareness in humans lacking an outer retina. Curr. Biol. 17 (24), 2122–2128. https://doi.org/10.1016/j.cub.2007.11.034.

Zhang, Y., Tu, Y., Wang, L., Zhang, W., 2020. Assessment of visual fatigue under LED tunable white light with different blue components. J. Soc. Inf. Disp. 28 (1), 24–35. https://doi.org/10.1002/jsid.866.

Zhou, L., Ruan, C., Li, N., Hou, D., Weirich, C., Lin, Y., 2024. The effect of light on negative emotion and cognitive regulation in individuals with depressive tendencies. Leukos 1–13. https://doi.org/10.1080/15502724.2023.2293468.