The Effects of Environmental Lighting on Emotion and Its Underlying Mechanisms

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Abstract

Environmental lighting, as an important zeitgeber, exerts widespread effects on various physiological and psychological functions, with its non-visual effects on mood having attracted particular attention from researchers. Studies have revealed that illuminance, color temperature, and wavelength of environmental lighting constitute important physical factors influencing mood; abnormal lighting patterns such as short photoperiods, nighttime artificial light, and continuous light/darkness can induce mood disorders; furthermore, the mood effects of light are modulated by exposure duration, timing, individual characteristics, subjective preferences, and genetic types. The pathways through which light influences mood primarily involve two mechanisms: first, intrinsically photosensitive retinal ganglion cells in the retina project light signals to brain regions associated with mood regulation, thereby directly influencing mood; second, light signals indirectly influence mood by synchronizing internal physiological rhythms, which in turn regulate hormone secretion, neurotransmission, and sleep. Future research investigating the visual effects of short-term light exposure should adopt more objective and diverse mood measurement techniques, integrating both non-visual and visual pathways to conduct in-depth comparisons between healthy and mood-disordered populations.

Full Text

Preamble

Effects of Ambient Light on Mood and Its Underlying Mechanisms

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Abstract Ambient light, as a crucial zeitgeber, exerts broad influences on various physiological and psychological functions, with its non-image-forming (NIF) effects on mood attracting particular attention from researchers. Studies have demonstrated that illuminance, correlated color temperature, and wavelength are important physical factors influencing mood. Abnormal lighting patterns such as short photoperiods, artificial light at night, and constant light/dark conditions can lead to affective disorders. The emotional effects of light are also moderated by exposure duration, timing, individual characteristics, subjective preferences, and genetic types.

Light influences mood through two primary pathways. On one hand, intrinsically photosensitive retinal ganglion cells in the retina project light signals to brain regions involved in emotional regulation, thereby directly affecting mood. On the other hand, light signals indirectly influence mood by synchronizing internal physiological rhythms and modulating hormone secretion, neurotransmission, and sleep under circadian control. Future research examining the visual efficacy of short-term light exposure should employ more objective and diverse emotional measurement techniques, integrate non-visual and visual pathways, and conduct in-depth comparisons between healthy and mood-disordered populations.

[**Keywords**] Ambient light, mood, physical factors, lighting patterns, underlying mechanisms
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Ambient light serves as an important zeitgeber, playing a pivotal role in regulating and maintaining synchronization between organisms' internal biological rhythms and external light-dark environments. Simultaneously, light can significantly modulate various physiological and psychological functions including autonomic nervous system activity, cognitive processing, and emotion—collectively termed non-image-forming (NIF) effects. This effect primarily depends on a third type of photoreceptor in the human retina distinct from traditional rods and cones: intrinsically photosensitive retinal ganglion cells (ipRGCs). Over the past decade, research on the NIF effects of light has flourished, particularly regarding light' s influences on alertness, cognitive function, sleep, and circadian rhythms (Fisk et al., 2018; LeGates et al., 2014; Mao et al., 2018; Ru et al., 2019). Additionally, studies indicate that ambient light is an important regulator of mood (LeGates et al., 2014). The symptomatic features and pathological mechanisms of Seasonal Affective Disorder (SAD) demonstrate a close association between light and mood; the detrimental effects of abnormal light-

ing patterns on mood and the antidepressant effects of light therapy have also been confirmed by preclinical and clinical studies (Golden et al., 2005; Lam et al., 2016; Lieverse et al., 2011; Rosenthal et al., 1984; Sit & Haigh, 2019). However, existing research lacks comprehensive and in-depth discussion of factors influencing light' s effects on mood, and the specific mechanisms remain unclear. Therefore, this article focuses on the physical characteristics of light affecting mood, lighting patterns, moderating factors, potential mechanisms, and clinical applications of light therapy.

2 Physical Factors of Light Affecting Mood

Mood refers to a core feeling of subjective state at any given moment, not necessarily about anything specific (McCloughan et al., 1999). In current laboratory studies on light and mood, researchers primarily manipulate physical characteristics such as environmental light illuminance, correlated color temperature, or wavelength to examine their effects on individuals'mood. Measurement methods mainly include self-report scales, facial expression recognition, and neurophysiological recording techniques (EEG, ERP, or fMRI).

2.1 Effects of Illuminance on Mood

Illuminance, a crucial physical characteristic of composite white light, refers to the luminous flux received per unit area of an illuminated object, measured in lux (lx). Lower illuminance indicates weaker light, and vice versa. Existing research suggests that over a period ($\geq$ 1 week), high environmental illuminance is significantly positively correlated with positive mood in healthy populations, with bright light modulating neural activity in the limbic system during emotional stimulus processing. For instance, field studies indicate that the longer individuals are exposed to bright light ($ $1000 lx), the more positive their mood (Harb et al., 2015; Jean-Louis et al., 2005). Fisher et al. (2014) used brain imaging to find that after three weeks of light therapy, healthy participants showed suppressed amygdala-driven bottom-up emotional attention networks and enhanced prefrontal cortex (PFC)-mediated top-down regulation of the amygdala when processing negative emotional stimuli, with these limbic region activities exhibiting illuminance-dependent changes—the higher the illuminance, the stronger the regulatory effect. Additionally, rodent studies show that reduced daytime light intensity over four weeks leads to increased depression- and anxiety-like behaviors in mice (Deats et al., 2014; Leach et al., 2013).

In laboratory studies of short-term light exposure, however, the effects of illuminance on mood are less consistent. Most results suggest that in simulated office lighting, participants exhibit more positive mood under high illuminance ($\geq$ 1000 lx) compared to low illuminance ($\leq$ 200 lx) (Bijleveld & Knufinke, 2018; Leichtfried et al., 2015; Ru et al., 2019). For example, Smolders et al. (2014) measured participants' positive and negative mood (using two 5-point Likert items) after 30 minutes of exposure to 1000 lx versus 200 lx, finding participants significantly more pleasant under high illuminance. A recent study simi-

larly found that compared to low illuminance (100 lx), participants' self-reported negative mood (PANAS) scores significantly decreased after 50 minutes of high illuminance exposure (1000 lx) (Ru et al., 2019). Furthermore, some research found that even slightly higher illuminance (360–400 lx) for a short duration (45 min) could improve negative mood at night (Bijleveld & Knufinke, 2018). However, some studies failed to find mood improvement effects of illuminance (Baron et al., 1992; Huiberts et al., 2015, 2016; Smolders et al., 2012). For instance, Smolders et al. (2012) found that one hour of bright light (1000 lx) did not significantly alter mood compared to low illuminance (200 lx). Huiberts et al. (2016) used longer exposure (90 min) and higher illuminance (1700 lx vs. 165 lx) but found no significant changes in mood state (measured by two 5-point Likert items).

The discrepancies in short-term bright light effects may stem from differences in lighting parameters, exposure duration, measurement tools, and methods across studies. For example, Ru et al. (2019) used the Positive and Negative Affect Schedule and moderate high illuminance (1000 lx), whereas Huiberts et al. (2016) and Smolders et al. (2012) used single items ("happy" and "sad") for mood measurement, with Huiberts et al. using even higher illuminance (1700 lx). Notably, the two Smolders studies used identical measurement methods but differed in duration (90 min vs. 60 min). These laboratory studies also focused on both cognitive and emotional functions, so different cognitive tasks during light exposure may interact with light' s emotional effects. Moreover, some studies found electrophysiological measures more sensitive to light effects than subjective ratings. Yoshiike et al. (2018) discovered that short-term (15 min) bright light (9000 lx) enhanced top-down regulation of fear stimuli and fear extinction by modulating prefrontal cortex hemodynamic responses, yet had no significant effect on subjective mood state (VAS measurement). Thus, some subjective mood measures may fail to detect subtle emotional effects of bright light.

2.2 Effects of Color Temperature on Mood

Color temperature is another physical attribute of composite white light, measured in Kelvin (K). Its NIF efficacy primarily depends on blue light components in the spectrum—higher color temperature indicates relatively more short-wavelength blue content, and vice versa. Current research on color temperature and mood has yielded inconsistent conclusions. Earlier studies suggested high color temperature significantly enhances positive mood. For example, a 14-week follow-up study of healthy populations found participants' mental health and vitality levels significantly higher under high color temperature white light (17000 K) compared to low color temperature fluorescent light (2900 K) (Mills et al., 2007). Hawes et al. (2012) compared four color temperatures (90 min, 3345 K, 4175 K, 5448 K, 6029 K) and found high color temperature (6029 K) significantly increased positive mood and reduced fatigue, with a positive correlation between color temperature and positive mood levels. Conversely, Smolders and

de Kort (2017) found participants showed less pleasure and more sadness under high color temperature white light (6000 K vs. 2700 K, 60 min). Meanwhile, some studies found no significant effects of short-term exposure to color temperature on mood (Baron et al., 1992; Knez, 2014). For instance, Knez (2014) found no significant differences in mood (measured by a 48-item self-developed scale) after 85 minutes of exposure to fluorescent lights at 3000 K, 4000 K, and 5500 K. Rodent studies even suggest high color temperature increases negative mood in mice—male mice exposed to cool white light (4000 K, 30 min) showed more anxiety than those under warm white light (2500 K) (Kapogiannatou et al., 2016). Yokoyama et al. (2019) also reported that 90 min of high color temperature light increased neural activity in the paraventricular nucleus (PVN) of mice, indicating more stress responses. Currently, relatively few studies have independently investigated color temperature' s NIF effects on mood, and differences in exposure duration, subjects (diurnal humans/nocturnal mice), and measurement indicators prevent consistent conclusions, warranting further research.

As inseparable attributes of composite white light, illuminance and color temperature have also been examined for their interactive effects on mood. Ru et al. (2019) investigated the cross-effects of indoor white light illuminance (100 lx vs. 1000 lx) and color temperature (2700 K vs. 6500 K) on subjective positive and negative mood in simulated office environments. Results only found that high illuminance or low color temperature significantly reduced subjective negative mood, with no interactive effects between illuminance and color temperature. This may relate to Ru et al.' s limited use of only two illuminance and color temperature levels. Future research should systematically explore interactive effects by setting multiple parameter levels.

2.3 Wavelength

Wavelength is the most important spectral characteristic of monochromatic light. The general visible light range for human eyes is 380 nm to 780 nm, with different colors corresponding to different wavelengths—red light approximately 622–780 nm, green light approximately 492–577 nm, and blue light 455–492 nm. In daily life, we increasingly encounter various colored light sources. Since ipRGCs mediating the non-visual pathway have peak sensitivity at approximately 480 nm (Berson et al., 2002; Freedman et al., 1999; Provencio et al., 2000), short-wavelength blue light is expected to produce more pronounced NIF effects than medium-wavelength green or long-wavelength red light (Berson et al., 2002; Brainard et al., 2001; Hattar et al., 2002). For example, Kim et al. (2013) used an interactive emotional lighting system to recognize individuals' emotional states in real-time (via photoplethysmography, skin temperature, and galvanic skin response), finding individuals felt relaxed under blue light while red light increased arousal levels. Smith and Spiridon (2018) reported blue light alleviated negative mood (anger) in individuals in unmanned aircraft cockpits. However, some studies found blue light increased negative mood in

special populations—Segal et al. (2016) exposed sleep-restricted individuals to 3 hours of blue, green, or no light, finding more hostility under blue light.

Brain imaging evidence indicates blue light has immediate effects on brain regions in cortical and subcortical areas involved in emotional perception and processing. Compared to green light, blue light significantly enhanced brain activity in bilateral temporal cortex and hippocampus—sound-sensitive regions —when processing angry voices, with strengthened functional connectivity between left temporal voice-sensitive areas and left amygdala and hypothalamus (Vandewalle et al., 2010). Additionally, Vandewalle et al. (2011) found SAD patients differ from normal controls in color light sensitivity—blue light (480 nm) enhanced posterior hypothalamus responses (dorsolateral to mammillary bodies) to negative auditory stimuli in SAD patients, while green light (550 nm) reduced these responses, an effect not observed in normal controls. A recent study also showed that short-term (40 min) exposure to blue light (469 nm) significantly activated the rostral anterior cingulate cortex (ACC) when processing reward certainty anticipation stimuli (Alkozei et al., 2016). Metz et al. (2017) used systemic physiology-augmented functional near-infrared spectroscopy (SPA-fNIRS) to measure colored light' s effects on human brain physiological activity, finding blue light (450 nm) significantly activated left prefrontal cortex compared to red (630 nm) and green (515 nm) light. Thus, at the non-visual level, short-wavelength blue light shows more pronounced modulatory effects on mood-related brain regions than long-wavelength red and green light. Visually, different colored lights may have different emotional functions due to their distinct color appearances. Early studies found red light evoked unpleasant associations with blood, injury, fire, and danger, while blue light related to positive thoughts (friendliness, romantic love, blue sky). This has been validated in color-emotion research (Elliot & Maier, 2014)—red is typically associated with negative emotions like danger, while blue and green relate to positive emotions like peace and calm. Laboratory studies have found colors affect physiological arousal and subjective emotional evaluation—red produces stronger stimulation of skin conductance and heart rate than yellow and blue, indicating higher arousal (Jacobs & Hustmyer Jr, 1974; Wilms & Oberfeld, 2018). Participants felt more relaxed and calm in blue environments compared to red and yellow (Al-Ayash et al., 2016). Similarly, exposure to red light significantly increased arousal levels (increased systolic pressure, skin conductance, respiratory rate, blink frequency) and reduced pleasure compared to blue and green light (Ali, 1972; Rajae-Joordens, 2010; Wilson, 1966). Red light appears to have arousing and activating capabilities, while blue and green light induce emotional calm. However, inconsistent findings exist—a study of older adults (mean age 71) found blue light less pleasant and more stimulating than red light (Laufer et al., 2009), suggesting color light effects on mood may be moderated by age. Researchers also found saturation and brightness of colored light are important factors modulating mood and arousal (Rajae-Joordens, 2010). Therefore, mood may be influenced not only by short-wavelength blue light but also by other colored lights through both visual and non-visual pathways.

3 Effects of Light Timing Patterns on Mood: Evidence from Special Populations and Animal Models

Before artificial lighting, human lighting patterns approximated a 12:12 h light-dark cycle. With electric lighting, electronic media, night shifts, rotating shift work, and trans-time-zone travel, human light exposure patterns have changed. Researchers have extensively examined how different lighting patterns affect mood, particularly the detrimental effects of short photoperiods, nighttime light, and constant light/darkness.

3.1 Effects of Short Photoperiods on Mood

Researchers initially became interested in how daytime light duration affects mood through studies of Seasonal Affective Disorder (SAD) patients. First described by Rosenthal (1984), SAD manifests as recurrent depressive symptoms appearing annually in autumn/winter and remitting completely or partially switching to mania in spring/summer. Research suggests shortened daylight in autumn/winter is the main cause of winter depression in SAD patients. Epidemiological surveys find SAD prevalence significantly higher in high-latitude regions with less annual solar radiation than low-latitude regions (Kegel et al., 2009), with approximately 5% prevalence and another 15% showing SAD subsyndromal symptoms (Magnusson & Boivin, 2003; Rosen & Rosenthal, 1991). Individuals moving from low to high latitudes experience more severe winter depression (Kurata et al., 2016; Low & Feissner, 1998). Rodent studies also show short photoperiods similar to winter increase anxiety- and depression-like behaviors. Prendergast and Nelson (2005) found male Siberian hamsters exhibited depression-like behaviors after only 14 days in short 8L/16D (8 h light, 16 h dark) photoperiods. Einat et al. (2006) placed obese gerbils in short 5L/19D photoperiods for 21 days, resulting in depression-like responses in forced swim tests. Nocturnal Siberian hamsters exposed to winter-like short days (8L/16D) showed depression-like responses in forced swim tests and anxiety-like responses in elevated maze tasks (Workman et al., 2011). In summary, short photoperiods have detrimental effects on mood, with shortened daytime light duration causing and exacerbating depressive and anxiety symptoms.

3.2 Effects of Nighttime Light on Mood

Although natural light patterns differ across latitudes, nighttime light exposure is similar worldwide. A recent satellite data study indicates over 80% of the world' s population and over 99% of Americans and Europeans live under nighttime light pollution (Falchi et al., 2016). Research suggests chronic nighttime light exposure increases risk for mood disorders. Early field studies found significant positive correlations between depressive symptoms in elderly adults and nighttime light exposure intensity and duration (Obayashi et al., 2013). A recent large-sample study (265,278 Koreans) showed individuals exposed to high-intensity outdoor light at night had higher depression likelihood, with depressive symptoms and suicidal ideation linearly correlated with nighttime outdoor light

intensity (Min & Min, 2018). Another U.S. adolescent study (10,123 adolescents) confirmed nighttime outdoor artificial light levels significantly positively correlated with mood disorder prevalence (bipolar disorder, major depression, anxiety disorders) (Paksarian et al., 2020). Rodent studies also indicate nighttime dim light increases depression-like behaviors (Bedrosian et al., 2011; Bedrosian et al., 2013), with dose-dependent effects—longer nighttime light exposure leads to more severe depressive symptoms (An et al., 2020). Therefore, chronic nighttime light exposure increases depression risk, with higher intensity and longer duration producing more severe depressive symptoms.

3.3 Effects of Constant Light/Darkness on Mood

Extreme lighting patterns like constant light (LL) and constant dark (DD) are rare in normal human life but may be frequently encountered by night and shift workers. Studies show constant light increases depression-like (Fonken et al., 2009; Tapia-Osorio et al., 2013) and anxiety-like behaviors (Tapia-Osorio et al., 2013; Zhou et al., 2018). Tapia-Osorio et al. (2013) found short-term (3–4 weeks) and long-term (6–7 weeks) constant light exposure in male Wistar rats produced mild depression-like symptoms in sucrose preference tests and increased anxiety in open field tests. Another recent study confirmed 4 weeks of constant light increased both depression- and anxiety-like behaviors in C57BL/6 male mice (Zhou et al., 2018). Complete light deprivation through constant darkness also affects emotional behavior in rodents—studies show constant darkness increases depression-like behaviors (Lu et al., 2016; Monje et al., 2011). Monje et al. (2011) placed adult male rats in constant darkness for 4 weeks, resulting in reduced hippocampal cell proliferation and increased depression-like behavior. A newer study also found 3 weeks of constant darkness induced depressive behavioral phenotypes in mice (Lu et al., 2016). However, compared to depressive mood, constant darkness' s effects on anxiety are weaker—some studies found constant darkness increased depression-like behavior in mice but had nonsignificant effects on anxiety-like behavior (Tapia-Osorio et al., 2013; Zhou et al., 2018). Therefore, lighting patterns completely unsynchronized with internal physiological rhythms, such as constant light and darkness, severely negatively affect mood and emotional behavior, inducing mood disorders like depression and anxiety.

Notably, some animal model studies used nocturnal mice or special populations with mood disorders, so results may not fully apply to diurnal humans or healthy populations. However, these results provide important insights and perspectives for exploring light' s mechanisms of action on mood. The applicability of animal or special population model results to humans requires further investigation, and ethically appropriate human studies are necessary for clearer understanding of light' s effects on human mood.

4 Moderating Factors of Light' s Effects on Mood

When exploring the NIF effects of ambient light on mood in humans and animals, researchers have identified several potential influencing factors. Temporal factors such as exposure duration and timing, individual characteristics like gender and age, subjective preferences, and genetic types may all play roles in light' s emotional functions.

4.1 Temporal Factors

Evidence suggests both bright light exposure duration and morning exposure timing are significantly negatively correlated with depressive mood. Longer bright light exposure over time (Esaki et al., 2019; Harb et al., 2015) and earlier morning bright light exposure (Figueiro et al., 2017; Jean-Louis et al., 2005) correlate with lower depression scores. Laboratory studies on short-term bright light exposure also suggest possible moderating effects of duration—Smolders et al. (2014) found 30 minutes of bright light (1000 lx) improved positive mood, while 50 minutes of bright light (1000 lx) produced non-significant effects on both positive and negative mood (Smolders et al., 2012). These two studies used similar measurement tools, lighting parameters, and experimental paradigms, suggesting prolonged high illuminance may be detrimental to subjective emotional experience. Conversely, color temperature' s effects on mood may depend on longer exposure—researchers found approximately one hour of high color temperature exposure had non-significant or slightly negative effects on mood (Smolders & de Kort, 2017), while relatively longer (90 min) high color temperature exposure significantly enhanced positive mood (Hawes et al., 2012). However, these studies contain other confounding factors, requiring comprehensive consideration of exposure duration, timing, and other moderating factors when assessing light' s acute effects on mood.

4.2 Individual Characteristics

Beyond temporal factors, individual characteristics (gender and age) significantly moderate light' s emotional effects. Studies show inconsistent emotional responses to light across gender and age groups. Two earlier studies found women' s negative mood decreased under low color temperature (3000 K) and increased under high color temperature (4000 K), while men' s negative mood increased under low color temperature and decreased under high color temperature (Knez & Enmarker, 1998; McCloughan et al., 1999). Additionally, under high illuminance (~810 lx), women's negative mood significantly decreased while men' s significantly increased (McCloughan et al., 1999). In abnormal lighting' s negative effects, SAD prevalence is significantly higher in women than men in high-latitude regions (Wirz-Justice et al., 2019), and rodent studies found female mice showed more depression-like behavior than males after 3 weeks in constant darkness (Lu et al., 2016), suggesting women are more sensitive to abnormal light' s negative effects than men. Age also moderates light' s emotional functions—Knez and Kers (2000) found after 90 minutes of light exposure,

young participants' negative mood increased more under high color temperature (4000 K), while older participants' negative mood increased more under low color temperature (3000 K). Additionally, children and adolescents appear more sensitive to nighttime light exposure (Obayashi et al., 2013), with adolescents (13–18 years) showing significantly higher sensitivity to short-wavelength light (melatonin suppression) than adults (32–51 years) (Nagare et al., 2019), possibly related to age-related differences in melatonin secretion, which decreases with age (Tan et al., 2018). In summary, gender and age are important moderating factors, though their underlying mechanisms require further investigation.

4.3 Subjective Preferences

In short-term light exposure, individuals' subjective evaluation and expectations also moderate emotional responses. Maier et al. (2016) reported that participants' expectations of lighting environments were more important than actual lighting levels in affecting psychological states—objective illuminance had non-significant effects on mood, but positive expectations about lighting environments influenced positive mood. Kombeiz and Dietl (2018) found similar results: lighting satisfaction, rather than lighting conditions themselves, more strongly influenced participants' positive evaluations of others, with lighting satisfaction significantly positively correlated with positive affect. Notably, a "familiarity effect" may also influence emotional responses (Baron et al., 1992), as people generally prefer familiar things, and familiar lighting environments may thus lead to more positive mood. Therefore, future lighting studies should comprehensively consider participants' expectations, visual experiences, and other factors.

4.4 Genetic Types

Genetic type is another important factor moderating light' s emotional functions. PER3 is one of the strongest rhythmic genes in humans and animals, playing important roles in determining circadian period and phase in peripheral tissues beyond the SCN. PER3 polymorphisms correlate with circadian preference, sleep homeostasis, cognition, light sensitivity, and mood disorders (Archer et al., 2018). $PER3^{5}/^{5}$ genotype individuals show stronger light sensitivity than $PER3^{4}/^{4}$ individuals (Chellappa et al., 2012); $PER3^{5}/^{5}$ individuals tend toward evening chronotype, while $PER3^{4}/^{4}$ individuals lean toward morning type (Dijk & Archer, 2010). A recent review proposed a strong positive correlation between evening chronotype and depression (Bauducco et al., 2020), suggesting PER3 polymorphism may play an important role in light-mood relationships. Additionally, since serotonin transporter (5-HTT) expression is regulated by insertion (L allele)/deletion (S allele) polymorphisms in the serotonin transporter gene promoter region (5-HTTLPR), the short (S) allele—associated with reduced serotonin signaling compared to the long (L) allele—is linked to increased risk for SAD and atypical depression (Heils et al., 1996; Rosenthal et al., 1998; Willeit et al., 2003). An earlier study also found 5-HTTLPR polymorphism moderated

light' s effects on prefrontal functional connectivity in healthy participants—after bright light intervention, carriers of LG or S alleles showed enhanced medial prefrontal cortex functional connectivity, while LA/LA individuals showed minimal effects (Fisher et al., 2014). Therefore, 5-HTTLPR polymorphism also moderates light' s emotional effects. Although only these two polymorphisms have been reported to moderate light' s emotional functions, genome-wide and targeted gene studies may reveal additional moderating polymorphisms.

In summary, environmental light' s effects on mood are moderated by multiple objective and subjective factors including timing, individual characteristics, subjective preferences, and genetic types. Recent research also found personality traits interact with light to affect mood (Veenstra & Koole, 2018)—individuals with high trait anger showed significantly higher state anger after reading angry scenarios under bright light but lower anger under dim light. Therefore, future research assessing light' s emotional functions must comprehensively consider these moderating factors and other potential influences. Clarifying these moderating variables can provide new perspectives on understanding the intrinsic mechanisms through which environmental light affects mood.

5 Mechanisms of Light' s Effects on Mood

The intrinsic mechanisms underlying environmental light' s effects on mood remain a frontier and hot topic. Although ipRGCs constitute only a small proportion of retinal ganglion cells (<5%), they have extensive influence. ipRGC subtypes (M1–M6) project to dozens of brain regions (Schmidt et al., 2011), many of which play important roles in driving light-mediated physiology and behavior. ipRGCs have direct projections to nuclei regulating depression and/or anxiety, such as the medial amygdala (MA) and lateral habenula (LHb), indicating light can have direct, immediate effects on mood. Additionally, ipRGCs transmit light signals to the suprachiasmatic nucleus (SCN), the master circadian pacemaker that synchronizes internal physiological rhythms with external light-dark environments. The SCN also transmits light information to other brain regions, including the ventral tegmental area (VTA), raphe nuclei, and pineal gland (LeGates et al., 2014). Furthermore, the ventrolateral preoptic area (VLPO) and suprachiasmatic nucleus (SC), which regulate sleep-wake cycles, receive both direct ipRGC projections and SCN projections. Therefore, light can directly affect mood without altering circadian rhythms, while also indirectly influencing mood through regulation of circadian rhythms and downstream physiological processes.

5.1 Direct Activation Effects

Although environmental light' s most important role is as a circadian pacemaker that influences other physiological and behavioral activities through internal rhythm synchronization, extensive research confirms that environmental light has immediate, direct effects on mood without affecting circadian rhythms. This

depends on ipRGCs in the retina directly transmitting light signals to emotion-regulating nuclei such as the medial amygdala (MA) and lateral habenula (LHb) (Hattar et al., 2006; Hattar et al., 2002; Schmidt et al., 2011). Human brain imaging evidence confirms direct neural responses to short-term acute light in cortical and subcortical structures, with environmental light significantly affecting neural activity in limbic regions like the amygdala and hippocampus (Vandewalle et al., 2009; Vandewalle et al., 2010), cingulate cortex (Alkozei et al., 2016), and prefrontal cortex (Fisher et al., 2014; Yoshiike et al., 2018). When processing negative emotional stimuli, bright light suppresses amygdala-driven bottom-up emotional attention networks and enhances PFC-mediated top-down regulation of the amygdala, with these limbic region activities showing illuminance-dependent changes—the higher the illuminance, the stronger the regulatory effect (Fisher et al., 2014; Yoshiike et al., 2018). Therefore, light' s modulation of limbic brain regions is an important mechanism for its direct mood effects. Specifically, light reduces amygdala responses to negative emotional stimuli, modulating bottom-up automatic emotional processing, while strengthening functional connectivity between PFC and amygdala to drive top-down inhibitory control. Moreover, since most studies find differences at brain region levels rather than subjective mood or behavioral response levels, light' s effects on mood may involve more complex pathways than single brain regions.

The lateral habenula (LHb) plays an important role in light pattern effects on mood. Legates et al. (2012) found mice showed increased depression-like behavior under abnormal light patterns (T7) without affected circadian rhythms or sleep, while melanopsin-knockout mice were protected from T7' s depressive effects, suggesting direct light effects on mood via ipRGCs. Subsequently, Fernandez et al. (2018) confirmed abnormal light cycles' (T7) mood effects were SCN-independent, with chronic activation of lateral habenula marginal zone (pHb) neurons via ipRGCs forming the basis for light' s mood regulation and depression induction. Specifically, light signals transmit directly via ipRGCs to pHb, activating pHb neurons that project to prelimbic (PL) and infralimbic (IL) cortices in prefrontal cortex and receive descending feedback. pHb also projects to dorsal striatum and nucleus accumbens—emotion-related regions. However, the ipRGCs-pHb circuit is not broadly involved in mood regulation but specifically tracks light pattern changes. Recently, An et al. (2020) found nighttime light' s depressive effects were mediated by melanopsin projections from ipRGCs to dorsal pHb (dpHb) and then to nucleus accumbens (NAc). Since dpHb is also regulated by the circadian system and more easily activated at night than day, the ipRGCs-dpHb-NAc pathway may preferentially transmit nighttime light information, increasing nighttime light-induced depression-like behavior. Huang et al. (2019) also found light therapy' s effects involved retinal-ventral geniculate/lateral geniculate-lateral habenula pathway inhibition of postsynaptic habenula neurons, which directly project to dorsal raphe and VTA—brain regions regulating mood-related behaviors (reward, depression-like, anxiety-like). This pathway may also alleviate anxiety. In summary, light directly affects mood by activating or inhibiting neural activity in relevant brain regions via ipRGCs

without affecting circadian rhythms or sleep.

5.2 Circadian Rhythm Effects

As described above, the SCN is the central circadian oscillator receiving massive axonal projections from retinal ipRGCs, including light/dark (LD) cycle information (Moore et al., 2002). After light signals reach the SCN via ipRGCs, the master clock interacts with many systems and processes in brain and peripheral tissues, regulating neurotransmission, hormone secretion, neurogenesis, metabolism, immune function, and sleep-wake patterns. Therefore, light signals have diverse pathways to affect mood after reaching the SCN. This section focuses on melatonin, monoamine neurotransmitters, and sleep.

5.2.1 Melatonin Melatonin (MT) is a neuroendocrine hormone secreted by the pineal gland. After light signals reach the hypothalamic SCN via the retinohypothalamic tract, the SCN projects neural signals through multisynaptic pathways to the pineal gland, regulating melatonin secretion (Kalsbeek et al., 2006). Melatonin secretion levels are important indicators of internal physiological rhythms. Melatonin is extremely sensitive to light, with its synthesis rhythm' s amplitude, phase, and period responding rapidly to light. Early studies showed healthy participants exposed to 45 lx light for 1 hour had 60% reduced plasma melatonin concentration (Brainard et al., 1988). Recent research found healthy humans under nighttime light with average intensity of 24.6 lx showed 50% reduced melatonin, with secretion delay duration increasing with light intensity (Phillips et al., 2019). Besides regulating SCN rhythm oscillations in reverse (Dubocovich, 2007), melatonin widely affects other physiological processes—studies confirm melatonin positively affects hippocampal cell proliferation (Crupi et al., 2010; Ramírez-Rodríguez et al., 2009), stimulates brain neurotrophin production (Kong et al., 2008), and reduces pro-inflammatory cytokine levels in brain and peripheral tissues (Brainard et al., 2001; Panda et al., 2002)—all highly relevant to depression pathophysiology. Notably, some researchers propose that altered melatonin secretion timing due to environmental light changes may be central to SAD pathophysiology (Pereira et al., 2017; Wehr, 1997). Melatoninergic drugs like agomelatine, a melatonin receptor agonist and 5-HT receptor antagonist, demonstrate good antidepressant effects in preclinical and clinical studies (Goodwin et al., 2009; Kennedy & Rizvi, 2010). Therefore, circadian-regulated melatonin changes represent a possible pathway for light' s mood-regulating functions.

5.2.2 Monoamine Transmission Monoamine neurotransmitters (dopamine, serotonin, etc.) and their receptors show rhythmic oscillations in concentration, release, and expression (Barassin et al., 2002; Khaldy et al., 2002; Malek et al., 2005; Weiner et al., 1992), suggesting central clock regulation. The circadian system regulates monoamine neurotransmitters through two main pathways: local expression of clock genes (Guilding & Piggins, 2007) and SCN indirect projections to dopamine-rich VTA and serotonin-rich dorsal and median raphe

nuclei (McClung, 2013), thereby affecting depression, anxiety, and reward behavior. Therefore, environmental light' s effects on monoamine transmission via the circadian system may underlie seasonal variations in mood and affective disorders.

Environmental light' s modulation of the dopaminergic system has been extensively documented. Under high daylight conditions, healthy participants show higher dopamine (DA) receptor availability in cerebrospinal fluid and lower striatal presynaptic DA synthesis (Eisenberg et al., 2010; Tsai et al., 2011). DA concentrations rhythmically oscillate in rat striatum and nucleus accumbens and respond to chronic constant light (Tamara et al., 2003). Light also significantly modulates the serotonergic system—brain 5-hydroxytryptamine (5-HT) production rate directly correlates with sunlight duration and rapidly increases with light intensity (Lambert et al., 2002). Daily sunlight and total radiation affect 5-HT-1A receptor binding in healthy individuals' limbic brain regions, with 20–30% reduction under low light (Spindelegger et al., 2012). Winter bright light therapy significantly increases 5-HT activity in anterior cingulate and prefrontal cortices (Gupta et al., 2013). The dopamine and 5-HT systems are considered important neural circuits in depression pathophysiology, with VTA DA projections to limbic regions (nucleus accumbens, olfactory tubercle, amygdala, hippocampus, medial PFC, cingulate) and raphe 5-HT axons widely activating cortex, hippocampus, medial amygdala, bed nucleus of stria terminalis, and hypothalamus (Li & Li, 2018). Notably, the serotonergic system also projects from midbrain raphe to SCN, providing modulatory input to the circadian pacemaker (Nestler & Hyman, 2010). In summary, circadian-regulated monoamine neurotransmitter transmission represents another pathway through which light may affect mood.

5.2.3 Sleep Sleep modulation is another important pathway for light' s effects on mood. Environmental light affects sleep through two pathways: first, light information entrains endogenous circadian rhythms, thereby determining sleep-wake timing (Prayag, Munch, et al., 2019); second, without affecting circadian rhythms, light projects signals via melanopsin to VLPO and SC, producing immediate effects on sleep and wakefulness (Altimus et al., 2008; Lupi et al., 2008; Tsai et al., 2009), with such acute effects observable at any time of day (Tsai et al., 2009). Early studies demonstrated light therapy effectively improved sleep efficiency and delta levels in NREM sleep in SAD patients, with effects independent of light timing, suggesting direct melanopsin-mediated effects rather than circadian-driven (Anderson et al., 1994; Campbell et al., 1993).

Sleep' s effects on mood constitute a major and important theme. Regarding sleep-wake cycles, when internal circadian rhythms (e.g., melatonin and temperature rhythms) are delayed relative to sleep/wake cycles, a phase angle between sleep and physiological cycles causes depression (Germain & Kupfer, 2008; Lewy et al., 2007). Regarding sleep architecture, REM sleep uniquely activates emotion-related brain regions (amygdala, hippocampus) while sup-

pressing aminergic neurotransmitter transmission (norepinephrine, serotonin). According to the SFSR (sleep to forget and sleep to remember) model, REM sleep promotes memory consolidation for emotional, especially negative, stimuli. Regarding sleep duration, sleep deprivation broadly affects emotion, including basic emotional processing (recognition, reaction, expression) and higher-order social-emotional functions (loneliness, helping behavior, abusive behavior), with underlying mechanisms including loss of prefrontal top-down regulation of amygdala, abnormal cortical processing in salience networks (insula, cingulate cortex), and altered sympathetic-vagal balance (Ben Simon et al., 2020). Additionally, acute sleep deprivation (SD) demonstrates rapid antidepressant effects (Boland et al., 2017), potentially through SD-induced changes in cytokines, cortisol, brain-derived neurotrophic factor, and neuroplasticity (Benedetti et al., 2008; Gorgulu & Caliyurt, 2009; Voderholzer et al., 2012). Therefore, although light' s neural mechanisms affecting sleep are relatively clear, how sleep under light' s influence further affects mood requires future in-depth discussion.

In summary, environmental light can indirectly affect mood through circadian rhythms, sleep, and other intermediate variables. However, because the circadian system continuously influences neurotransmission, hormone secretion, immune responses, and sleep-wake cycles, light' s pathways to affect mood become more complex and diverse. Future research can construct comprehensive models of environmental light' s mood effects using diverse paradigms from animal models, healthy participants, and depression patient pathological models.

6 Clinical Applications of Light Therapy

The best evidence for light' s emotional efficacy is its widespread application in treating Seasonal Affective Disorder (SAD) and other affective disorders. Besides effectiveness for SAD, light therapy also shows efficacy for non-seasonal affective disorders (major depression, bipolar disorder, perinatal depression) and emotional symptoms accompanying other clinical diseases.

6.1 Applicable Populations

In the 1980s, light therapy was first used to treat Seasonal Affective Disorder (Rosenthal et al., 1984). Due to its good antidepressant effects, low cost, convenience, and minimal side effects, light therapy is widely applied to SAD and other non-seasonal affective disorder patients. Numerous studies have validated light therapy as monotherapy or combined with antidepressants or total sleep deprivation in affective disorder patients (Chang et al., 2018; D' Agostino et al., 2020; Lam et al., 2016; Lieverse et al., 2011; Zhao et al., 2018). Multiple meta-analyses show light therapy has small-to-moderate effects on depression symptoms (effect sizes 0.41–0.62), with some studies showing monotherapy has larger, more significant antidepressant effects than combined drug treatment (Al-Karawi & Jubair, 2016; Dallaspezia & Benedetti, 2020; Perera et al., 2016; Tseng et al., 2016). Notably, light therapy positively affects sleep, mood, and

motor function in Parkinson' s disease patients (Fifel & Videnovic, 2018; Videnovic et al., 2017; Willis et al., 2012). Studies also show positive effects of light therapy on cognition, mood, and behavior in Alzheimer' s disease patients, reducing anxiety, depression, or agitation symptoms (Hanford & Figueiro, 2013; Mitolo et al., 2018).

6.2 Light Therapy Usage

Common light sources in light therapy include light boxes, desk lamps, goggles, ceiling lights, and LED lights. Regarding light intensity, series studies prove that intensities from 176 lx to 10000 lx at 50 cm from the eyes produce positive antidepressant effects (Benedetti et al., 2003; Jiang et al., 2020; Loving et al., 2005; Strong et al., 2009). For wavelength, blue, green, and white light all significantly improve mood, with white light most widely used (Alotaibi et al., 2015). Since melanopsin is most sensitive to blue spectrum, some research suggests blue light may be superior to white light for mood improvement at low illuminance (Anderson et al., 2009). However, other researchers found no clear advantage for blue light over white light in mood disorder treatment (Anderson et al., 2016; Chang et al., 2018; Gordijn et al., 2012; Zhao et al., 2018), and blue light may affect rods and cones, reducing photoreceptor responsiveness (Kuse et al., 2014; Stephenson et al., 2012). Therefore, given limited understanding of blue light' s potential impacts, using monochromatic blue light in therapy requires caution.

Regarding light timing, researchers suggest adjustments based on treatment targets. For SAD patients, timing should be determined by pathological mechanisms—whether circadian phase is advanced or delayed. Phase-advanced patients should receive evening light, while phase-delayed patients should receive morning light (Choukroun & Geoffroy, 2019). For bipolar depression, morning or midday light works better, gradually increasing 15 minutes weekly until reaching 60 minutes at week 4, reducing mania transition risk after phototherapy. Daily light duration depends on intensity: 2500 lx corresponds to 2 hours, 5000 lx to 1 hour, and 10000 lx to 30 minutes. Phototherapy periods generally last 2–6 weeks in research; clinically, researchers recommend starting in autumn/winter when daylight shortens and continuing until spring/summer when symptoms remit spontaneously. During treatment, patients must keep eyes open but need not look directly at the light; they can eat or read as long as light enters the pupils (Maruani & Geoffroy, 2019).

7 Future Directions

7.1 Clarifying Short-Term Light Exposure Patterns

Research conclusions on short-term light' s mood effects are inconsistent, likely due to many interfering factors. First, light timing throughout the day differentially affects circadian rhythms—morning light advances circadian phase while evening light delays it, potentially differentially affecting mood. Second, despite

all being short-term exposures, durations vary across studies. Recent research shows different ipRGC subtypes have varying response durations to bright light (Mure et al., 2019), making it unclear whether temporal boundaries moderate light' s mood effects. Additionally, some studies suggest high illuminance or color temperature enhances positive mood, while others find they worsen mood. Future research should explore illuminance and color temperature effects by setting multiple parameter levels. Moreover, a recent study proposed light' s NIF effects primarily depend on melanopic illuminance levels (Brown, 2020)—whether using melanopic illuminance as an operational standard better explores light's NIF mood effects than illuminance and color temperature requires further investigation.

7.2 Diversified and Objective Mood Measurement Dimensions

Most studies on light' s mood effects use subjective self-report scales. In mood disorder populations, clinical diagnostic depression scales (e.g., Hamilton Rating Scale for Depression) are commonly used. For immediate light effects, diverse subjective tools are employed: Positive and Negative Affect Schedule (PANAS), Profile of Mood States (POMS), Self-Assessment Manikin (SAM), semantic differential scales (paired adjectives), etc. These diverse measures increase difficulty in cross-study comparisons and are susceptible to subjective interference. Research shows light affects cortical, subcortical, and peripheral systems at different exposure durations (Prayag, Jost, et al., 2019), suggesting temporal differences between neural and behavioral responses to light's immediate mood effects. Future studies should use cognitive neuroscience techniques to simultaneously examine subjective mood experiences and objective neural activity changes under different lighting conditions, evaluating light' s emotional efficacy through multimodal data fusion analysis of subjective experience, behavioral records, physiological responses, and neural activity.

7.3 Visual Functions of Light in Mood Induction

Current research on environmental light' s mood effects primarily focuses on ipRGC-mediated NIF effects. However, as a physical stimulus, environmental light inherently conveys specific emotional meanings (Quartier et al., 2014). Studies show individual characteristics like lighting satisfaction, expectations, and preferences significantly affect emotional responses (Kuller et al., 2006; Maier et al., 2016). Additionally, different illuminance, color temperature, wavelength, and lighting modes (direct/indirect) create different visual perceptions —low color temperature feels warm and relaxing, high color temperature feels formal and energizing (Cui et al., 2018; Tantanatewin & Inkarojrit, 2016; Wei et al., 2014). Therefore, a core question is whether visual perception formed primarily by rods and cones also affects mood, and if so, what is its contribution and how can it be separated? This requires future investigation.

Environmental light' s effects on mood constitute a crucial topic. Current research focuses primarily on light therapy' s antidepressant effects and physiologi-

cal rhythm disruption from different lighting patterns. Short-term light' s mood effects have been explored but with large discrepancies. No clear consensus exists on light's mood effect pathways. In fact, light's physical parameters, timing, duration, and patterns may have inconsistent mood effects (improving or worsening), suggesting different mechanisms. Many questions about environmental light' s effects on human mood remain unanswered. Today, with increasingly blurred external light-dark cycles, human light exposure duration has greatly extended, and desynchronization between social rhythms and normal light-dark cycles due to lifestyle or work patterns has become more common. Investigating how these changes affect mood can inform reasonable interventions in objective environments and subjective lifestyles, improving life satisfaction and mental health, while providing more objective scientific evidence for clinical and non-clinical light applications.

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