健康照明应用研究发展与展望

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摘要 本质感光视网膜神经节细胞(intrinsically photosensitive retinal ganglion cells, ipRGC), 通过视网膜下丘脑束(retinohypothalamic tract, RHT)与下丘脑视交叉上核(suprachiasmatic nucleus, SCN)等在大脑区域形成投射(即非视觉通路), 对人的生理产生影响。这一非视觉效应的发现赋予了照明研究与应用全新内涵, 即通过照明技术与智能控制技术的有机结合, 因人、因时、因地合理控制照度及其分布, 为用户创造“安全、舒适、有益身心”的健康照明光环境。而发光二极管(light emitting diode, LED)照明技术的应用和健康照明新内涵又对基于视觉感知的评价指标提出了新的要求。本文对照明与视觉、非视觉通路的影响相关研究成果进行综述, 提出我国健康照明光环境的研究与实施的思考和判断。

关键词 视觉通路, 非视觉通路, 健康照明, 视觉舒适, 生命节律

光是生命的源泉, 是人居环境的要素, 光环境质量被看作是影响人们工作、生活的重要因素之一。长期以来, 照明光环境的研究重点围绕传统照明应用条件下的视觉功效与舒适开展, 并建立了较为完备的技术标准体系, 对指导照明光环境设计与实践起到了十分重要的作用^[1]。

视网膜上存在一个新的神经通路, 通过视网膜下丘脑神经束(retinohypothalamic tract, RHT)与大脑的下丘脑相连接, 参与激素分泌、身体核心温度调节、新陈代谢等一系列非视觉活动^[2~4]。这一发现使得照明的内涵发生了巨大的变化, 即以照明技术与智能控制技术的有机结合作为技术手段, 以因人、因时、因地合理控制照度及其分布作为控制策略, 以创造“安全、舒适、有益身心”的健康照明光环境作为目标。

与此同时, 这种LED(light emitting diode)照明技术的应用和健康照明新内涵对基于视觉感知的评价指标

提出了新的要求。因此, 本文对照明与视觉、非视觉通路的影响相关研究成果进行综述, 提出我国健康照明光环境的研究与实施的思考和判断。

1 视觉通路的研究与进展

照明光环境相关的研究工作长期以来都是基于人的视觉通路和高级认知行为开展的, 针对照度水平与视觉辨认、认知作业功效, 光源显色性以及眩光评价方法等均建立了能够满足照明实践需要的评价方法和限值规定, 为相关照明标准体系的建立提供了重要的技术支撑。近年来, LED技术得到了快速发展和广泛应用。由于LED光源具有光谱可调、可变, 布置灵活等特性, 与建筑照明所使用的荧光灯等传统光源具有显著的性能差异, 导致基于现有光源技术所建立的光环境评价方法和体系无法适用于LED照明光环境, 特别是在眩光评价、光源显色性以及频闪等方面问题尤为

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突出^[5]。

1.1 眩光评价

自20世纪40年代以来,随着照明水平的不断提高,不舒适眩光问题日益突出,眩光评价方法研究逐步引起行业的关注,并长期成为照明领域内的研究热点。多年来人们进行了大量的工作并导出了各自的评价公式,这些公式大部分已在实践中得到应用。当前不舒适眩光的主要评价方法包括视觉舒适概率系统(vision comfort probability, VCP)、窗的不舒适眩光指数(discomfort glare index, DGI)、眩光限制系统(亮度限制曲线)、眩光指数(glare rating, GR)和统一眩光值(unified glare rating, UGR)等。根据现有的眩光评价研究,影响不舒适眩光感受的主要因素包括眩光源的亮度、大小、数量以及人眼的适应亮度等。

以上眩光评价方法的提出对指导照明设计实践起到了十分重要的作用。然而,这些方法也存在着不具有普适性、缺乏心理学和生理学理论支撑等明显的局限性,无法满足LED照明快速发展和创新应用的需要。因此,关于不舒适眩光的研究一直是国际照明领域的研究热点。

近年来,国际上在该领域的研究工作主要集中在针对LED光源的非均匀特性对眩光的影响研究^[6-9],却忽视了环境亮度分布及光谱的不同和眩光源自身对人眼适应状态的影响。非均匀亮度空间人眼适应亮度计算问题也一直是照明领域悬而未决的关键问题^[10]。针对这一技术难题,中国建筑科学研究院有限公司建立了世界上首个直径2.4 m的全视野高动态范围视野计,其具体性能参数见表1。利用该实验装置开展的前期实验已经验证了亮度分布和光谱等因素对人眼适应状态的显著影响,其研究成果对确定不舒适眩光的生理、心理机制,完善评价方法,指导照明设计实践具有十分重要的技术支撑作用^[11]。

1.2 光源显色性

光源显色性是影响照明光环境和产品性能的重要因素,它包括光源颜色的保真性以及色偏好两个方面。国际照明委员会(International Commission on Illumination, CIE)在1965年提出了基于标准颜色试样的显色性评价方法,即显色指数,并在1974和1995年进行了修正,形成《光源显色性的表示和测量方法》(CIE 13.3-1995)。直到现在,显色指数,特别是一般显色指数(color

表1 全视野高动态范围视野计主要性能参数

Table 1 Main parameters of perimeter with full view and high dynamic range

参数	数值
直径(m)	2.4
像素数量	723360
最大亮度(cd/m ²)	1000
像素间距(mm)	1.875/3/4/5
AD转化	12位
颜色	R/G/B

rendering index, CRI)仍然在全世界范围内广泛使用。然而,CRI方法仅考虑了光源颜色保真性,无法反映LED技术,特别是多芯片混光LED的显色性优势,而且其具有使用被废止的色度空间、参考光源不连续、使用的标准颜色样品数量少且饱和度低等问题,因此一直被照明行业广泛关注。当前,北美照明学会已经发布了新的技术备忘录《光源显色性评估方法》(IES TM 30-2015),增加了色域指数等光源显色性评价指标。CIE于2007年发布了《白光LED光源显色性》-2007,对光源显色性的评价方法研究进展做了详细介绍,并在2017年发布了《CIE 2017版科学研究用颜色保真度指数》(CIE 224-2017)。然而,CIE 224-2017明确规定所提出的评价方法仅供科学研究使用,因此无法代替现行的利用显色指数评价光源显色性的方法。

鉴于当前关于替代CRI的显色性评价方法在国际上尚未达成广泛一致,任何显色性评价方法的修订都会对照明产业和应用产生十分巨大的影响。因此,我国新出版的国家标准《光源显色性评价方法》(GB/T 5702-2019)在基本保持原有标准评价方法不变的基础上,以资料性附录形式补充了色域指数、彩度指数等光源对物体色貌的彩度影响的评价参数,在确保标准方法的延续性和稳定性的基础上为用户提供更多选择,更加准确地反映光源对物体视看效果的影响。关于光源显色性评价方法的研究仍然是未来照明行业的研究热点。

1.3 频闪问题

根据《国际照明术语》(CIE S 017-2011),频闪是因亮度或光谱分布随时间快速波动而引起的视觉现象。根据频闪对人身心影响特性的差异,可以将频闪分为:(1)可察觉的频闪,或称为闪烁。它主要是指频率较低

(一般在3~70 Hz)的一种闪烁,它会导致不舒适和干扰,甚至会诱发癫痫的发作。(2)不可察觉的频闪。这种频闪因频率相对较高(>70 Hz),不能被肉眼察觉,而容易被人忽视。它会导致错觉引发工伤事故,危害身体健康;影响工作,使人出现视觉疲劳、眼花、偏头痛等问题;也可能会诱发青少年近视。

近年来,伴随着LED照明产品的广泛应用,根据前期调研,80%以上的LED照明产品相较于传统的气体放电灯具有明显的频闪控制优势,但也存在部分产品由于使用低劣驱动电源导致频闪问题更加突出和严重的情况。因此,频闪问题已经引起社会的广泛关注。电气和电子工程师协会(Institute of Electrical and Electronics Engineers, IEEE)于2015年发布标准IEEE 1789-2015,对不同频率的频闪比限值做出了规定。然而,该方法未考虑频闪波形对观测者的影响,一直受到行业质疑。因此,CIE于2016年发布的技术说明CIE TN 06-2016对频闪测量仪器提出了明确要求。

国际电工委员会(International Electrotechnical Commission, IEC)于2018年3月发布了技术报告《通用照明用设备——照明设备频闪效应客观测试方法》(IEC TR 63158-2018),提出利用频闪效应可见度(stroboscopic visibility measure, SVM)来评价频闪效应的计算方法。根据Małgorzata Perz的研究,当前该方法还是基于频闪效应的可见度来进行评价,而未考虑频闪对人的认知作业能力以及身体健康的影响。因此,频闪效应问题在未来仍将是照明领域的研究热点。中国建筑科学研究院有限公司已经搭建了可以最大生成100 kHz频闪波形的频闪模拟装置,将开展认知作业、视觉疲劳等领域的相关研究工作。

2 非视觉通路的研究与进展

长期以来,人们一直认为视网膜上仅有杆状体细胞和锥状体细胞两种感光细胞能够将光信号转变为电信号,并通过视网膜神经节细胞(retinal ganglion cells, RGC)将成像和非成像视觉信息以放电形式传递至RGC轴突投射对应的大脑区域。然而,这一观点一直受到相关研究的质疑。如研究发现,某些杆状体细胞和锥状体细胞退化的盲人虽然视觉感知意识丧失,但仍然会在照明条件下出现褪黑激素抑制现象;没有杆状体细胞和锥状体细胞的老鼠仍然会维持光诱导和瞳孔对光反射等生理现象。2002年,Berson等人^[12]首次发现了视网膜神经节层上的第三类感光细胞——本质感光视

网膜神经节细胞(intrinsically photosensitive retinal ganglion cells, ipRGC)。它的感光色素(或视蛋白)melanopsin(由*Opn4*基因编码的蛋白质)与杆状体细胞和锥状体细胞不同,其光谱响应特性却与此前光诱导节律观测结果相一致^[13~16]。进一步的实验证明,这种细胞不直接参与人的视觉成像功能,而是通过RHT与下丘脑视交叉上核(suprachiasmatic nucleus, SCN)等大脑区域形成投射(即非视觉通路)。对生命节律、惊醒度等生理体征影响机理的发现,赋予照明研究与应用全新内涵。

2.1 非视觉通路的作用机理

根据melanopsin的光谱响应特性,弹状感光细胞(rhabdomeric photoreceptors)^[17,18]的感光敏感度远低于杆状体细胞和锥状体细胞^[19],所以由melanopsin所激发的光传导应该只会发生在中、高照度条件下。然而,ipRGC可以在很低的照度条件下产生放电^[20],证明ipRGC可以同时接收到位于视网膜外层的杆状体细胞和锥状体细胞的信号^[21]。这一结论也得到此前研究所发现的“无melanopsin动物仍然可以存在对光的非视觉反应”的实验结果的支持^[22,23]。然而,杆状体细胞和锥状体细胞的信号对ipRGC光反应的影响,当前尚没有定论^[24]。

2.2 非视觉通路的功能

人类视网膜上一共有150万个神经节细胞,而其中带有感光色素(或视蛋白)melanopsin的神经节细胞,即ipRGC仅有3000个左右^[25]。利用追踪分子技术发现,这些ipRGC通过视网膜节细胞下丘脑束投射到大脑区域,包括SCN、橄榄顶盖前核(olivary pretectal nucleus, OPN)、膝状体间小叶(intergeniculate leaflet, IGL)、外侧下丘脑、脑侧室前视核等,其中的SCN和OPN主要接收ipRGC信号^[26,27](图1)。

非视觉通路的主要功能包括以下6个方面。

(1) 生物钟。相关研究表明,SCN作为哺乳动物生物钟的控制中枢,可能通过多种体液和神经信号使外周生物钟保持同步,以产生节律性活动,适应外界环境变化。这也构成了哺乳动物生命运行的基础^[28,29]。2017年的诺贝尔生理学或医学奖也正是颁发给了发现生物钟基因及其工作原理的3位美国科学家。光是最有效的授时因子,ipRGC传递的感光信号正是SCN感知外部环境进而调节生物钟相位的主要信号来源,对生物钟的维持和调节具有十分重要的作用^[30,31],会调节节律的相

图1 (网络版彩色)ipRGC投射大脑区域及功能简图

Figure 1 (Color online) Diagram of brain regions projected by ipRGC and function

位。光照射时间对人生物钟影响的最小阈值应该在数秒甚至分钟量级,远远长于视觉通路。这种较长时间的感光信息的积分现象对确保生物钟避免出现短时波动具有重要作用^[32]。

(2) 瞳孔的光反射(pupillary light reflex). ipRGC所投射橄榄状顶盖前核对两侧的瞳孔直径具有交感的调节作用,因此ipRGC所传递的信号对瞳孔直径的调节具有重要作用^[33]。在亮度发生变化后,瞳孔所做出的快速反应主要由杆状体细胞和/或锥状体细胞产生的信号控制。在瞳孔快速收缩后,瞳孔将逐步放大。如果此时的光照强度已经超过melanopsin的阈限,则瞳孔直径在光照条件不变情况下将保持稳定状态, melanopsin的影响随着照射时间的增长而增加,直至由其起主导作用(照射时间超过3 min时)。而当灯光突然关闭且关闭前光照强度超过melanopsin的阈限时,由于melanopsin的影响,瞳孔的大小将被保持数秒,称为照射后瞳孔反应(post illumination pupil response, PIPR)^[34](图2^[35])。

(3) 视觉适应。Barlow和Levick^[36]在1969年发现猫的视网膜上存在一种分子可以起到亮度编码作用,即它的放电强度随着照射强度的增加而单调增加。而这也正是ipRGC的melanopsin与视网膜上已知感光细胞的最大差别。在连续照射条件下,它可以在较长时间内产生稳定的感光信号,准确地反映环境亮度水平^[19,20,22,37~39]。因此, melanopsin具有类似相机上的曝光表的作用,根据环境亮度条件决定视觉通道的适应状

态^[40]。

(4) 睡眠。近年来多个研究表明, ipRGC的信号会传导至下丘脑,腹外侧视前核(ventrolateral preoptic nucleus, VLPO)具有诱导睡眠的作用^[41,42],但是杆状体细胞和锥状体细胞同样对睡眠具有影响^[43]。

(5) 警醒度。较高的照明水平可以提高昼行动物的警醒度和情绪^[44]。

(6) 视觉。根据Lucas等人^[16]、Dacey等人^[21]、Schmidt等人^[45]的研究,部分ipRGC还会投射到外侧膝状体背核(dorsolateral geniculate nucleus, dLGN),表明ipRGC可能会参与颜色视觉、模式视觉以及亮度感知等视觉成像、视觉感知行为,并得到了部分研究结果的支持^[46,47]。

2.3 影响要素

2.3.1 光谱

1980~2000年,大部分照明与人节律、内分泌、行为以及光治疗关系方面的研究都是基于明视觉照度作为控制变量^[30]。然而, melanopsin的光谱响应曲线与杆状体细胞和锥状体细胞的具有明显差异,且很多研究未提供光谱数据,导致不同研究结论存在较大差异。Brainard等人^[14]、Thapan等人^[48]的多个独立研究结果表明,人节律系统的光谱响应峰值在460 nm左右,而不同物种的melanopsin具有基本一致的光谱响应曲线,其吸收光谱的峰值在480 nm左右^[7,16,49]。研究人员也提出

图2 瞳孔光反射发生过程图^[35]Figure 2 Process diagram of pupillary light reflex^[35] 图3 不同研究确定的melanopsin响应曲线结果对比图^[54]Figure 3 Comparison diagram of melanopsin response curve based on different studies^[54]

了多个节律调节的光谱响应曲线^[9,43,50~53](图3^[54])。2013年,14位节律和神经生理学等领域的知名专家齐聚曼彻斯特,经过认真讨论和分析当前研究成果,一致认为melanopsin和锥状体细胞、杆状体细胞组合形成不同使用环境和非视觉功能的非视觉光谱响应曲线,而不

同环境下各感光细胞对非视觉功能的影响仍然未知^[30,55]。但是,根据专家共识,CIE于2018年给出了melanopsin的光谱响应曲线,为健康照明的应用提供了重要基础^[56],也为我国健康建筑建设和实施提供了重要依据^[57]。目前,中国建筑科学研究院有限公司与中国科

学院心理研究所正在开展关于样本的非视觉效应机理及评价方法的研究工作。

2.3.2 强度

CIE 158(CIE 2004/2009)指出,人的非视觉效应受到眼部接收到的光的强弱影响。因此,健康照明的评价指标应该是眼睛位置的垂直表面,而不是作业面的照射强度^[58]。科研人员也在努力建立这种照射强度与人的光生物/光化学反应的关系,根据非视觉光谱响应曲线(如褪黑激素抑制光谱响应曲线)确定的有效照射强度,替代现有的照度。很多研究表明,这种有效照射强度与非视觉效能评价指标之间存在着logistic模型关系,如图4所示。而Zeitzer等人^[59]的研究表明,对于褪黑激素抑制和节律相位调整,所发生的有效辐射强度分别为200和500 lx。因此,《WELL建筑标准》和中国建筑学会团体标准《健康建筑评价标准》分别以CIE E光源和CIE D65光源作为基准计算的眼睛位置的生理等效照度作为健康照明的评价指标,而后者与CIE DIS 026相一致^[51,52,60]。但是,当前的标准均未考虑使用者年龄问题。由于瞳孔调节范围的减少、晶状体黄化、视网膜退化等原因,相同照明条件下,45岁成年人的光诱导节律的效果仅为10岁儿童的一半^[60~63]。

然而,相关研究表明,相同生理照度条件下,小发光面积、高亮度光源对褪黑激素的抑制效果要低于大发光面积、低亮度光源,其可能原因是ipRGC信号达到饱和。另外,研究表明,人眼位置的辐射强度并不是最有效的非视觉效应评价指标^[64,65]。

2.3.3 方向

光的入射方向是影响非视觉效应的非常重要、但又经常被忽视的因素之一^[46]。入射方向对非视觉效应影响的原因包括以下两个方面:(1) ipRGC在视网膜上分布不均匀。多个研究表明,下半部分的视网膜对褪黑激素抑制等非视觉效应更加有效^[48,66,67]。因此,当光线来自上半部视野时,产生的非视觉效应会更加有效。(2) 视野的影响。在室内照明条件下,人眼视线上方的垂直视角为50°~55°。而在户外太阳光直射条件下,眼皮会产生无意识下的遮挡(可能由于ipRGC的控制)。CIE DIS 026给出了不同环境下的典型视场,如表2所示^[51,68~70]。

因此,在考虑照明的非视觉效应时,应该充分考虑空间亮度分布,特别是上半视场范围内的表面亮度对人的影响^[71]。目前,中国建筑科学研究院有限公司搭建了全球首个高动态、全视野适应亮度实验装置,已开

图4 (网络版彩色)褪黑激素抑制与照度的关系。横坐标为对数坐标
Figure 4 (Color online) Relationship between illumination and suppression of melatonin. The x-coordinate scale is expressed in logarithmic coordinates

表2 不同照明条件下的典型视场

Table 2 Typical view field under different lighting conditions

照明环境	垂直视角	双眼水平视角
室内	视线上方0°~50° 视线下方0°~70°	180°
室外	视线上方0°~20° 视线下方0°~70°	180°

展了亮度分布对非视觉效应影响的研究工作。

2.3.4 时间

尽管照明对节律系统具有影响,但是充足的证据证明,光照射时间对节律系统的影响存在明显差异^[72,73]。当光照射发生在夜间人体核心温度最低点前时,人的节律将会推迟;而当光照射发生在人体核心温度最低点之后时,人的节律相位将会前移^[74,75]。因此,在早晨接受足够的光照射对改善白天的工作效率具有很重要的作用;而夜间使用显示器、卧室灯管,则会导致人的节律推迟^[76~78]。

同时,还有研究表明,白天接受较强的光照射可以提升人的警醒度和认知能力^[79~81];而白天不能接受足够的光照射时,将会导致人更容易受到夜间灯光的影响^[82,83]。因此,健康照明的一个重要内涵就是根据不同时间为人们提供合理的照明水平和光谱,更好地满足人非视觉效应的需求。

3 健康照明光环境应用的思考与展望

天然光是人类百万年来感知世界和昼夜变化的主

要光源,是人类形成生命节律的重要基础,无疑也是人类工作、生活的最佳照明光源^[84]。然而,伴随着工业化社会的发展和照明技术的广泛应用,人们80%~90%的时间都是在室内度过^[85],昼间光照射不足而引起的睡眠质量下降等健康问题日益突出^[86~88]。近年来,伴随着LED、智能控制技术的飞速发展,以及人类关于光对人的身心影响研究的不断深入,特别是光环境的研究与应用已从原有的视觉功效发展到与情绪、睡眠、认知、节律等各个方面有关的光与健康的问题,让照明逐步走向动态照明,即根据时间调整照明光谱及强度,从而为人们创造安全、舒适、有益身心的健康照明光环境,这也对照明应用提出了更高的技术要求,主要表现在:

(1) 当前的光环境评价体系主要是基于视觉安全、工效和舒适目标,根据传统照明技术特征而建立起来的。面对健康照明新内涵和LED照明智能化和一体化发展新要求,当前亟须对眩光、颜色质量、频闪等评价指标进行完善,并根据非视觉通路光谱、强度、方向、时间等影响因素,研究非视觉效应影响机理,结合照明应用实践建立非视觉效应评价体系,进一

步明确健康照明内涵,指导健康照明应用发展。

(2) 从光谱和强度变化角度而言,天然光无疑是在昼间实现动态照明理念的高效照明光源的最佳选择。大量证据表明,足够的采光对保持人的良好生理、情绪状态以及社交、认知行为具有十分重要的意义^[89~91]。因此,要创造健康照明光环境,首先就要利用新型的采光技术、智能控制技术与人工照明技术有机结合,实现采光照明一体化实施目标,有效避免由于天然光变化的不确定性和分布的不均匀性给用户带来不舒适性,真正实现建筑采光的最大应用。

(3) 健康照明的核心内涵就是以人为本。相关研究表明,光对人节律等非视觉效应存在明显的个体差异。伴随着全球人口老龄化问题的日益突出,预计到2050年全球65岁以上老年人占比将超过40%。年龄老化和视觉障碍问题将导致人的视觉通路和非视觉通路的敏感度显著下降,进一步加剧人对光需求的个体差异^[92]。因此,亟须开展研究,通过利用智能控制技术,实现因人、因时、因需而变的目标,建立基于非视觉效应的动态光环境设计实施技术体系,为健康照明的实施提供有效保障。

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Summary for “健康照明应用研究发展与展望”

Application of healthful lighting: Research progress and prospects

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Light is a key component for life on Earth. Lighting quality is thought to be one of the most important factors influencing people's work and living conditions in building spaces. A complete standardization system has been established on the basis of comprehensive research concerning visual performance and comfort under lighting situations with traditional lighting technology; this has played an important role in guiding the proper design and application of lighting environments. In the past decades, science and technology related to lighting have advanced significantly in the following areas.

(1) Technology has transformed lighting with the development of light emitting diodes (LEDs), which are now a practical source for general illumination. The unique properties of LEDs, such as their small size and availability in saturated colors ranging from red, green, and blue to different tones of white, offer tremendous new application possibilities. Because most existing quality measures for such applications are derived from research with and referring to the use of diffuse fluorescent lighting, there has been significant concern with respect to the feasibility of current measures for evaluating indoor lighting with LED lighting systems.

(2) Vision and biological sciences have achieved a deepening knowledge of the complex relationship between light and health, adding both opportunities and responsibility to the work of those who design lighting systems, and have heightened public awareness with respect to how lighting affects our lives. Intrinsically photosensitive retinal ganglion cells (ipRGC) send light information via the retinohypothalamic tract (RHT) directly to the suprachiasmatic nucleus (SCN) of the hypothalamus and other targets in the brain; they have given lighting research and applications a brand-new connotation to provide the right light for the right person in the right place using the integration of LED lighting and smart lighting control technology to provide occupants with healthful lighting environments that provide safety, comfort, and human wellbeing.

In this paper, on the basis of a systematic review of recent advances in the areas of lighting, and vision and the implications of healthful lighting, the following suggestions concerning research and the implementation of healthful lighting in China are given.

(1) The widening application of LED technology and its connotations for healthful lighting, as well as the challenges faced by existing lighting quality measures, need to be studied. A healthful lighting evaluation system needs to be established with improved evaluation criteria for glare, color quality, and temporal light artifacts. In addition, a better understanding of the mechanisms of non-visual effects needs to be acquired in the areas of vision, neurophysiology, and psychology.

(2) From the point of view of the dynamic characteristics of its intensity and spectrum, daylight is the optimal light source for healthful lighting. Therefore, the integration of daylighting technology, smart lighting control, and LED lighting will be the most effective method to realize this concept in real applications without resulting in high levels of energy consumption and discomfort associated with a fluctuating and nonuniform daylight distribution.

(3) The core connotation of healthful lighting is its human-centric feature. Individuals differ widely in their visual capabilities and needs; this is not considered in current lighting recommendations, which have been developed on the basis of average results, usually for able-bodied young adults. Globally, with the increasing proportion of older people and people with visual impairments, the suitability of lighting recommendations based primarily on research with younger populations is being questioned. For healthful lighting, the development of suitable lighting technologies or design practices to assist diverse populations is necessary for healthful lighting applications.

visual pathway, non-visual pathway, healthful lighting, visual comfort, circadian rhythm

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