DR. PRAKASH ADHIKARI (Orcid ID : 0000-0003-4834-8500)

Article type : Regular Research Paper

The accuracy of artificial and natural light measurements by actigraphs

Daniel S. Joyce[1,2,5], Andrew J. Zele[1,2], Beatrix Feigl[1,3,4], Prakash Adhikari[1,2*]

[1]Visual Science and Medical Retina Laboratories, Institute of Health and Biomedical Innovation, Queensland University of Technology (QUT), Brisbane, QLD 4059, Australia

[2]School of Optometry and Vision Science, Queensland University of Technology (QUT) Brisbane, QLD 4059, Australia

[3]School of Biomedical Sciences, Queensland University of Technology (QUT), Brisbane, QLD 4059, Australia

[4]Queensland Eye Institute, Brisbane, Australia

[5]Current Address: Department of Psychiatry and Behavioral Sciences, School of Medicine, Stanford University, Stanford, USA

*Corresponding Author: p.adhikari@qut.edu.au

60 Musk Avenue, Kelvin Grove, QLD 4059, Australia

Conflict of interests: None

Author contributions

DSJ, AJZ, BF, and PA designed research.

PA and AJZ performed data collection.

DSJ and PA performed data analysis and interpretation.

DSJ and PA wrote the manuscript.

DSJ, AJZ, BF, and PA edited the manuscript.

Abstract

Actigraphs are the gold standard for measuring light exposure in human non-laboratory experiments due to their portability and long battery lives. However, actigraphs typically have a limited illuminance operating range not representative of real-world conditions, and for many actigraphs, the accuracy of their light measurement has not been verified independently. We assessed the illuminances recorded by Activinsights GENEActiv Original and Philips Actiwatch 2 actigraphs in comparison to a calibrated, laboratory standard photometer, under both artificial LED and natural sunlight illuminations that might be encountered by a person under real-world conditions. We show that in response to ~20,000 lux white LED light, the GENEActiv and Actiwatch 2 underestimate illuminance by recording 50% and 25% of the true value respectively. Under ~30,000 lux sunlight, the GENEActiv readily saturates while the Actiwatch 2 reports ~46% of the true illuminance. These underestimations are highly linear and we provide correction factors to estimate the illuminance levels of the ambient environment measured by the actigraphs. We also evaluate the application of neutral density filters for extending the operating range of both devices in natural sunlight illuminations (as high as 30,000 lux during our measurements) and demonstrate that this may be a viable approach for increasing the operating range of the Actiwatch 2 but not the GENEActiv. We conclude that both actigraphs provide good performance monitoring of the temporal patterning of light, whereas the absolute illuminance values require correction to accurately evaluate the effects of light intensity on human health and behaviours.

Key words:

actigraph, photometer, illuminance, LED, sunlight

Introduction

Photoentrainment to the pattern of light and dark influences a variety of human behavioural processes including circadian rhythms, sleep, alertness and mood (Czeisler et al., 1986; Dawson & Campbell, 1991; Golden et al., 2005; LeGates, Fernandez, & Hattar, 2014; Rüger, Gordijn, Beersma, Vries, & Daan, 2006). Photoreceptors in the eye that transduce environmental light information to brain areas for mediating these processes (Altimus et al., 2010; Bellingham & Foster, 2002; Chen, Badea, & Hattar, 2011; Rollag, Berson, & Provencio, 2003) are affected in disease (Adhikari, Zele, Thomas, & Feigl, 2016; Dumpala, Zele, & Feigl, 2019; Joyce, Feigl, Kerr, Roeder, & Zele, 2018; Maynard, Zele, Kwan, & Feigl, 2017) and the magnitude and timing of light exposure are associated with the circadian rhythm phase (Duffy, Kronauer, & Czeisler, 1996), sleep quality (Ancoli-Israel et al., 2003; Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003) and mood (Rüger et al., 2006), The efficacy of light therapy in treating disorders, including sleep abnormalities and depression (Campbell et al., 1995; Golden et al., 2005; Mishima et al., 1994; Montgomery & Dennis, 2002; Rosenthal, Sack, Gillin, & et al., 1984; Terman & Terman, 2014), underscores the importance of understanding and optimising light exposures for human wellbeing and health.

While calibrated research-grade photometers and radiometers accurately quantify light levels, they are not practical for measuring the light exposure of a freely moving individual over time. The standard instrument used for this purpose is a wrist worn actigraphy device (Bernhofer, Higgins, Daly, Burant, & Hornick, 2014; Flynn et al., 2014; Grandner, Kripke, & Langer, 2006; Higgins, Hornick, & Figueiro, 2010; Higgins, Winkelman, Lipson, Guo, & Rodgers, 2007; Liu et al., 2005; Shochat, Martin, Marler, & Ancoli-Israel, 2000). However, the accuracy of many of these devices in measuring environmental light exposure has not been verified independently, while those devices that have been independently measured show inaccuracies. For example, compared to a calibrated Extech Light Meter, the Sleepwatch-L device underestimates the indoor illuminance (11 AM to 5 PM; both artificial and natural lights) during daylight hours by up to 64% (Higgins et al., 2007). To further verify the use of actigraphs in measuring light exposure, here we determine the accuracy of environmental LED light and natural sunlight measurements reported by Activinsights GENEActiv Original and Philips Actiwatch 2 devices.

Methods

Actigraphs

Two commercially available actigraph devices were tested in this study, the GENEActiv Original (n = 6; Activinsights, Kimbolton, Cambridgeshire, UK) and Actiwatch 2 (n = 6; Philips Respironics, Murrysville, PA, USA). The GENEActiv device has a stated operating range of 5 to 3000 lux, 5 lux resolution, an accuracy of +/- 10% at 1000 lux and a wavelength range of 400 to 1,100 nm (ActivInsights, 2015) (Fig. 1a). The Actiwatch 2 device has a stated operating range of 5 to 100,000 lux spanning 400 to 900 nm (other parameters not stated) (Philips Respironics, 2008). Both devices include visible and partial infrared portions of the electromagnetic spectrum, and record illuminance rather than the spectral power distribution of the light.

Protocol

The LED and sunlight illuminances were continuously measured with the GENEActiv and Actiwatch 2 devices as well as a calibrated ILT1700 photometer (International Light Technologies, Peabody, Massachusetts, USA). For the artificial light measurements (Experiment 1), an enclosed light exposure cabinet was constructed with a high-reflectance white surface. The light exposure cabinet comprised a dimmable 4,000 k white light LED panel (Lumex NovaBlade LL9PX66N) typical of artificial lighting conditions in an office environment. The spectral power distribution (SPD) of the LED light was measured in the plane of the actigraph devices with a high resolution spectroradiometer (Stellarnet Inc. EPP2000, Tampa, Florida, USA) (Fig. 1a). The luminaire used a Samsung LM 561 B-5630 LED chip on board module controlled with a pulse width modulated (PWM) signal at 400 hz, higher than the upper limit of human flicker perception (Smith, Pokorny, Lee, & Dacey, 2008; Zele & Vingrys, 2005). The LED panel had a 120° beam angle and high colour rendering index (> 90) and was diffused by a flat cosine panel. The LED output was controlled using the DALI protocol with Dynet Software (Smartscape Automation, Brisbane, Australia). Measurements were conducted in a 6-hour protocol, where the light ranged from 4.39 to 20,600 lux and featured gradual increases and decreases in illuminance, periods of darkness, and rapid step-wise changes in illuminance (Fig. 1b). In Experiment 2, we assessed the performance of the actigraphs under natural sunlight. The actigraphs and photometer sensor were placed on a level, unshaded surface on the roof of a building in Brisbane, Australia on a bright sunny morning in December (summer) for one hour. To determine whether the operating ranges of the devices could be extended, we applied flexible, lightweight 0.3, 0.6 and 1.2 neutral density (ND) filters (LEE Filters, Hampshire, UK) to the actigraph photosensors. For all recordings, the actigraph wristbands were removed and the devices arranged at even intervals in a circle around the ILT1700 photometer sensor. The sampling frequencies of each device were set to 60 Hz and then downsampled into 1 s epochs by each manufacturer's software. The photometer was set to an integration time of 500 ms and a measurement taken every 500 ms, before averaging. For analyses, the data in

Experiment 1 were averaged and in Experiments 1 and 2 the data were further downsampled into 1 min epochs using MATLAB (R2016a, Mathworks, Natick, MA, USA). Post-hoc analysis revealed that the intra-device coefficients of variation (CoV, SD/mean) were <4% for both the GENEActiv and Actiwatch 2 devices.

Fig. 1

Results

Under broadband LED illumination, compared to the photometer, both actigraph devices (GENEActiv n = 6 Actiwatch 2 n = 6) underestimate the illuminance but show the same temporal light profile (Fig. 2a). Both devices show systematic underestimation of the peak 20,800 lux illuminance reported by the photometer, the GENEActiv peaks at 9,527 lux whereas the Actiwatch 2 peaks at 5,755 lux (Fig. 2a), 46% and 28% of the photometer value respectively (Fig. 2b,d), with the underestimation independent of true illuminance. Although the devices underestimate the true illuminance, the relationships between photometer and actigraph outputs are highly linear (Fig. 2c) including both within and above the 5 to 3,000 lux operating range of the GENEActiv device. The magnitude of underestimation by the actigraphs was most variable at illuminances < 2,500 lux (Fig. 2d).

Fig. 2

We next evaluated the performance of the devices in measuring the illuminance of sunlight. As sunlight illuminance can readily exceed the stated operating range of both devices (upper limit: 3,000 lux for GENEActiv and 100,000 lux for Actiwatch 2), flexible neutral density filters were attached to individual devices to determine whether the operating range could be extended (0.3, 0.6, 1.2 ND filters and no filter (0 ND); n = 4 GENEActiv and n = 4 Actiwatch 2). We show that under sunlight, without ND filters, both devices underestimate the true illuminance in comparison to the calibrated photometer (Fig. 3a,b). The GENEActiv appears to saturate under these conditions, reporting ~18,000 lux at peak whereas the Actiwatch 2 does not. For the ND-attenuated devices, reported illuminance decreased as ND value increased as expected however, this effect was non-systematic for the GENEActiv devices (*c.f.* 0.3 vs. 0.6 ND tracings, Fig. 3c). When the data are normalised to maximum, the tracings demonstrate poor concordance for the GENEActiv devices, indicative of saturation (Fig. 3c), but good concordance for the Actiwatch 2 devices (Fig. 3d). Response variability is higher under sunlight conditions for the Actiwatch 2 (Fig. 3e) compared to LED light (Fig. 2c). Actigraph outputs show a positive linear relationship with photometer outputs (Fig. 3e,f). The Actiwatch 2 systematically underestimates illuminance while the GENEActiv transitions from overestimating to underestimating as illuminance increases (Fig. 3f). The actigraph output expressed as a percentage of the corresponding photometer output decreases with increasing illuminance (Fig. 3f) indicating that the magnitude of illuminance underestimation by the actigraphs increases with increasing light level. GENEActiv saturation at light levels > 18,000 lux manifests in the regression, but the statistically significant regression is driven by the data <18,000 lux.

Fig. 3

Discussion

This study evaluates the light measurement performance of two commercially available actigraphs, the Activinsights GENEActiv and the Philips Actiwatch 2 under artificial (LED) illumination and sunlight. The data demonstrate that while both devices have good performance monitoring the temporal patterning of light, they have poor illuminance-sensing accuracy under moderately intense artificial and natural sunlight conditions as might be encountered in the real-world (Fig. 2 and 3). In the absence of rigorous manufacturer-provided calibrations, our linear regression models provide a tool to scale the actigraph output for accurate representation of environmental illumination, including artificial as well as natural lights as measured by the laboratory standard photometer.

Across both artificial light and sunlight conditions, illuminance is typically underestimated by the actigraph devices but differed depending on the light level and source. For LED lighting, these underestimates are systematic and linear, particularly for higher intensities (Fig. 2). Under sunlight, the estimates are more variable with the GENEActiv transitioning from overestimating light intensity to underestimating once saturation occurred (Fig. 3a,f). That sunlight contains infrared (IR) spectrum which however is negligible for our LED lights (0.6% of the total spectral power distribution) (Fig. 1a), the overestimation of sunlight illuminance may be due to the GENEActiv sensitivity (400-1,100 nm) which ranges into the infrared region well beyond the human luminous efficiency functions (400-700 nm) used by the ILT1700 photometer to quantify illuminance (lux). Specifying the measurement of ambient illuminance in a spectrum broader than human vision can result in the intrusion of undesired radiometric components. Our analysis suggests that due to the highly linear relationship between device and photometer measurements, a conversion factor can be applied to estimate actual illuminance from that reported by the devices. This holds for LED lighting for both the GENEActiv and Actiwatch 2 (Fig. 2c) and for sunlight for the Actiwatch 2 only (Fig. 3e), but not for the GENEActiv under sunlight as they readily saturate under the conditions tested. The application of neutral density filters may be one cost-effective method to extend the operating range of these devices to include high light levels that may be encountered in daily living. Flexible neutral density filters ranging from 0.3 to 1.2 ND maintain the fidelity of the (filtered) light intensities recorded by the Actiwatch 2 (Fig. 3b), but were ineffective for the GENEActiv due to continued saturation (Fig. 3a). More generally, the data demonstrate that the absolute illuminance values reported by the actigraphs are not accurate at illuminances both within and outside of their stated operating ranges, either under artificial LED light or natural sunlight. This finding extends the growing body of evidence demonstrating significant inaccuracies in measuring light intensity with actigraphs, including substantial inter-device variation in light sensing between units from the same manufacturer (Cao & Barrionuevo, 2015; Price, Khazova, & O'Hagan, 2012).

Wrist-worn light sensing devices have potential to monitor naturalistic behaviours including prolonged light exposures over days or weeks, in situations where traditional laboratory-based light measurement devices are impractical. Current-generation iterations of the GENEActiv and Actiwatch 2 can provide information as to the temporal patterning of light, but they do not accurately report illuminance under either artificial or natural lighting conditions, both within and without their stated operating ranges. We encourage actigraph users to apply these correction factors to more accurately quantify ambient light levels. It would be advantageous if actigraphs included high-fidelity logging of not just the temporal patterning, but also the illuminance patterning of light across ecologically valid ranges, in both artificial and natural light. Increasing the accuracy and precision of these wearable devices is required to quantify, under naturalistic conditions, how the irradiance, patterning, and spectral qualities of light are sensed by the image and non-image forming visual pathways to drive human behaviour.

Acknowledgments

We thank Rick Morrison for assistance with the design of the light exposure cabinet, data collection, and programming of LED software.

Funding

Australian Research Council Discovery Projects ARC-DP170100274 (AJZ, BF) and Australian Research Council Future Fellowship ARC-FT180100458 (AJZ).

References

ActivInsights. (2015). GENEActiv.

Adhikari, P., Zele, A. J., Thomas, R., & Feigl, B. (2016). Quadrant field pupillometry detects melanopsin dysfunction in glaucoma suspects and early glaucoma. *Scientific Reports, 6*, 33373. doi:10.1038/srep33373

Altimus, C. M., Güler, A. D., Alam, N. M., Arman, A. C., Prusky, G. T., Sampath, A. P., & Hattar, S. (2010). Rod photoreceptors drive circadian photoentrainment across a wide range of light intensities. *Nature Neuroscience, 13*, 1107. doi:10.1038/nn.2617

Ancoli-Israel, S., Gehrman, P., Martin, J. L., Shochat, T., Marler, M., Corey-Bloom, J., & Levi, L. (2003). Increased light exposure consolidates sleep and strengthens circadian rhythms in severe Alzheimer's disease patients. *Behavioral Sleep Medicine, 1*(1), 22-36. doi:10.1207/S15402010BSM0101_4

Bellingham, J., & Foster, R. G. (2002). Opsins and mammalian photoentrainment. *Cell and Tissue Research, 309*(1), 57-71. doi:10.1007/s00441-002-0573-4

Bernhofer, E. I., Higgins, P. A., Daly, B. J., Burant, C. J., & Hornick, T. R. (2014). Hospital lighting and its association with sleep, mood and pain in medical inpatients. *Journal of Advanced Nursing, 70*(5), 1164-1173. doi:10.1111/jan.12282

Campbell, S. S., Terman, M., Lewy, A. J., Dijk, D.-J., Eastman, C. I., & Boulos, Z. (1995). Light treatment for sleep disorders: Consensus report:V. Age-related Disturbances. *Journal of Biological Rhythms, 10*(2), 151-154. doi:10.1177/074873049501000207

Cao, D., & Barrionuevo, P. A. (2015). Estimating photoreceptor excitations from spectral outputs of a personal light exposure measurement device. *Chronobiology International, 32*(2), 270-280. doi:10.3109/07420528.2014.966269

Chen, S. K., Badea, T., & Hattar, S. (2011). Photoentrainment and pupillary light reflex are mediated by distinct populations of ipRGCs. *Nature, 476*(7358), 92-95. doi:10.1038/nature10206

Czeisler, C., Allan, J., Strogatz, S., Ronda, J., Sanchez, R., Rios, C., . . . Kronauer, R. (1986). Bright light resets the human circadian pacemaker independent of the timing of the sleep-wake cycle. *Science, 233*(4764), 667-671. doi:10.1126/science.3726555

Dawson, D., & Campbell, S. S. (1991). Timed exposure to bright light improves sleep and alertness during simulated night shifts. *Sleep, 14*(6), 511-516. doi:10.1093/sleep/14.6.511

Duffy, J. F., Kronauer, R. E., & Czeisler, C. A. (1996). Phase-shifting human circadian rhythms: influence of sleep timing, social contact and light exposure. *The Journal of Physiology, 495*(1), 289-297. doi:10.1113/jphysiol.1996.sp021593

Dumpala, S., Zele, A. J., & Feigl, B. (2019). Outer retinal structure and function deficits contribute to circadian disruption in patients with type 2 diabetes. *Investigative Ophthalmology and Visual Science, 60*(6), 1870-1878. doi:10.1167/iovs.18-26297

Flynn, J. I., Coe, D. P., Larsen, C. A., Rider, B. C., Conger, S. A., & Bassett, D. R. (2014). Detecting indoor and outdoor environments using the ActiGraph GT3X+ light sensor in children. *Medicine and Science in Sports and Exercise, 46*(1), 201-206. doi:10.1249/mss.0b013e3182a388c0

Golden, R. N., Gaynes, B. N., Ekstrom, R. D., Hamer, R. M., Jacobsen, F. M., Suppes, T., . . . Nemeroff, C. B. (2005). The efficacy of light therapy in the treatment of mood disorders: A review and meta-analysis of the evidence. *American Journal of Psychiatry, 162*(4), 656-662. doi:10.1176/appi.ajp.162.4.656

Grandner, M. A., Kripke, D. F., & Langer, R. D. (2006). Light exposure is related to social and emotional functioning and to quality of life in older women. *Psychiatry Research, 143*(1), 35-42. doi:10.1016/j.psychres.2005.08.018

Higgins, P. A., Hornick, T. R., & Figueiro, M. G. (2010). Rest-activity and light exposure patterns in the home setting: A methodological case study. *American Journal of Alzheimer's Disease and Other Dementias, 25*(4), 353-361. doi:10.1177/1533317510363467

Higgins, P. A., Winkelman, C., Lipson, A. R., Guo, S.-E., & Rodgers, J. (2007). Light measurement in the hospital: A comparison of two methods. *Research in Nursing and Health, 30*(1), 120-128. doi:10.1002/nur.20167

Joyce, D. S., Feigl, B., Kerr, G., Roeder, L., & Zele, A. J. (2018). Melanopsin-mediated pupil function is impaired in Parkinson's disease. *Scientific Reports, 8*(7796). doi:10.1038/s41598-018-26078-0

Judd, D. B., MacAdam, D. L., & Wyszecki, G. (1964). Spectral distribution of typical daylight as a function of correlated color temperature. *Journal of the Optical Society of America, 54*(8), 1031-1040. doi:10.1364/JOSA.54.001031

LeGates, T. A., Fernandez, D. C., & Hattar, S. (2014). Light as a central modulator of circadian rhythms, sleep and affect. *Nature Reviews: Neuroscience, 15*, 443. doi:10.1038/nrn3743

Liu, L., Marler, M. R., Parker, B. A., Jones, V., Johnson, S., Cohen-Zion, M., . . . Ancoli-Israel, S. (2005). The relationship between fatigue and light exposure during chemotherapy. *Supportive Care in Cancer, 13*(12), 1010-1017. doi:10.1007/s00520-005-0824-5

Maynard, M. L., Zele, A. J., Kwan, A. S., & Feigl, B. (2017). Intrinsically photosensitive retinal ganglion cell function, sleep efficiency and depression in advanced age-related Macular Degeneration. *Investigative Ophthalmology and Visual Science, 58*(2), 990-996. doi:10.1167/iovs.16-20659

Mishima, K., Okawa, M., Hishikawa, Y., Hozumi, S., Hori, H., & Takahashi, K. (1994). Morning bright light therapy for sleep and behavior disorders in elderly patients with dementia. *Acta Psychiatrica Scandinavica, 89*(1), 1-7. doi:10.1111/j.1600-0447.1994.tb01477.x

Montgomery, P., & Dennis, J. A. (2002). Physical exercise for sleep problems in adults aged 60+. *The Cochrane Library*. doi:10.1002/14651858.CD003404

Philips Respironics. (2008). Characterization of light sensor performance for three models of Actiwatch.

Phipps-Nelson, J., Redman, J. R., Dijk, D.-J., & Rajaratnam, S. M. W. (2003). Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *Sleep, 26*(6), 695-700. doi:10.1093/sleep/26.6.695

Price, L., Khazova, M., & O'Hagan, J. (2012). Performance assessment of commercial circadian personal exposure devices. *Lighting Research & Technology, 44*(1), 17-26. doi:10.1177/1477153511433171

Rollag, M. D., Berson, D. M., & Provencio, I. (2003). Melanopsin, ganglion-cell photoreceptors, and mammalian photoentrainment. *Journal of Biological Rhythms, 18*(3), 227-234. doi:10.1177/0748730403018003005

Rosenthal, N. E., Sack, D. A., Gillin, J., & et al. (1984). Seasonal affective disorder: A description of the syndrome and preliminary findings with light therapy. *Archives of General Psychiatry, 41*(1), 72-80. doi:10.1001/archpsyc.1984.01790120076010

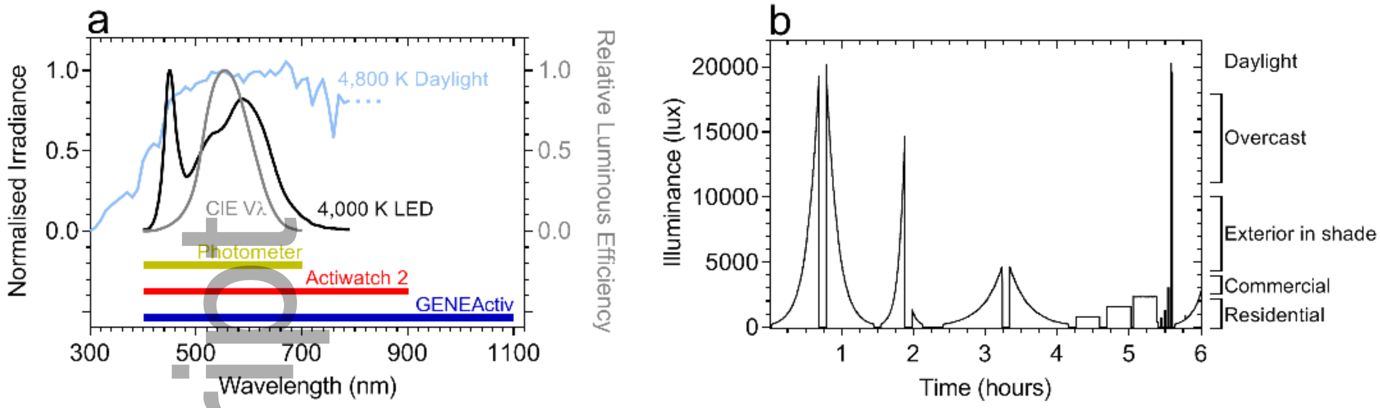
Rüger, M., Gordijn, M. C. M., Beersma, D. G. M., Vries, B. d., & Daan, S. (2006). Time-of-day-dependent effects of bright light exposure on human psychophysiology: Comparison of daytime and nighttime exposure. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology, 290*(5), R1413-R1420. doi:10.1152/ajpregu.00121.2005

Shochat, T., Martin, J., Marler, M., & Ancoli-Israel, S. (2000). Illumination levels in nursing home patients: effects on sleep and activity rhythms. *Journal of Sleep Research, 9*(4), 373-379. doi:10.1046/j.1365-2869.2000.00221.x

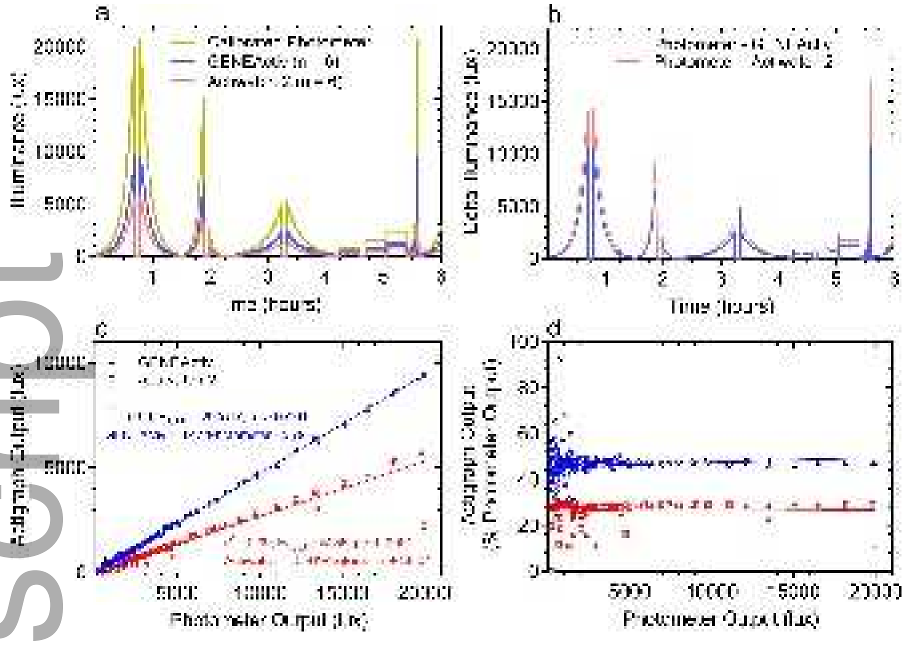
Smith, V. C., Pokorny, J., Lee, B. B., & Dacey, D. M. (2008). Sequential processing in vision: The interaction of sensitivity regulation and temporal dynamics. *Vision Research, 48*(26), 2649-2656. doi:10.1016/j.visres.2008.05.002

Terman, M., & Terman, J. S. (2014). Light therapy for seasonal and nonseasonal depression: Efficacy, protocol, safety, and side effects. *CNS Spectrums, 10*(8), 647-663. doi:10.1017/S1092852900019611

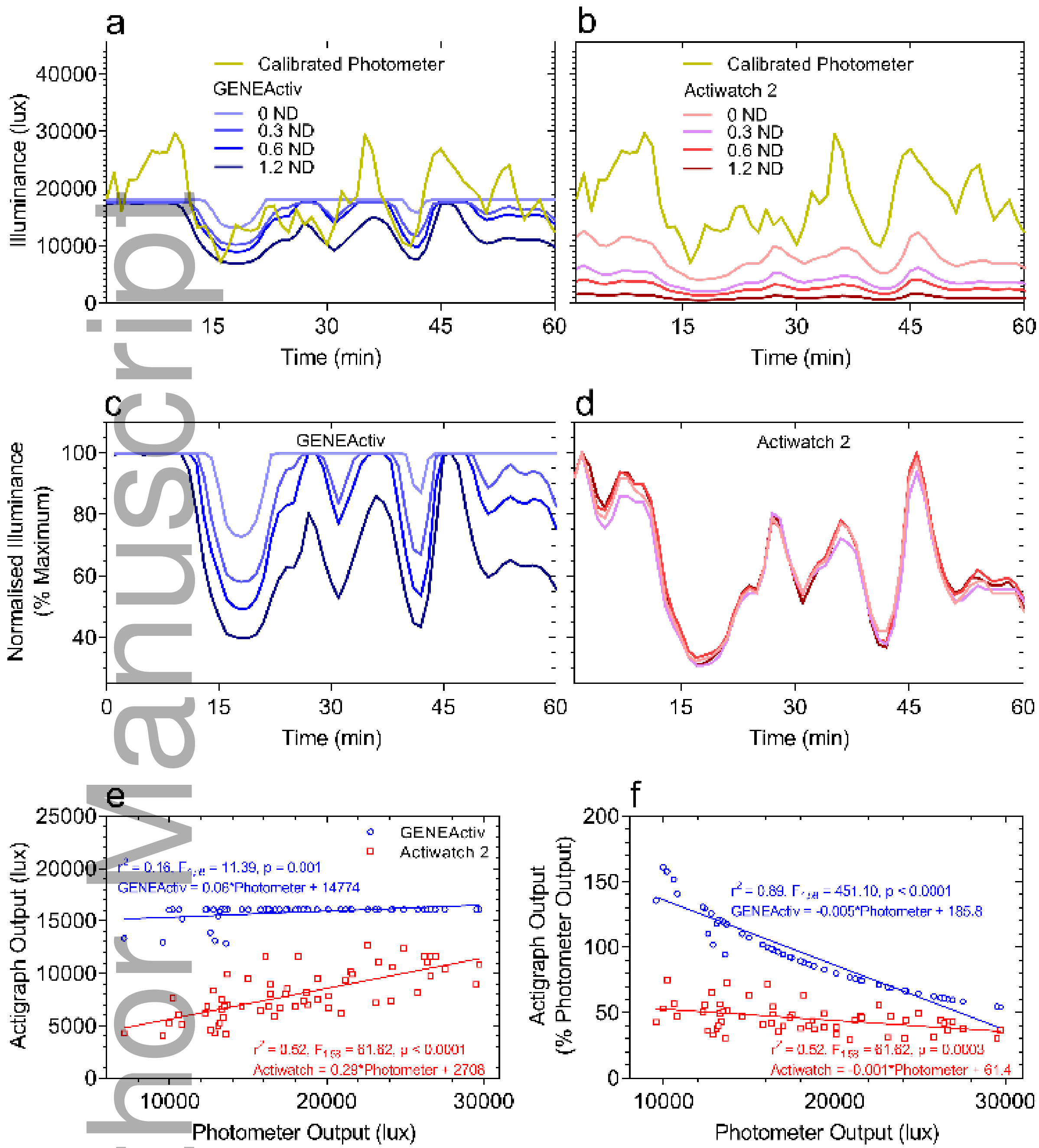
Zele, A. J., & Vingrys, A. J. (2005). Cathode-ray-tube monitor artefacts in neurophysiology. *Journal of Neuroscience Methods, 141*(1), 1-7. doi:10.1016/j.jneumeth.2004.05.005



jsr_12963_f1.tif



jsr_12963_f2.tif



jsr_12963_f3.tif