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Intra- and inter-model variability of light detection using a commercially available light sensor

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ABSTRACT

Purpose

The veracity of claims made by researchers and clinicians when reporting the impact of lighting on vision and other biological mechanisms is, in part, reliant on accurate and valid measurement devices. We aim to quantify the intra- and inter-watch variability of a commercially available light sensor device which has been widely used in vision and other photobiological research.

Methods

Intra- and inter-watch differences were investigated between four Actiwatch Spectrum Pro devices. The devices were used to obtain measurements on two separate occasions, under three different controlled light conditions; the Gretag Macbeth Judge II lightbox was used to produce Simulated Daylight (D65), Illuminant A (A) and Cool White Fluorescent (CWF) lighting.

Results

Significant inter-watch differences were noted when considering tricolour (red, green, blue) and the white sensor outputs under each of the three illuminants ($p<0.01$). A significant interaction was also found between tricolour sensor and watch used ($p<0.01$).

Intra-watch differences were noted for the tricolour and for the white sensor outputs under the three illuminants (≤ 0.05), for all but one watch which showed no significant intra-watch difference for the white ‘sensor output’ under the D65 illuminant.

Conclusion

Use of spectral sensitivity devices is an evolving field. Before drawing causal relationships between light and other biological processes, researchers should acknowledge the limitations of the instruments used, their validation, and the resultant data. The outcomes of the study indicate caution must be exercised in longitudinal data collection and the mixing of watches amongst study participants should be avoided.

INTRODUCTION

Wearable accelerometers and light sensors have been widely adopted for clinical and research purposes. [1,2,3,4,5,6] Studies exploring circadian entrainment; sleep quality; and physical activity have been particularly embracive of such technologies. [7,8,9,10,11,12] More recently, vision researchers have made greater use of light and activity monitors. [13,14,15,16] The appeal of such devices is unsurprising; they offer a seemingly objective, and largely unobtrusive, method of recording data whilst reducing reliance on more subjective recall methods such as questionnaires or interviews.

There is a compelling link between onset of myopia, shortsightedness, and time spent outdoors, [17] the study of which relies upon accurate and valid monitoring of lighting exposure. Whilst a range of light sensors have been employed for such photobiological studies, models from the Phillips Respironics' Actiwatch (Philips Healthcare, Best, NL) range have proven to be particularly popular for vision related studies within child and adult cohorts.

While the research interest in various iterations of the Actiwatch has led to numerous validation and evaluative studies relating to the accelerometery aspect, [18,19,20,21,22,23,24,25] there are comparatively fewer studies validating the light detection features. [26,27,28,29,30]
Given the paucity of data and the growing interest in light detection research, this study aims to investigate intra- and inter-model variability in light detection of a commercially available device from Philips Respironics: the Actiwatch Spectrum Pro.

METHODS

Four static Actiwatch Spectrum Pro devices were used to obtain measurements in a controlled lighting environment. The Phillips Actiware software was used to set epoch length to 15 s for ~5 min exposure periods, from which 13 consecutive sampling points (i.e. ~3 min' worth) were extracted for analysis. In general, the data were only extracted for analysis after at least ~1 min of recording to minimise any erratic measurements due to potential sensor adaptation or otherwise.

The included data were also checked to ensure the 'Activity' outputs were recorded as zero for the period during which light data were extracted i.e. the watch had not moved or fallen during the process of recording.

To investigate intra- and inter-watch differences, the four Actiwatch Spectrum Pro devices were used to obtain measurements on two separate occasions, under three different controlled light conditions. A Gretag Macbeth Judge II lightbox (Gretag Macbeth, New Windsor, New York, USA) was used to simulate the lighting conditions: Simulated Daylight (D65), Illuminant A, and Cool White Fluorescent (CWF) lighting, which have published colour temperatures of 6500 K, 2856 K, and4150 K. All watches were affixed such that the watch was statically face-up and in the horizontal plane within the lightbox.

The Actiwatch Spectrum Pro refers to 'white', 'red', 'green', 'blue' outputs. As white light watch outputs are understood to be generated from integration of all three tricolour sensors, white light data were analysed separately. The manufacturer's literature indicates that the Actiwatch Spectrum Pro measures wavelengths between 400 and 700 nm, [31] including capturing wavelength sensitivity with respect to the tricolour sensors blue (400-500 nm), green (500-600 nm), and red (600-700 nm) with band widths of ~100 nm. [32]

Statistical analysis

A series of paired t-tests were used to investigate intra-watch differences, i.e. differences between runs 1 and 2 for white, red, green, and blue sensor outputs, following exposure to the three illumination conditions. Bias and limits of agreement were generated for each intra-watch combination.

A mixed design repeated-measures analysis of variance (ANOVA) was used to determine inter-watch differences. The watch used was considered the between-subject factor, with lighting and the tricolour sensors as the within-subject factors; the analysis was repeated for the white sensor with only lighting as the within subject factor.

RESULTS

For watch 2, anomalous measurements e.g. the recording of a zero response, were found under multiple conditions, and anomalous results were recorded for illuminant A (see Fig. 1), thus watch 2 was not included in all analyses.

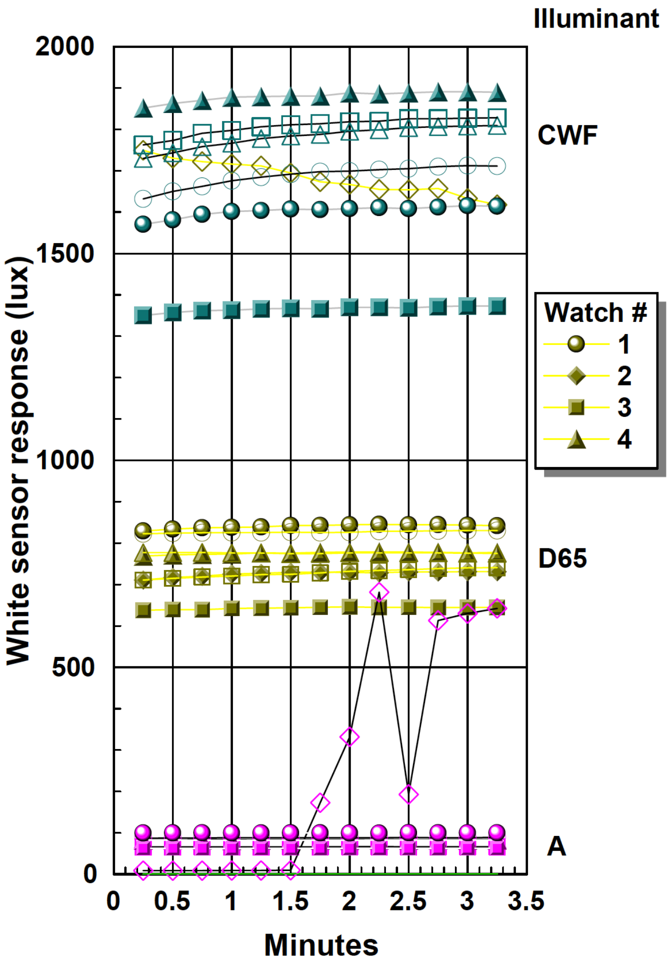

Fig. 1. White sensor response of the four watches for illuminants CWF (teal), D65 (yellow), and illuminant A (purple). Watch 1 denoted by circles, watch 2 by diamonds, watch 3by squares, and watch 4 by triangles. Filled symbols represent run 1 and empty symbols run 2.

Intra-watch differences

A series of paired t-tests showed a significant intra-watch differences for the 'white' light output under each lighting conditions (D65, A, CWF) for all watches ($p < 0.01$) except watch 4 which only showed a significant intra-watch difference under the CWF and the illuminant A lighting conditions, but not D65 ($p > 0.05$). Separately, paired t-tests showed significant intra-watch differences ($p \leq 0.05$) under each of the illuminant conditions for the tricolour outputs (R,G,B); all differences remained significant following application of a Bonferroni correction(0.05/3 = 0.0167) except the red sensor of watch 4 under illuminant A ($p = 0.05$).

The bias (i.e. the mean difference between run 1 and run 2) and the limits of agreement were calculated for outputs under each of the lighting conditions; these are shown in Tables 1 and 2. Large differences in bias were noted, ranging from -956.89 to 13.61 for the D65 condition; -255.12 to 11.65 for illuminant A; and -441.60 to 97.37 for illuminant CWF for the white data outputs. Similarly, the range of bias was also observed between watches for the tricolour outputs.

	Watch 1	Watch 2	Watch 3	Watch 4
DAYLIGHT				
Bias	13.61	-956.89	-84.86	-0.39
Standard Dev	3.25	45.89	7.75	3.67
Lower LOA	7.25	-1046.82	-100.04	-7.58
Upper LOA	19.97	-866.95	-69.68	6.80
t-test p value	<0.01	<0.01	<0.01	0.71
% difference in means	-1.6	56.9	11.7	0.1
ILLUMINANT A				
Bias	11.65	-255.12	-3.83	-1.50
Standard Dev	0.44	285.88	0.346952	0.42
Lower LOA	10.78	-815.45	-4.50618	-2.32
Upper LOA	12.52	305.20	-3.14613	-0.69
t-test p value	<0.01	0.01	<0.01	<0.01
% difference in means	13.2	100	5.8	1.8
CWF				
Bias	-84.69	-8.30	-441.60	97.37
Standard Dev	12.72	0.33	14.85	14.51
Lower LOA	-109.63	-8.95	-470.70	68.93
Upper LOA	-59.75	-7.65	-412.50	125.80
t-test p value	<0.01	<0.01	<0.01	<0.01
% difference in means	5	100	24.4	-5.5

Table 1. Bias (mean difference between runs 1 and 2), standard deviation (SD) of the bias, upper and lower limit of agreement *LOA*, and percentage difference (change from run 1 to 2) is shown for all four watches under each of the lighting conditions for white light outputs only.

	RED				GREEN				BLUE			
DAYLIGHT	Watch 1	Watch 2	Watch 3	Watch 4	Watch 1	Watch 2	Watch 3	Watch 4	Watch 1	Watch 2	Watch 3	Watch 4
Bias	51.54	-777.23	108.38	-19.77	-49.23	-4756.23	-584.77	14.69	16.54	-320.00	23.77	18.62
Standard Dev	4.39	14.78	5.59	3.11	7.60	348.25	14.70	2.10	2.96	11.13	6.73	2.14
Lower LOA	42.93	-806.19	97.43	-25.87	-64.12	-5438.81	-613.58	10.58	10.73	-341.81	10.57	14.42
Upper LOA	60.14	-748.27	119.34	-13.67	-34.34	-4073.65	-555.96	18.80	22.34	-298.19	36.97	22.81
t-test p value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
% difference in means	-6.6	46.7	-35.0	3.5	3.6	92.1	47.2	-1.9	-2.0	40.9	-5.7	-5.7
ILLUMINANT A												
Bias	74.69	-246.52	2.46	-0.92	17.23	-253.23	-0.91	-1.40	4.49	-140.52	-1.13	-0.32
Standard Dev	2.39	276.87	1.33	1.50	0.44	292.56	0.23	0.36	0.18	156.01	0.10	0.12
Lower LOA	70.00	-789.18	-0.15	-3.86	16.37	-826.64	-1.36	-2.10	4.13	-446.29	-1.33	-0.55
Upper LOA	79.38	296.13	5.07	2.01	18.09	320.18	-0.46	-0.70	4.85	165.26	-0.93	-0.09
t-test p value	<0.01	0.01	<0.01	0.05	<0.01	0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01
% difference in means	-15.1	100	-1.1	0.2	-16.6	100	1.9	2.3	-13.3	100	6.6	1.4
CWF												
Bias	-36.15	-5.94	-160.85	56.92	-75.38	0.00	-230.23	26.15	-43.00	-2.50	-171.62	40.62
Standard Dev	12.61	0.14	6.35	7.51	7.76	0.00	4.97	7.31	7.46	0.10	5.38	6.28
Lower LOA	-60.87	-6.22	-173.29	42.20	-90.60	0.00	-239.97	11.82	-57.62	-2.69	-182.16	28.31
Upper LOA	-11.44	-5.66	-148.40	71.64	-60.17	0.00	-220.49	40.49	-28.38	-2.31	-161.07	52.92
t-test p value	<0.01	<0.01	<0.01	<0.01	<0.01	n/a	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
% difference in means	2.7	100	17.3	-4.8	6.1	n/a	26.4	-3.1	4.2	100	22.8	-5

Table 2. Bias (mean difference between runs 1 and 2), standard deviation of the bias, upper and lower LoAs are shown for all four watches under each of the lighting condition Bonferroni correction).

Figure 1 shows the white light sensor outputs for the watches when exposed to the three illuminants, including runs 1 and 2. The watches, except watch 2, show relatively constant recordings during the 3 min. Figure 2 shows the same for the tricolour (R, G, B) outputs with each measurement being the mean recording ±standard deviation of the time exposure. Visual inspection of the difference vs. mean plots showed that while there was generally no obvious relationship between bias and means for the incandescent lighting conditions (for white or RGB), for the other two lighting conditions there may have been an increase in differences between readings with increasing mean, although this was not always apparent in every case.

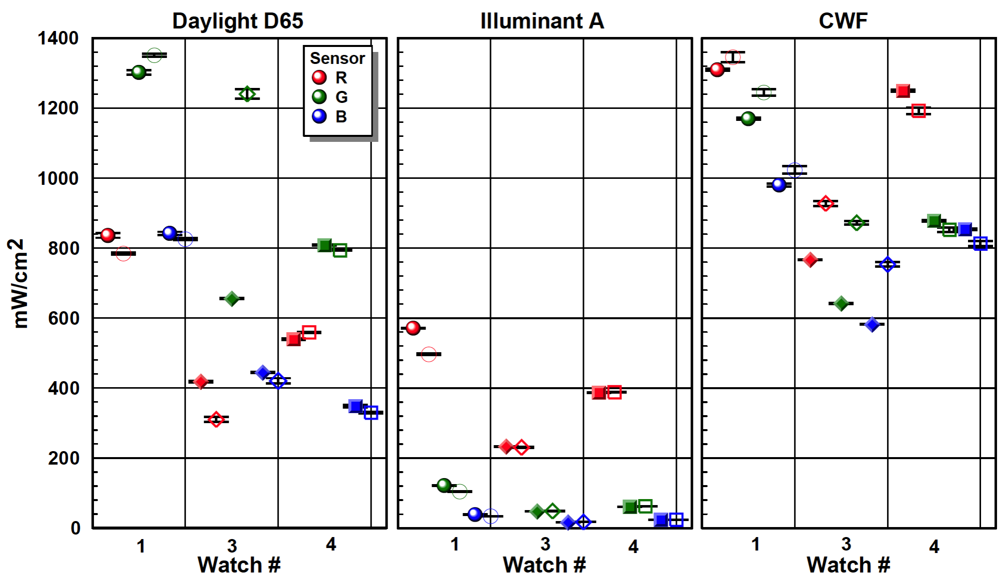

Fig. 2. Response of red (R), green (G) and blue (B) sensors in watches 1, 3, and 4 under daylight D65, illuminant A and CWF illumination. Two runs are shown; run 1 – filled symbols and run 2 – empty symbols. Error bars represent the standard deviation of measurements taken over the course of ~3mins.

Inter-watch differences

A mixed design repeated measures ANOVA, using the first run of measurements, where watch (watch 1, 3, 4) was the between-subject factor, and both lighting and the tricolour sensors served as the within-subject factors, showed a significant overall difference between watches ($p<0.001$) for the R, G, B outputs. Similarly, a significant inter-watch difference was noted for white outputs too ($p\leq0.001$). As may be expected there was a significant main effect of lighting on outputs ($p<0.001$) for both the tricolour sensor and, separately, for white sensor responses; and an interaction between lighting and sensor for the tricolour responses ($p<0.001$) i.e. some sensors reacted more, and in other cases less, to each illuminant.

Inter-watch differences were highlighted through significant interactions between illuminant and watch used; this was the case for both tricolour and, separately, white responses ($p<0.001$). Differences were also found between watches for the tricolour sensors ($p<0.001$). Outcomes for run 2 (with watches 1, 3, 4) showed the same results.

DISCUSSION

Our data show multiple intra-watch differences for measurements obtained using the same watches and lighting conditions on different dates; the data also show a significant inter-watch difference i.e. differences between the outputs of individual watches. The interaction between watch used and sensor (R, G, B) further reinforces the need for calibration of watches prior to their use. [27]
Despite the differences, other than the watch which appeared to produce largely anomalous and erratic results (watch 2), our data showed the percentage change between runs 1 and 2 was generally small for the white light response (see Tables 1 and 2).

As part of their studies, Figueiro et al. (2015) [28] tested six Actiwatch Spectrum devices under various light sources. A measurement range of 20% (from lowest to highest) under high pressure sodium lighting to 9% under 3500 K fluorescent lighting was reported, the range for daylight was approximately 12%. For comparison, excluding watch 2, our range of maximum and minimum measurements across all watches (i.e. the maximum and minimum of all readings across watches 1,3, 4) fluctuated 25% from highest to lowest readings under daylight; 38% under illuminant A; and 29% under the CWF illuminant for the white output. Similarly, others have also reported a high degree of variation between different Actiwatch devices. [27]

While our testing protocol did not evaluate the impact of oblique and direct lighting separately, the use of a lightbox ensured uniform light distribution. Previous work has shown the Actiwatch Spectrum sensors to be sensitive to orientation. [28,29] Price et al. (2012) reported mean percentage of cosine response errors (f) as approximately 25.3%; 33.2%; 32.6%; and 48.6% when the plane of incidence was horizontal and approximately 61.1%; 60.9%; 61.0%; and 64.7% when vertical for the white, red, green, and blue outputs respectively. Figueiro et al. (2015) [28] also reported on spatial sensitivity, for the Actiwatch Spectrum; f errors were 30.7%;39.4%; and 57.2% for the red, green, and blue sensors, respectively. The Actiwatch Spectrum sensors are set back from the watch surface by approximately 2 mm (Price et al. 2012); and encased in an external cover; the positioning of the sensors is understood to limit incident light, [28] particularly for the blue sensor [29].

With respect to future work in ophthalmology

The findings suggest that the Actiwatch Spectrum Pro is a useful tool for characterising light, however, caution must be exercised.

Our work provides some indication of the magnitude of error one might expect when collecting data under different lighting conditions.

Repeatability may be lower for some watches, which will affect the validity of any comparisons between data captured at different time points i.e. longitudinal studies.

The presence of inter-watch differences demonstrates a need to use the same watch for the same individual throughout a study i.e. the watches are not interchangeable. A lack of interchangeability also limits the ability to draw comparisons between datasets from different individuals who have used different watches.

CONCLUSION

In summary, our findings are in general agreement with previous work evaluating the Actiwatch and support the need for calibration. Spectral sensitivity devices appear to be part of an evolving field. Before drawing causal relationships between light and other biological processes, researchers should be clear to acknowledge the limitations of their instruments and understand the potential margins of error which may affect their dataset; it is only then that meaningful differences can be distinguished from noisy data.

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REFERENCES

1. Gafurov, D., Snekkenes, E., Bours, P., Gait authentication and identification using wearable accelerometer sensor. In 2007 IEEE workshop on automatic identification advanced technologies. *IEEE*:220-225, 2007

2. Alvarez, D., González. R. C., López, A., Alvarez, J. C.. Comparison of step length estimators from wearable accelerometer devices. In Encyclopedia ofHealthcare Information Systems. *IGI Global*: 244-250, 2008.

3. Mehta DD, Zanartu M, Feng SW, Cheyne II HA, Hillman RE. Mobile voice health monitoring using a wearable accelerometer sensor and a smartphone platform. IEEE Trans. Biomed. Eng. 2012;59(11):3090-6.

4. Casale P, Pujol O, Radeva P. Human activity recognition from accelerometer data using a wearable device. In Iberian Conference on Pattern Recognition and Image Analysis 2011 Jun 8 (pp. 289-296). Springer, Berlin.

5. Warren S, Yao J, Barnes GE. Wearable sensors and component-based design or home health care. In Proceedings of the Second Joint 24th Annual Conference and the Annual Fall Meeting of the Biomedical Engineering Society Engineering in Medicine and Biology 2002 Oct 23 (Vol. 3, pp. 1871-1872). IEEE.

6. Alvarez AA, Wildsoet CF. Quantifying light exposure patterns in young adult students. J. Modern Optics. 2013;60(14):1200-8.

7. Smarr BL, Burnett DC, Mesri SM, Pister KS, Kriegsfeld LJ. A wearable sensor system with circadian rhythm stability estimation for prototyping biomedical studies. IEEE Trans. Affect. Comput. 2015 Dec 23;7(3):220-30.

8. Lee HA, Lee HJ, Moon JH, Lee T, Kim MG, In H, Cho CH, Kim L. Comparison of wearable activity tracker with actigraphy for sleep evaluation and circadian rest-activity rhythm measurement in healthy young adults. Psychiat. Investig. 2017;14(2):179.

9. Miwa, H., Sasahara, S. I., Matsui, T., Roll-over detection and sleep quality measurement using a wearable sensor. In2007 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society. *IEEE*:1507-1510, 2007

10. Majoe, D., Bonhof, P., Kaegi-Trachsel, T., Gutknecht, J., Widmer, L., Stress and sleep quality estimation from a smart wearable sensor. In5th International Conference on Pervasive Computing and Applications. *IEEE*: 14-19, 2010.

11. Yang CC, Hsu YL. A review of accelerometry-based wearable motion detectors for physical activity monitoring. Sensors. 2010;10(8):7772-88.

12. Wang JB, Cadmus-Bertram LA, Natarajan L, White MM, Madanat H, Nichols JF, Ayala GX, Pierce JP. Wearable sensor/device (Fitbit One) and SMS text-messaging

prompts to increase physical activity in overweight and obese adults: a randomized controlled trial. Telemed. e-Health. 2015;21(10):782-92.

13. Read SA, Collins MJ, Vincent SJ. Light exposure and physical activity in myopic and emmetropic children. Optometry Vis. Sci. 2014;91(3):330-41.

14. Lundberg K, Suhr Thykjær A, Søgaard Hansen R, Vestergaard AH, Jacobsen N, Goldschmidt E, Lima RA, Peto T, Wedderkopp N, Grauslund J. Physical activity and myopia in Danish children—The CHAMPS Eye Study. Acta ophthalmol. 2018;96(2):134-41.

15. Verkicharla PK, Ramamurthy D, Nguyen QD, Zhang X, Pu SH, Malhotra R, Ostbye T, Lamoureux EL, Saw SM. Development of the Fit Sight fitness tracker to increase time outdoors to prevent myopia. Translational Vis. Sci. Technol..2017;6(3):20.

16. Ostrin LA. Objectively measured light exposure in emmetropic and myopic adults. Optometry Vis. Sci. 2017;94(2):229-38.

17. French AN, Ashby RS, Morgan IG, Rose KA. Time outdoors and the prevention of myopia. Exp. Eye Res. 2013;114:58-68.

18. King MA, Jaffre MO, Morrish E, Shneerson JM, Smith IE. The validation of a new actigraphy system for the measurement of periodic leg movements in sleep. Sleep Med. 2005;6(6):507-13.

19. Finn KJ, Specker BO. Comparison of Actiwatch® activity monitor and Children's Activity Rating Scale in children. Med. Sci. Sports Exercise2000;32(10):1794-7.

20. Routen A, Upton D, Edwards M, Peters D. Intra-and inter-instrument reliability of the actiwatch 4 accelerometer in a mechanical laboratory setting. J. Human Kinet. 2012;31:17-24.

21. Ekblom O, Nyberg G, Bak EE, Ekelund U, Marcus C. Validity and comparability of a wrist-worn accelerometer in children. J. Phys. Activ. Health.2012;9(3):389-93.

22. Gironda RJ, Lloyd J, Clark ME, Walker RL. Preliminary evaluation of reliability and criterion validity of Actiwatch-Score. J. Rehabilit. Res. Develop.2007 1;44(2).

23. Yang SC, Yang A, Chang YJ. Validation of Actiwatch for assessment of sleep-wake states in preterm infants. Asian Nurs. Res. 2014;8(3):201-6.

24. Puyau MR, Adolph AL, Vohra FA, Butte NF. Validation and calibration of physical activity monitors in children. Obesity Res. 2002;10(3):150-7.

25. Rupp TL, Balkin TJ. Comparison of Motion logger Watch and Actiwatch actigraphs to polysomnography for sleep/wake estimation in healthy young adults. Behavior Res. Methods. 2011;43(4):1152-60.

26. Jardim AC, Pawley MD, Cheeseman JF, Guesgen MJ, Steele CT, Warman GR. Validating the use of wrist-level light monitoring for in-hospital circadian studies. Chronobiology Int. 2011;28(9):834-40.

27. Markvart J, Hansen ÅM, Christoffersen J. Comparison and correction of the light sensor output from 48 wearable light exposure devices by using a side-by-side field calibration method. Leukos. 2015;11(3):155-71.

28. Figueiro MG, Hamner R, Bierman A, Rea MS. Comparisons of three practical field devices used to measure personal light exposures and activity levels. Lighting Res. Technol 2013;45(4):421-34.

29. Price LL, Khazova M, O'Hagan JB. Performance assessment of commercial circadian personal exposure devices. Lighting Res. Technol. 2012;44(1):17-26.

30. Cao D, Barrionuevo PA. Estimating photoreceptor excitations from spectral outputs of a personal light exposure measurement device. Chronobiol. Int.2015;32(2):270-80.

31. Phillips website. Actiwatch Spectrum PRO; [accessed 10th Aug 2020]. https://www.usa.philips.com/healthcare/product/HCNOCTN446/actiwatch-spectrum-pro-get-the-actiwatch-advantage/specifications

32. Characterization of Light Sensor Performance For Three Models of Actiwatch. Phillips Medical Systems; [accessed 10th August 2020]. http://www.actigraphy.com/assets/ActiwatchLightSensorPerformance-71c44d6474b549abcd85a903695855d6989fa3d8b2c5aa046bd972289f716fd8.pdf