Reliability and validity of the Actiwatch and Clouclip for measuring illumination in realworld conditions

Citation for published version:
Howell, CM, McCullough, SJ, Doyle, L, Murphy, MH & Saunders, KJ 2021, 'Reliability and validity of the Actiwatch and Clouclip for measuring illumination in realworld conditions', *Ophthalmic and Physiological Optics*, vol. 41, no. 5, pp. 1048-1059. https://doi.org/10.1111/opo.12860

Digital Object Identifier (DOI):
10.1111/opo.12860

Published In:
Ophthalmic and Physiological Optics

Received: 9 December 2020 | Accepted: 9 June 2021 | Published online: 13 August 2021

DOI: 10.1111/opo.12860

OPO THE COLLEGE OF OPTOMETRISTS

ORIGINAL ARTICLE

Reliability and validity of the Actiwatch and Clouclip for measuring illumination in real-world conditions

Colleen M Howell[1] | **Sara J McCullough**[1] | **Lesley Doyle**[1] | **Marie H Murphy**[2] | **Kathryn J Saunders**[1]

[1]Optometry and Vision Science Research Group, School of Biomedical Sciences, Ulster University, Coleraine, UK

[2]Sport and Exercise Sciences Research Institute, School of Sport, Ulster University, Jordanstown, UK

Correspondence
Colleen M. Howell, Optometry and Vision Science Research Group, School of Biomedical Sciences, Ulster University, Coleraine, Northern Ireland, UK.
Email: howell-c1@ulster.ac.uk

Funding information
Department for the Economy

Abstract

Purpose: To compare real-world measures of illumination obtained with the Actiwatch-2 and Clouclip-M2 with 'gold standard' photometry measures and to evaluate the ability of Actiwatch-2 to correctly identify photometer-defined conditions: scotopic (≤0.01 lux), mesopic (0.02–3 lux), indoor photopic (>3–1,000 lux) and outdoor photopic (>1,000 lux); and Clouclip to correctly identify photometer-defined conditions within its operating range (>1 lux). Inter-device reliability of Clouclip for illumination and viewing distance measures was also investigated.

Methods: A Hagner-S2 photometer was used as reference. Measures of illumination were obtained from a range of real-world conditions. To investigate inter-device reliability, five Clouclips were simultaneously exposed to varied light conditions and object distances.

Results: Strong correlations existed between illumination measured with the photometer and both Actiwatch-2 ($\rho = 0.99$, $p < 0.0001$) and Clouclip ($\rho = 0.99$, $p < 0.0001$). However, both devices underestimated illumination compared to the photometer; disparity increased with increasing illumination and was greater for Actiwatch-2 than Clouclip measures. Actiwatch-2 successfully categorised illumination level (scotopic, mesopic, indoor and outdoor photopic) in 71.2% of cases. Clouclip successfully categorised illumination levels as scotopic/mesopic (≤3 lux) and indoor and outdoor photopic in 100% of cases. Mean differences and limits of agreement (LOA) were 430.92 ± 1,828.74 and 79.35 ± 407.33 lux, between the photometer and Actiwatch-2 and photometer and Clouclip, respectively. The Intraclass Correlation Coefficients for illumination and viewing distance measured with five Clouclips were 0.85 and 0.96, respectively.

Conclusion: These data illustrate that different Clouclip devices produce comparable measures of viewing distance and illumination in real-world settings. Both Actiwatch-2 and Clouclip underestimate illumination in the field compared to gold standard photometer measures. The disparity increases at higher levels of illumination and the discrepancy was greater for Actiwatch-2 measures. For researchers interested in categorising light exposure, Clouclip classifies illumination levels

>2 lux more accurately than Actiwatch-2 but cannot discriminate between scotopic and low mesopic light.

KEYWORDS
Actiwatch, Clouclip, light exposure, myopia, near work, sensor technology

INTRODUCTION

Wearable devices which monitor aspects of daily living such as light exposure,[1,2] sleep,[3] physical activity[1,3] and near work behaviours[4–6] are increasingly being used by researchers to provide objective data pertinent to systemic[7] and ocular health issues[6,8–11] including obesity, diabetes, hypertension, mental well-being and the development of myopia. Research from around the world has identified that based on current trends, half the world's population will be myopic by 2050,[12] and modern lifestyles could be contributing to the rise in myopia worldwide.[13] Ulster University's Northern Ireland Childhood Errors of Refraction (NICER) study has demonstrated that the prevalence of myopia amongst white UK teenagers has more than doubled in the last 50 years and is appearing in children at a younger age than in previous decades.[14] An earlier onset of myopia results in an increased risk of progression to high myopia, inflating the risk of secondary sight threatening ocular pathologies.[15] The prevalence of myopia is increasing at a rate that cannot solely be attributed to genetic pressures and is therefore a cause for global concern.[13,16] Researchers are seeking a better understanding of the environmental and lifestyle factors that may contribute to the earlier incidence of myopia in order that strategies for delaying myopia onset may be applied. The potentially modifiable risk factors for childhood myopia include spending less time outdoors,[1,9,17] increased educational pressure,[18–20] spending more time on near activities,[18,21,22] leading less active lifestyles,[23–25] having poor sleep quality[26–30] and increased time spent using hand-held electronic devices.[24,31]

Wearable devices can provide objective measures of multiple risk factors and remove the limitation of recall-bias from self-/parental-reports of childhood behaviours collected through questionnaire or diaries.[2,32,33] Wearable devices are generally lightweight, easy to wear and allow for data collection in the free-living setting.[34,35] These features make wearable devices an attractive method with which to collect myopia-related risk factor data. Furthermore, self-reported measures of time spent outdoors are unable to record the intensity of light to which the individual is exposed, and previous research has determined that time spent outdoors is often misreported and poorly correlated with objective sensor-derived data.[2,32] To date, it is not clear which elements of the outdoor experience are beneficial in relation to reducing the risk for myopia, but further information on children's light exposure in terms of the timing of exposure to different levels of illumination, and the duration and frequency of these exposures is needed. Therefore, it is important to determine which devices are valid and reliable for estimating the intensity of light as well as the amount of time spent outdoors. Time spent in illumination levels >1,000 lux is often used as a proxy for time spent outdoors.[1,33,36,37]

The devices employed to measure illumination objectively in the present study were the Respironics Actiwatch 2 (Philips Healthcare, philips.com), the Clouclip Model M2 (HangZhou Glasson Technology, clouclip.com) and the Hagner Universal Photometer S2 (Hagner, hagner.se). The Actiwatch 2 is a wristworn device which records physical activity and illumination. The Clouclip is a spectacle-mounted device which records near viewing distance and eye-level illumination.

The inter-device reliability of the Actiwatch 2 for illumination and activity measures has been reported as excellent; with intraclass correlation coefficients of 0.99 and 0.98 for light and activity, respectively.[1] The Actiwatch brand refers to a family of wearable devices including; the Actiwatch 2, Actiwatch-L, Actiwatch Spectrum and Actiwatch 64, and this family of devices have previously been validated against both 'gold standard' polysomnography and room respiration calorimetry (measures total energy expenditure) and found to be a reliable method for measuring sleep[38,39] and physical activity, respectively.[40–43] Actiwatch 2 measures of illumination have also been compared with a 'gold standard' photometer in

Key points

- Illumination measures taken in real-world settings by Clouclip more closely reflect 'true' illumination measured by a photometer than those obtained with the Actiwatch 2, particularly at higher levels of illumination.
- Clouclip more accurately classifies illumination levels ≥2 lux than the Actiwatch 2, but the restricted operating range means it cannot discriminate between time spent in scotopic vs low mesopic light.
- Photometry measurements of >1,000 lux were obtained from indoor as well as outdoor locations. This should be considered when using illumination measures as a proxy for time spent outdoors.

both laboratory and outdoor lighting conditions by Joyce *et al*.[44] The authors found that the Actiwatch 2 underestimated the 'true' level of illuminance in comparison to the photometer. However, the linear relationship illustrated between the two devices suggests that it may be possible to apply a conversion factor in order to estimate 'true' illumination.[44] The Actiwatch-L has also been compared to eye-level illumination from a Daysimeter. Comparison between these devices demonstrated that their measures were correlated below 5,000 lux, but that at higher illuminations the Actiwatch-L underestimated the light exposure by more than 100 lux. In contrast, in lower illuminations at night the Actiwatch-L was found to overestimate the illumination compared to the Daysimeter.[45] Two other studies compared the Actiwatch Spectrum measures to calibrated photometer measures, with one study also comparing readings between the Actiwatch Spectrum and Daysimeter. Both studies found the Actiwatch Spectrum to consistently overestimate illumination in comparison to the calibrated photometers,[46,47] and the Daysimeter devices.[46] There are currently no data examining how well the Actiwatch 2 is able to categorise illumination into scotopic, mesopic and photopic (indoor/outdoor) levels.

Previous published abstracts[4,5] and a recently published paper[36] have shown that the Clouclip is highly accurate for measurements of illumination and viewing distance in a laboratory setting, and that the Clouclip could accurately distinguish between indoor (<1,000 lux) and outdoor (>1,000 lux) environments.[4,36] As the Clouclip is relatively new there are currently no studies where the inter-device reliability of the Clouclip is investigated; hence, the consistency of measures taken by different Clouclip units is unknown. Recently, Bhandari and Ostrin[36] reported that the Clouclip slightly underestimated 'true' illumination in comparison with a photometer in a range of real-world conditions in Houston, Texas, USA (29°N, 95°W). They also reported that the Clouclip could accurately distinguish between indoor (<1,000 lux) and outdoor (>1,000 lux) environments.[4,36] It is not yet clear how well the device discriminates between indoor photopic and mesopic levels of illumination.

Landis *et al*.[48] reported significant differences in the light exposure profiles experienced by myopic and non-myopic children in Australia, and hypothesise that these differences suggest that both scotopic and outdoor photopic light have a potential role in the prevention of myopia development. However, at present we have limited information on how accurately either the Clouclip M2 or the Actiwatch 2 classify illumination into different categories.

The present study aims to:

- assess the inter-device reliability of the Clouclip M2 for illumination and viewing distance measures and
- assess the ability of the Actiwatch 2 and Clouclip M2 to measure and accurately categorise illumination using 'gold standard' photometry as the reference.

METHODS

Devices employed

The devices employed to measure illumination objectively in the present study were the Respironics Actiwatch 2 (Philips Healthcare, philips.com), the Clouclip Model M2 (HangZhou Glasson Technology, clouclip.com) and the Hagner Universal Photometer S2 (Hagner, hanger.se).

The Actiwatch 2 is a lightweight and waterproof wrist-worn 'actigraphy' device measuring 43 × 23 × 10 mm. The Actiwatch 2 contains a silicone photodiode light sensor to measure visible light illuminance with a range of 0.01–100,000 lux, and a solid-state piezoelectric accelerometer to measure physical activity ranging from 0.35–7.5 Hertz (recorded as activity counts per minute [cpm]).[1] The Actiwatch 2 has an adjustable epoch of 15, 30 or 60 s. The device is connected to a computer containing the Actiware software using a docking station for charging and data retrieval. The data are uploaded onto the Actiware software and from here can be exported as a CSV file and converted to an Excel spreadsheet (Microsoft, microsoft.com) for further analysis.

The Clouclips were provided by Aeir Eye Hospital Group, China. The Clouclip M2 is a 45.3 × 13.4 × 8.0 mm device, designed for attachment to the right temple of a spectacle frame using a rubber sleeve. The devices have a built-in infrared distance sensor to determine near viewing distance (ranging from 5 to 120 cm), a light intensity sensor to record eye-level ambient illumination (ranging from 1 to 65,536 lux) and a three-axis accelerometer (X, Y, Z axis) to determine when it is being worn. The Clouclip records near viewing distance every 5 s and illumination every 2 min. The device is Bluetooth capable and has a magnetic USB charger for syncing the device to an app and uploading the data to the cloud; from here raw data can be downloaded as an Excel spreadsheet using login credentials.[5,36]

The Hagner Universal Photometer S2 is a combined luminance and illuminance (illumination) meter which is designed for measurements in the field and laboratory. The light sensitive components of the photometer are two silicon diodes, filtered to give a spectral response close to that of the human eye. Illumination is measured directly with an external cell connected to the instrument by a cable approximately 3 m long. The external cell is cosine corrected and therefore reads the level of incident light correctly, independent of the direction of the light source. The reading is obtained from the deflection of the external meter. Illumination can be measured in the range 0.1–100,000 lux.[49] The Hagner S2 photometer used to determine the 'true' level of illumination was calibrated prior to data collection by the manufacturers B Hagner AB (16 October 2019). All measurements for the present study were taken between May and June 2020 in Northern Ireland, UK (55°N, 6°W).

Clouclip inter-device reliability

Five Clouclip M2 devices were used to evaluate the inter-device reliability of illumination (lux) and viewing distance (cm) measures. The number of Clouclips under evaluation was restricted to five in order that the spectacle frames on which they were mounted could be fixed to a moveable surface in such a way that the devices would receive uniform illumination (see *Figure 1*). The moveable surface was sized to ensure that it could be transported efficiently through a variety of spaces over a 60-min period of data collection whilst maintaining the horizontal orientation of each Clouclips' light sensor. Light levels were not manipulated; they represented the normal variation experienced in a range of real-world settings both indoors and outside (spanning the illumination categories under investigation, scotopic through to outdoor photopic).

Clouclips are activated through a mobile phone app and it was not possible to simultaneously start recording on all devices. In order to ensure that the time of data logging of the Clouclips matched, each unit was activated consecutively and then all devices were left in darkness before illumination was introduced, and the test protocol commenced. The point at which the devices detected the onset of illumination was used to synchronise the data after download. To evaluate the reliability of viewing distance measures the board was held at a range of distances from a solid, flat surface (e.g., a wall or door). The actual distances from the solid surface to the Clouclips were not independently recorded. Data were uploaded from each device to a cloud location using the Clouclip app. A synchronised 60-min sample of both the illumination and viewing distance data was extracted from each device and the inter-device intraclass correlation coefficients for both illumination (lux) and viewing distance (cm) were calculated.

Validity of Actiwatch 2 and Clouclip measures and categorisation of illumination: comparison with Hagner-S2 universal photometer

In order to evaluate how well the two wearable devices classified ambient illumination into previously published categories (*Table 1*), a free-standing, anatomically accurate adult-sized skeleton (height: 176 cm [comparable to UK average male height of 175.3 cm[50]]) was employed to 'wear' the devices. A skeleton was chosen in order to maintain consistent, device-appropriate positioning of each devices' light sensors throughout data collection. To enable measurements of illumination to be taken by the photometer in the same plane as each wearable device's light sensor, the two devices could not be compared to the photometer at the same time and therefore were not worn concurrently. The skeleton was stationed in a range of locations spanning all four light exposure categories (*Table 1*) over a period of 100 min per device, including locations with illumination close to the boundaries of each category. The locations included indoor and outdoor locations in a family home (e.g., cupboard without windows, living room, kitchen by window, outdoors in shade, outdoors in bright light) providing a range of illuminations from near darkness indoors to outdoor sunshine (nine conditions in total), and included locations with illumination close to the boundaries of each light exposure category.

FIGURE 1 Schematic drawing of the Clouclips mounted on spectacle frames attached to a solid, portable board for inter-device reliability measures. Diagram not to scale

Clouclip versus Photometer: the photometer's light sensor was held at eye level, to match the position of the Clouclip mounted on a pair of spectacles worn by the skeleton (*Figure 2*), and readings taken for periods of 12 min (an expansion of Bhandari and Ostrin's four minute measuring period[36]) in each condition. The Clouclip has a fixed illumination collection epoch of two minutes and the photometer readings were taken every 15 s. Coinciding time points from the Clouclip raw data sheets were matched with the photometer's readings (averaged across two minutes) to reflect the two-minute measurement epoch of the Clouclip. As noted by Bhandari and Ostrin,[36] the skeleton's head needed to be 'wobbled' from side to side between illumination measurements in order to prevent the Clouclip from going into sleep mode (if no motion was detected for 40 s).

Actiwatch 2 versus Photometer: the protocol described above was repeated with the skeleton wearing an Actiwatch 2. The photometer's light sensor was held at wrist level, to match the position of the Actiwatch 2 (*Figure 2*), and readings taken for periods of 12 min in each condition. The Actiwatch 2 illumination epoch was set to 15 s throughout and recordings were taken from the photometer every 15 s. Data were extracted from the Actiwatch 2 raw data sheets and matched with measures taken by the photometer at corresponding time points.

Statistical analysis

Clouclip inter-device reliability

SPSS Version 25 (IBM, ibm.com) was used for all statistical analyses. Reliability analysis using two-way mixed, average

TABLE 1 Categories used to classify light exposure

Light exposure categories	LUX value	References
Scotopic light	≤0.01 lux	SolarLight[51]
Mesopic light	0.02–3 lux	Charman[52]
Indoor photopic light	>3–1,000 lux	Bhandari and Ostrin[36]
Outdoor photopic light	>1,000 lux	Ulaganathan *et al.*[37]

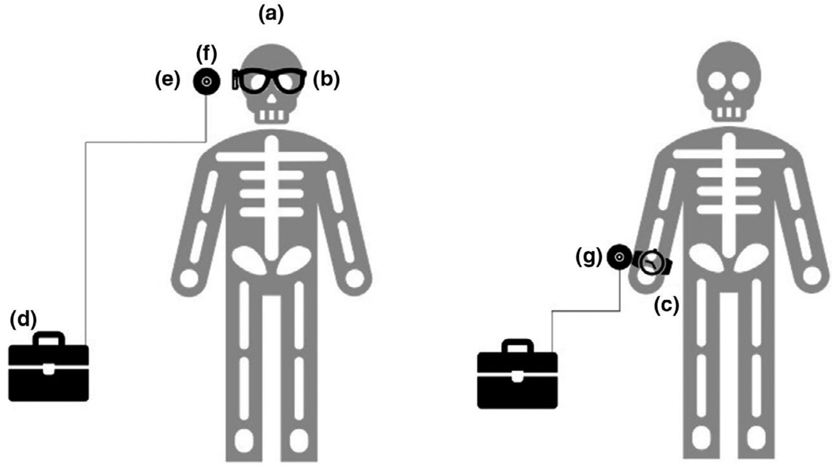

FIGURE 2 The skeleton (a) setup with the spectacle mounted Clouclip (b) and Actiwatch 2 (c). The photometer (d) was setup with the light sensor (e) held at eye-level (f) and wrist-level (g) to allow comparison of outputs with the Clouclip and the Actiwatch 2, respectively. Diagram not to scale

measures and absolute agreement models was used to calculate the inter-device intraclass correlations for the Clouclip metrics under test (illumination and viewing distance). This enabled comparison of the 60-min sample of illumination (every 2 min) and viewing distance (every 5 s) for all five Clouclips under investigation.

Validity of Actiwatch 2 and Clouclip measures and categorisation of illumination: comparison with Hagner-S2 universal photometer

Scatterplots were constructed to illustrate the relationship between measurements made with the Actiwatch 2 and the photometer, and the Clouclip and the photometer, across a range of illuminations. Illumination data from the photometer, Actiwatch 2 and Clouclip were tested for normality using the Shapiro-Wilk test and were found to follow a non-normal distribution (all $p < 0.001$); therefore, Spearman's Rank Order Correlations were used. Illumination category 'cut-offs' were included in a graphical representation to illustrate the capability of the Actiwatch 2 to successfully categorise ambient light levels into each of the four categories described in *Table 1*[36,37,51,52]: scotopic (≤0.01 lux), mesopic (0.02–3 lux), indoor photopic (>3–1,000 lux) and outdoor photopic (>1,000 lux) light. As the Clouclip cannot measure illumination below 1 lux, environmental illuminations of ≤1 lux were recorded as 1 lux in the output Excel file. Therefore, Clouclip is unable to differentiate between scotopic and low mesopic illumination. For the purpose of this study, the scotopic and mesopic categories were combined and the ability of the Clouclip to successfully categorise ambient light levels within its operating range was evaluated in terms of the following categories: scotopic/mesopic (≤3 lux), indoor photopic (>3–1,000 lux) and outdoor photopic (>1,000 lux) light, and was also presented in graphical and numerical format. The agreement between measures recorded by the wearable devices and the photometer were compared using Bland and Altman analyses.[53] The mean difference in illumination measures and 95% limits of agreement (LOAs) were plotted for each wearable device against the photometer, and regression analyses were used to check for proportional bias. Receiver Operating Characteristic (ROC) curve analysis was performed to assess the area under curve (AUC), sensitivity and specificity of the photometer, Actiwatch 2 and Clouclip in identifying a measurement taken indoors and outdoors using the traditional cut-off >1,000 lux.

TABLE 2 Inter-device intraclass correlation coefficients for the Clouclip parameters

Clouclip parameter	Inter-device intraclass correlation coefficients (ICC)
Illumination (lux)	0.85
Viewing distance (cm)	0.96

RESULTS

Clouclip inter-device reliability

The inter-device intraclass correlation coefficients (ICCs) for the Clouclip devices under test are shown in *Table 2* below. The ICCs indicate good and excellent inter-device reliability for illumination and viewing distance measures, respectively.

Validity of Actiwatch 2 and Clouclip measures and categorisation of illumination: comparison with Hagner-S2 universal photometer

The natural light measured (by the photometer) ranged between 0–3,700 lux and 0–6,850 lux when comparing the photometer and Clouclip, and photometer and Actiwatch

2, respectively. Strong correlations were found between 'true' photometer-measured illumination and both measures, the Actiwatch 2 (ρ = 0.99, $p < 0.0001$), and the Clouclip (ρ = 0.99, $p < 0.0001$) (*Figure 3*). Both devices underestimated the illumination levels in comparison to the photometer when exposed to high levels of outdoor light (>2,500 lux). However, the Actiwatch 2 consistently underestimated the illumination in all lighting conditions to a greater degree than the Clouclip (*Figure 3*). The disparity between both wearable devices' recordings and the photometer output increased with increasing illumination. *Table 3* presents how successfully the Actiwatch 2 and Clouclip devices categorised illumination levels, using the photometer reading as the reference value.

As seen in *Figure 3*, while the Clouclip outputs were more closely aligned with the photometer's categorisation, neither the Actiwatch 2 nor the Clouclip correctly categorised all the illumination levels to which they were exposed. Adjusted cut-off criteria for scotopic, mesopic, indoor and outdoor photopic categories calculated from application of the linear fit equations from *Figure 3* are presented in *Table 4* for both devices.

Figures 4 and *5* illustrate the Bland and Altman analyses evaluating the agreement between measures of illumination taken with the photometer and the two wearable devices. The mean differences between the Actiwatch 2 and photometer, and Clouclip and photometer were 430.92 and 79.35 lux, respectively. The limits of agreement (LOAs) between measures made with the Actiwatch 2 compared with the photometer (±1,828.74 lux) were wider than those derived by the Clouclip comparison with the photometer (±407.33 lux). Regression analyses demonstrated significant proportional bias for both the Actiwatch 2 compared to the photometer (r = 0.99, $p < 0.001$) and the Clouclip compared to the photometer (r = 0.78, $p < 0.001$).

During testing it was noted that light levels of > 1,000 lux were occasionally recorded in indoor environments, such as when the skeleton was situated adjacent to a window/door. ROC curve analysis was carried out to determine the sensitivity (i.e., a measurement of >1,000 lux results in correct identification of an outdoor position) and specificity (i.e., a measurement of ≤1,000 lux results in correct identification of an indoor position) of each device, for differentiating between an indoor and outdoor setting using the

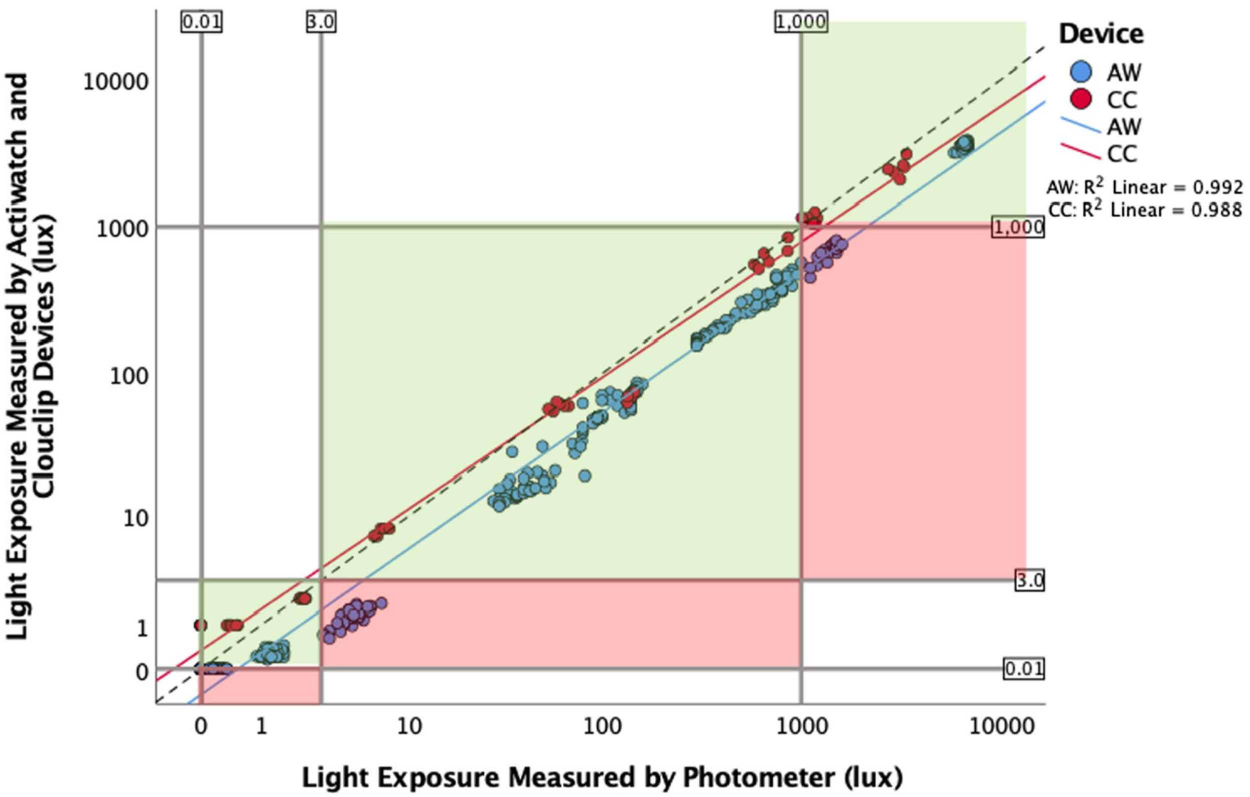

FIGURE 3 Illumination measures taken with the photometer versus Clouclip (CC) and the photometer versus Actiwatch 2 (AW) plotted on a logarithmic scale. The measures taken by the Clouclip every 2 min and the photometer measures averaged over the corresponding 2 min are represented by a single data point (red). The measures taken by the Actiwatch 2 and photometer every 15 s are also represented by a single data point (blue). The black dashed line represents the line of unity (1:1). The solid red and blue lines indicate the correlation between the photometer and Clouclip measures and the photometer and Actiwatch 2 measures, respectively. Data points falling in the shaded green areas represent the measurements made by the wearable devices provided a classification of light level which agreed with the photometer, while the shaded red areas represent incorrect classification by the wearable devices. The Actiwatch 2 and photometer are unable to differentiate between illumination levels lower than 0.01 and 0.1 lux, respectively. Lower illuminations are recorded as 0.01 lux and 0 lux, respectively. The Clouclip is unable to differentiate between illumination levels less than or equal to 1 lux. Lower illuminations are recorded by the Clouclip as 1 lux

TABLE 3 The agreement between the photometer and both wearable devices when categorising illumination levels with the number of measures in each condition noted

Light exposure measurement by photometer	Category	Actiwatch 2 categorisation
≤0.01 lux	Scotopic	100% (44/44)
0.02–3 lux	Mesopic	50% (44/88)
>3–1,000 lux	Indoor Photopic	77.3% (150/194)
>1,000 lux	Outdoor Photopic	62.9% (44/70)
Overall	All categories	71.2% (282/396)
Light exposure measurement by photometer	**Category**	**Clouclip Categorisation**
≤3 lux	Scotopic/Mesopic	100% (18/18)
>3–1,000 lux	Indoor Photopic	100% (24/24)
>1,000 lux	Outdoor Photopic	100% (12/12)
Overall	All categories	100% (54/54)

The scotopic and mesopic categories are combined for the Clouclip due to the device's floor effect preventing it from distinguishing between scotopic and low mesopic illuminations.

TABLE 4 The adjusted criteria for Actiwatch 2 and Clouclip devices to better align classification with that defined by the photometer

Light exposure categories (lux)	Empirically derived Actiwatch 2 criteria (lux)
Scotopic ≤0.01	≤0.01
Mesopic 0.02–3	0.02–0.78
Indoor photopic 3–1,000	>0.78–533.15
Outdoor photopic >1,000	>533.15
Light exposure categories (lux)	**Empirically derived Clouclip criteria (lux)**
Scotopic/mesopic ≤3	≤3
Indoor photopic 3–1,000	>3–850
Outdoor photopic >1,000	>850

These criteria were derived from the application of linear fit equations from *Figure 3*. A combined 'scotopic/mesopic' category for measures ≤3 lux has been applied to the Clouclip because the operating range of the device does not allow for measurements ≤1 lux to be differentiated.

traditional cut-off of >1,000 lux. The results are presented in *Table 5*.

DISCUSSION

This is the first study that has examined the Clouclip's inter-device reliability for both near viewing distance and illumination measures. Moreover, this is the first to investigate the ability of the Actiwatch 2 and the Clouclip to identify different illumination categories (scotopic, mesopic, indoor photopic and outdoor photopic) used by researchers to explore and compare children's activity and light exposure profiles.

The present, real-world data clarifies the strengths and limitations of using the Clouclip to study illumination measures in Northern Ireland, UK (55°N, 6°W), demonstrating good and excellent inter-device reliability for the first time, with intraclass correlation coefficients of 0.85 and 0.96 for illumination and near viewing distance measures, respectively.[54] Bhandari and Ostrin[36] reported that the Clouclip slightly underestimated 'true' illumination in comparison to a photometer. Our findings support those of Bhandari and Ostrin, illustrating that the Clouclip underestimates 'true' lux values in higher levels of illumination, but to a lesser degree than the Actiwatch 2 outputs.

Underestimation of the 'true' illumination value results in the Actiwatch 2's relatively poor ability to identify successfully environmental light as scotopic, mesopic, indoor photopic or outdoor photopic. Misclassification was most prevalent in dimmer illumination; low levels of mesopic light were classified by the Actiwatch 2 as scotopic, indoor photopic light as mesopic, and outdoor photopic light as indoor photopic (*Figure 3*). Given that outdoor photopic light is generally in the range 1,000 to 10,000 lux,[55] but can be as high as 100,000 lux on a very bright summer day,[33] the opportunities for misclassification of outdoor light (between 1,000 and 2,500 lux) by the Actiwatch 2 are likely to be limited to measures made at dusk or dawn, particularly in the winter months. The empirically calculated criteria

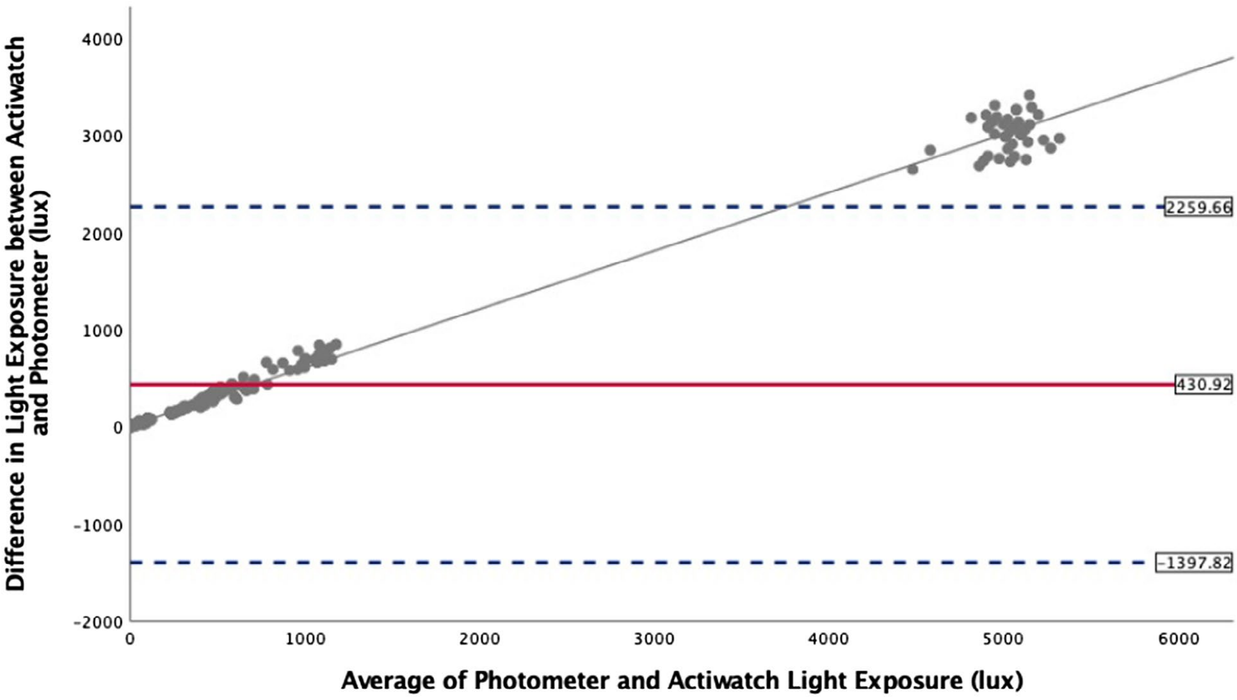

FIGURE 4 Bland and Altman plot for illumination measures recorded with the photometer and Actiwatch 2. The red line represents the mean difference between illumination measures. The dashed blue lines represent the upper and lower limits of agreement and the grey line illustrates the proportional bias ($r = 0.99$, $p < 0.001$)

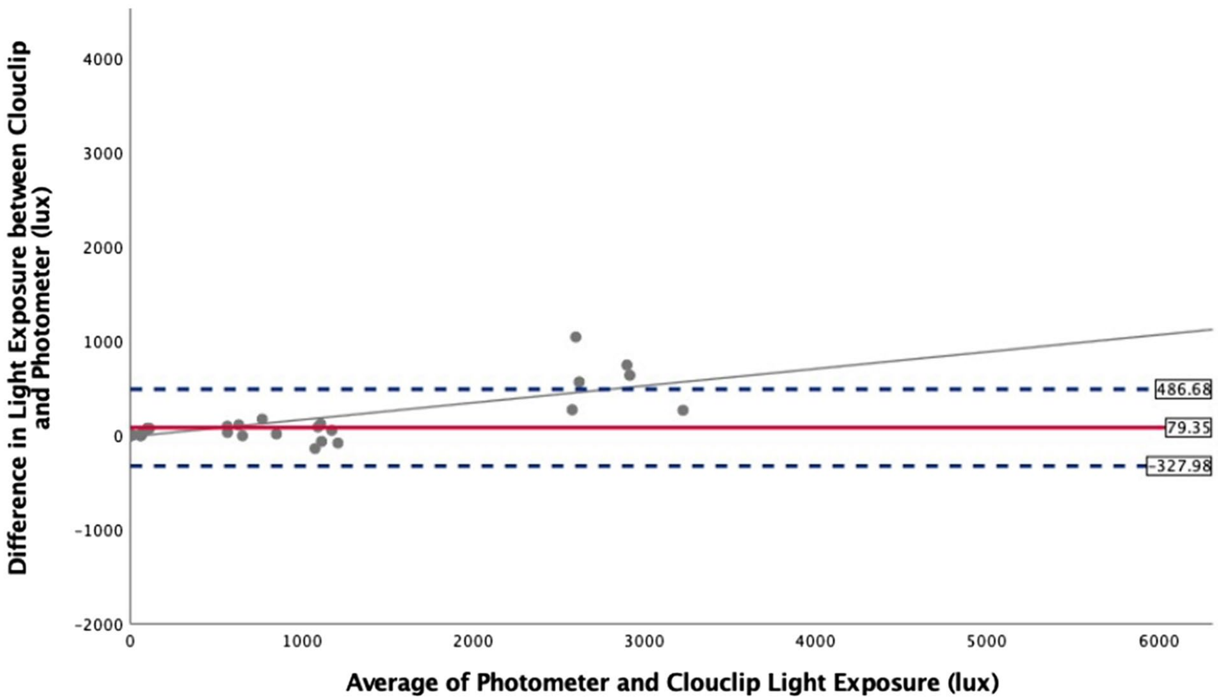

FIGURE 5 Bland and Altman plot for illumination measures recorded with the photometer and Clouclip. The red line represents the mean difference between illumination measures. The dashed blue lines represent the upper and lower limits of agreement and the grey line illustrates the proportional bias ($r = 0.78$, $p < 0.001$)

presented in *Table 4* can be applied to both Actiwatch 2 and Clouclip outputs to allow categorisation that aligns more closely with photometer measures. Joyce *et al.* also recommended the use of a conversion factor when using the Actiwatch 2 to accurately quantify ambient illumination.[44]

TABLE 5 The results of receiver operating characteristic (ROC) curve analysis reporting the sensitivity and specificity of using >1,000 lux to identify whether the measurement was taken outdoors or indoors for each of the devices.

Device used	Area under curve (AUC)	Sensitivity (%)	Specificity (%)
Photometer	1.00	90.5	100
Actiwatch 2	1.00	99.7	100
Clouclip	1.00	91.7	100

In findings similar to the present study, Joyce *et al*. found that the Actiwatch 2 underestimated the true illumination in comparison with a calibrated photometer, but that the relationship between the illumination outputs by the Actiwatch 2 and photometer was strongly linear.[44] Jardim *et al*.[45] also reported that both eye-level (Daysimeter) and wrist-level (Actiwatch-L) illumination measures were significantly correlated with each other at <5,000 lux, but above that level, the Actiwatch-L underestimated the illumination. The average difference across the entire day between the eye-level and wrist-level illumination was 130 lux, with a range of differences of 5–1,000 lux.[45] In contrast to two previous studies which found the Actiwatch Spectrum to consistently overestimate illumination in comparison to calibrated photometers,[46,47] our data demonstrated consistent underestimation of the 'true' illumination value by the Actiwatch 2. The Actiwatch-L and Actiwatch 2 both have a silicon photodiode light sensor, while the Actiwatch Spectrum has colour sensitive photodiodes that could explain the variation in under- and over-estimation of illumination when compared to photometer measures.

The present study demonstrates that the Clouclip measures of illumination are more comparable to the 'true' illumination measured by a calibrated photometer than those achieved with the Actiwatch 2. The relationship between the Clouclip and photometer measures found in the present study ($\rho = 0.99$) are similar to those reported by Bhandari and Ostrin,[36] who also reported a strong relationship between measures made by the Clouclip and photometer ($r = 0.96$). In higher levels of illumination (>2500 lux), the Clouclip underestimated the 'true' lux value in comparison with the photometer, but this is unlikely to result in misclassification of the outdoor photopic light category. The Clouclip is unable to distinguish between scotopic and mesopic light ≤1 lux, and therefore is not a useful tool to explore exposure to extremely low light levels as it cannot discern between scotopic and low mesopic illumination. However, when used to distinguish between mesopic and indoor photopic, and indoor and outdoor photopic light levels, the Clouclip performed more successfully than the Actiwatch 2 (*Table 3*). Classification by the Clouclip remained accurate even when illumination levels measured by the photometer were close to the category borders. Bhandari and Ostrin[36] reported that the Clouclip could reliably detect outdoor illumination (defined as >1,000 lux) in a more southerly location of Houston, Texas, USA (29°N) than the present study.

Several studies have used the Actiwatch 2 to quantify differences between myopes and non-myopes in terms of time spent in different lighting conditions.[1,11,48] However, the criteria used to delineate one type of illumination from another has been inconsistent, making comparison between data sets challenging. Landis *et al*. reported that non-myopes spent a greater amount of time in scotopic light conditions compared with myopic children.[48] When combined with the rather extended definition of scotopic used by Landis *et al*. (<1–1 lux) compared to more commonly accepted values (≤0.01 lux)[51] as used in the present study and the underestimation of illumination by the Actiwatch 2 reported here, the light levels in Landis *et al*.'s study attributed as 'scotopic' could have been anywhere between scotopic and low mesopic. While the non-myopic children spent more time in these lower lighting levels than their myopic peers, it is not clear whether the illumination was truly rod activating as the authors suggest. It has also been reported using Actiwatch 2 data that non-myopes spend more time in outdoor photopic (>1,000 lux) light levels than myopes.[1,11,48] The results of the present study suggest that the amount of time exposed to light of >1,000 lux is likely to have been underestimated using a cut-off of >1,000 lux measured by these wristworn devices, although the effect will be consistent across refractive groups. For researchers wishing to evaluate time spent in different light levels including the very dimmest illumination, the broader measurement range of the Actiwatch 2 make it a more useful tool than the Clouclip, but researchers should be aware of, and calibrate for, the underestimation of true illumination using empirically derived cut-offs.

The Bland and Altman analyses comparing illumination measures between the Actiwatch 2 and photometer (*Figure 4*), and the Clouclip and photometer (*Figure 5*), indicate the superior ability of the Clouclip to determine 'true' illumination compared to the Actiwatch 2, as illustrated by the smaller mean difference and narrower LOAs for the Clouclip (79.35 ± 407.33 lux) compared to the Actiwatch 2 (430.92 ± 1,828.74 lux). However, there is significant proportional bias for both devices, illustrating that as the illumination increases the measures recorded by the wearable devices deviate more from the 'true' value.

A notable finding of the present study was that readings >1,000 lux were recorded by the photometer in indoor domestic locations, when the sensor was near a window/door with bright sunlight streaming in. Illumination readings of >1,000 lux are commonly used by researchers to denote time spent outdoors.[1,33,37,48] The present field study determined that even when using a calibrated photometer to measure illumination, a value of >1,000 lux does not always indicate an outdoor location. Using this cut-off to indicate an outdoor location as measured by the calibrated photometer has a sensitivity (i.e., a measurement of >1,000 lux results in correct identification of an outdoor position) of 90.5% and specificity (i.e., a measurement of

≤1,000 lux results in correct identification of an indoor position) of 100% (*Table 5*). The Clouclip suffers from a similar limitation, but because the Actiwatch 2 consistently under-estimates 'true' lux, the >1,000 lux values recorded with the Actiwatch 2 will reflect outdoor location more consistently than when recorded by the other devices used in the present study, with a sensitivity of 99.7% and specificity of 100%. Time spent outdoors not only confers higher light levels, but also more varied spectral content as well as differences in dioptric demand and spatial content experienced by the eye. Given that there is still debate about the mechanisms by which time spent outdoors protects against myopia,[15,56] this distinction may be important. If researchers want to accurately discriminate between time spent indoors and outdoors, activity may need to be certified by video or GPS data when using the Clouclip. The use of activity diaries can also support objectively gathered data in profiling time spent outdoors.

The results of the present study highlight some benefits and limitations of the Actiwatch 2 and Clouclip devices for measuring illumination. Both devices are wearable and therefore ideal for field-use. The Actiwatch 2 can record illumination across a wider range of light levels and is therefore useful when investigating time spent in conditions ranging from near-dark scotopic illumination through to bright outdoor photopic light levels. However, the Actiwatch 2 underestimates light levels to a greater extent than the Clouclip and more often misclassifies illumination than the Clouclip, if the traditional criteria for categorisation are applied. The empirically derived cut-offs for illumination described in *Table 4* are likely to be more appropriate for determining time spent in different types of illumination if researchers are using a categorical approach to analyse environmental light exposure. The Clouclip outputs more closely resemble 'true' illumination as measured by the photometer, and the spectacle mounted device accurately classifies light exposures >1 lux. However, the Clouclip's utility is limited by a short battery life, a restricted recording epoch and an inability to determine between scotopic and low mesopic light levels, as illumination ≤1 lux is recorded as 1 lux in the output spreadsheet. Additionally, the restricted two-minute recording epoch could result in under- or over-estimation of time spent in different categories of illumination if the wearer is moving rapidly between different environments. This may be particularly relevant when conducting research aimed at understanding light exposure profiles of children; the Clouclip will not capture dynamic changes in environment as readily as the Actiwatch 2, which has the option of shorter recording epochs (15, 30 or 60s).

The present study was intentionally carried out in the field rather than a laboratory setting to gain insight into the real-world utility of the devices. However, the non-laboratory setting resulted in reliance on the natural light conditions encountered and it was not possible to control the specific lux range to which the devices were exposed. The outdoor illumination values are reflective of the real-world light levels experienced in the present study's location, Northern Ireland, UK (55°N, 6°W). Interpretation of the results is restricted to evaluation of the devices' performance in these naturally occurring light conditions. It should also be recognised that the devices were not compared with the photometer under identical conditions due to practical constraints, including the need to continually 'wobble' the skeleton's head to prevent the Clouclip entering 'sleep mode'. The Clouclip wasn't exposed to the same high illuminations that were available when undertaking testing with the Actiwatch 2, and therefore the two devices' outputs could not be directly compared to each other.

CONCLUSION

The present data illustrate that different Clouclip devices produce comparable measures of viewing distance and illumination in a real-world setting. Both Actiwatch 2 and Clouclip devices underestimate illumination in the field when compared to 'gold standard' photometer measures. This disparity increases at higher levels of illumination and is greater for the Actiwatch 2 measures. For researchers interested in categorising light exposure into different classifications from mesopic through to outdoor photopic levels, the Clouclip is a more useful tool, but when scotopic and low mesopic differentiation is required, the Actiwatch 2's broader measurement range is required. Empirically calculated criteria for defining scotopic, mesopic, indoor and outdoor photopic illuminations are presented for the Actiwatch 2 devices, and empirically calculated criteria for defining scotopic/mesopic, indoor and outdoor photopic illuminations are presented for the Clouclip devices. These could be applied by researchers to improve the accuracy of categorisation, or researchers may consider undertaking such calibration activity for the devices used in their own research. Finally, caution should be applied when using a cut-off of >1,000 lux as a proxy for outdoor settings.

ACKNOWLEDGEMENT

Funded by the Department for the Economy, Northern Ireland.

CONFLICT OF INTEREST

The authors report no conflicts of interest and have no proprietary interest in any of the materials mentioned in this article.

AUTHOR CONTRIBUTION

Colleen Marie Howell: Conceptualization (equal); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (equal); Project administration (lead); Validation (equal); Visualization (equal); Writing-original draft (lead); Writing-review & editing (equal). **Sara J McCullough:** Conceptualization (equal); Investigation (equal); Methodology (equal); Supervision (equal);

Validation (equal); Visualization (equal); Writing-review & editing (equal). **Lesley Doyle:** Conceptualization (equal); Investigation (equal); Methodology (equal); Supervision (equal); Validation (equal); Visualization (equal); Writing-review & editing (equal). **Marie H Murphy:** Resources (equal); Software (equal); Supervision (equal); Writing-review & editing (equal). **Kathryn Saunders:** Conceptualization (equal); Funding acquisition (lead); Investigation (equal); Methodology (equal); Resources (lead); Software (lead); Supervision (lead); Validation (equal); Visualization (equal); Writing-review & editing.

ORCID

Colleen M Howell https://orcid.org/0000-0002-7411-2203
Sara J McCullough https://orcid.org/0000-0002-4438-1154
Lesley Doyle https://orcid.org/0000-0001-9549-7192
Kathryn J Saunders https://orcid.org/0000-0002-9289-5731

REFERENCES

1. Read SA, Collins MJ, Vincent SJ. Light exposure and physical activity in myopic and emmetropic children. *Optom Vis Sci* 2014;91:330–341.
2. Ostrin LA, Sajjadi A, Benoit JS. Objectively measured light exposure during school and summer in children. *Optom Vis Sci* 2018;95:332–342.
3. Rosenberger ME, Buman MP, Haskell WL, McConnell MV, Carstensen LL. Twenty-four hours of sleep, sedentary behavior, and physical activity with nine wearable devices. *Med Sci Sports Exerc* 2016;48:457–465.
4. Bhandari KR, Lan W, Ostrin LA. Continuous, objective assessment of viewing behavior for printed and electronic tasks. *Optom Vis Sci* 2019;96:E-abstract 195211.
5. Wen L, Lan W, Huang Y, Wu Y, Li X, Yang Z. A novel device to record the behavior related to myopia development-preliminary results in the lab. *Invest Ophthalmol Vis Sci* 2016;57:ARVO E-abstract 2491.
6. Cao Y, Lan W, Wen L, et al. An effectiveness study of a wearable device (Clouclip) intervention in unhealthy visual behaviors among school-age children: A pilot study. *Medicine (United States)* 2020;99:17992.
7. Humphreys BR, McLeod L, Ruseski JE. Physical activity and health outcomes: Evidence from Canada. *Health Econ (United Kingdom)* 2014;23:33–54.
8. Ostrin LA, Read SA, Vincent SJ, Collins MJ. Sleep in myopic and non-myopic children. *Transl Vis Sci Technol* 2020;9:22. https://doi.org/10.1167/tvst.9.9.22
9. French AN, Ashby RS, Morgan IG, Rose KA. Time outdoors and the prevention of myopia. *Exp Eye Res* 2013;114:58–68.
10. Sherwin JC, Hewitt AW, Coroneo MT, Kearns LS, Griffiths LR, Mackey DA. The association between time spent outdoors and myopia using a novel biomarker of outdoor light exposure. *Invest Ophthalmol Vis Sci* 2012;53:4363–4370.
11. Read SA, Collins MJ, Vincent SJ. Light exposure and eye growth in childhood. *Invest Ophthalmol Vis Sci* 2015;56:6779–6787.
12. Holden BA, Fricke TR, Wilson DA, et al. Global prevalence of myopia and high myopia and temporal trends from 2000 through 2050. *Ophthalmology* 2016;123:1036–1042.
13. Morgan IG, French AN, Ashby RS, et al. The epidemics of myopia: Aetiology and prevention. *Prog Retin Eye Res* 2018;62:134–149.
14. McCullough SJ, O'Donoghue L, Saunders KJ. Six year refractive change among white children and young adults: evidence for significant increase in myopia among white UK children. *PLoS One* 2016;11:e0146332.
15. Flitcroft DI. The complex interactions of retinal, optical and environmental factors in myopia aetiology. *Prog Retin Eye Res* 2012;31:622–660.
16. Wu PC, Huang HM, Yu HJ, Fang PC, Chen CT. Epidemiology of myopia. *Asia-Pacific J Ophthalmol* 2016;5:386–393.
17. Sherwin JC, Reacher MH, Keogh RH, Khawaja AP, MacKey DA, Foster PJ. The association between time spent outdoors and myopia in children and adolescents: A systematic review and meta-analysis. *Ophthalmology* 2012;119:2141–2151.
18. Saw SM, Cheng A, Fong A, Gazzard G, Tan DTH, Morgan I. School grades and myopia. *Ophthalmic Physiol Opt* 2007;27:126–129.
19. Mountjoy E, Davies NM, Plotnikov D, et al. Education and myopia: Assessing the direction of causality by mendelian randomisation. *BMJ* 2018;361:k2022. https://doi.org/10.1136/bmj.k2022
20. Guggenheim JA, Williams C. Role of educational exposure in the association between myopia and birth order. *JAMA Ophthalmol* 2015;133:1408–1414.
21. Saw SM, Chua WH, Hong CY, et al. Nearwork in early-onset myopia. *Invest Ophthalmol Vis Sci* 2002;43:332–339.
22. Ip JM, Saw SM, Rose KA, et al. Role of near work in myopia: Findings in a sample of Australian school children. *Invest Ophthalmol Vis Sci* 2008;49:2903–2910.
23. O'Donoghue L, Kapetanankis VV, McClelland JF, et al. Risk factors for childhood myopia: Findings from the NICER study. *Invest Ophthalmol Vis Sci* 2015;56:1524–1530.
24. Harrington SC, Stack J, O'Dwyer V. Risk factors associated with myopia in schoolchildren in Ireland. *Br J Ophthalmol* 2019;103:1803–1809.
25. Deere K, Williams C, Leary S, et al. Myopia and later physical activity in adolescence: A prospective study. *Br J Sports Med* 2009;43:542–544.
26. Jee D, Morgan IG, Kim EC. Inverse relationship between sleep duration and myopia. *Acta Ophthalmol* 2016;94:e204–e210.
27. Ayaki M, Torii H, Tsubota K, Negishi K. Decreased sleep quality in high myopia children. *Sci Rep* 2016;6:33902. https://doi.org/10.1038/srep33902
28. Xu X, Wang D, Xiao G, Yu K, Gong Y. Sleep less, myopia more. *Theory Clin Pract Pediatr* 2017;1:11–17.
29. Gong Y, Zhang X, Tian D, Wang D, Xiao G. Parental myopia, near work, hours of sleep and myopia in Chinese children. *Health (Irvine Calif)* 2014;6:64–70.
30. Kearney S, O'Donoghue L, Pourshahidi LK, Cobice D, Saunders KJ. Myopes have significantly higher serum melatonin concentrations than non-myopes. *Ophthalmic Physiol Opt* 2017;37:557–567.
31. Liu S, Ye S, Xi W, Zhang X. Electronic devices and myopic refraction among children aged 6–14 years in urban areas of Tianjin, China. *Ophthalmic Physiol Opt* 2019;39:282–293.
32. Alvarez AA, Wildsoet CF. Quantifying light exposure patterns in young adult students. *J Mod Opt* 2013;60:1200–1208.
33. Ostrin LA. Objectively measured light exposure in emmetropic and myopic adults. Optom Vis Sci 2017;94:229–238.
34. Verkicharla PK, Ramamurthy D, Nguyen QD, et al. Development of the FitSight fitness tracker to increase time outdoors to prevent myopia. *Transl Vis Sci Technol* 2017;6:20. https://doi.org/10.1167/tvst.6.3.20
35. Smith MT, McCrae CS, Cheung J, et al. Use of actigraphy for the evaluation of sleep disorders and circadian rhythm sleep-wake disorders: An American Academy of Sleep Medicine systematic review, meta-analysis, and GRADE assessment. *J Clin Sleep Med* 2018;14:1209–1230.
36. Bhandari KR, Ostrin LA. Validation of the Clouclip and utility in measuring viewing distance in adults. *Ophthalmic Physiol Opt* 2020;40:801–814.
37. Ulaganathan S, Read SA, Collins MJ, Vincent SJ. Influence of seasons upon personal light exposure and longitudinal axial length changes in young adults. *Acta Ophthalmol* 2019;97:e256–e265.
38. Hyde M, O'Driscoll DM, Binette S, et al. Validation of actigraphy for determining sleep and wake in children with sleep disordered breathing. *J Sleep Res* 2007;16:213–216.

39. Weiss AR, Johnson NL, Berger NA, Redline S. Validity of activity-based devices to estimate sleep. *J Clin Sleep Med* 2010;6:336–342.
40. Ekblom O, Nyberg G, Bak EE, Ekelund U, Marcus C. Validity and comparability of a wrist-worn accelerometer in children. *J Phys Act Health* 2016;9:389–393.
41. Puyau MR, Adolph AL, Vohra FA, Zakeri I, Butte NF. Prediction of activity energy expenditure using accelerometers in children. *Med Sci Sports Exerc* 2004;36:1625–1631.
42. Puyau MR, Adolph AL, Vohra FA, Butte NF. Validation and calibration of physical activity monitors in children. *Obes Res* 2002;10:150–157.
43. Neil-Sztramko SE, Rafn BS, Gotay CC, Campbell KL. Determining activity count cut-points for measurement of physical activity using the Actiwatch2 accelerometer. *Physiol Behav* 2017;173:95–100.
44. Joyce DS, Zele AJ, Feigl B, Adhikari P. The accuracy of artificial and natural light measurements by actigraphs. *J Sleep Res* 2019;29:e12963. https://doi.org/10.1111/jsr.12963
45. Jardim ACN, Pawley MDM, Cheeseman JF, Guesgen MJ, Steele CT, Warman GR. Validating the use of wrist-level light monitoring for in-hospital circadian studies. *Chronobiol Int* 2011;28:834–840.
46. Figueiro MG, Hamner R, Bierman A, Rea MS. Comparisons of three practical field devices used to measure personal light exposures and activity levels. *Light Res Technol* 2013;45:421–434.
47. 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 - J Illum Eng Soc North Am* 2015;11:155–171.
48. Landis EG, Yang V, Brown DM, Pardue MT, Read SA. Dim light exposure and myopia in children. *Invest Ophthalmol Vis Sci* 2018;59:4804–4811.
49. B Hagner AB. Hagner Universal Photometer Technical Manual [Internet]. Solna Sweden: Bo Hagner; 1968. pp. 1–19. Available from: https://www.hagner.se. Accessed 5 August, 2021.
50. Moody A. Adult anthropometric measures, overweight and obesity. In: Statistics. Chapter 10, Vol. 1. The Health and Social Care Information Centre; 2012. pp. 138–146. https://healthsurvey.hscic.gov.uk/media/1021/chpt-10_adult-measures.pdf
51. SolarLight. Measures Illumination According to the Dark and Light Luminous Efficiency Curve of the Eye [Internet]. 2014 [cited 2020 Dec 1]. pp. 99–100. Available from: https://solarlight.com/wp-content/uploads/2014/11/Meters_SL-3101-.pdf
52. Charman WN. Visual Performance. In: Rosenfield M, Logan N, editors. Optometry: Science, Techniques and Clinical Management, 2nd edn. Edinburgh: Butterworth-Heinemann; 2009. pp. 70–71.
53. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986;1:307–310.
54. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med* 2016;15:155–163.
55. ATP Instrumentation. How to measure light | Using your light meter correctly What is Light? Types of Light How to Measure Light Instruments for Measuring Light When to use a Lux Meter [Internet]. 1989 [cited 2021 Feb 2]. Available from: https://atp-instrumentation.co.uk/blogs/articles/how-to-measure-light-using-your-light-meter-correctly
56. Ngo C, Saw SM, Dharani R, Flitcroft I. Does sunlight (bright lights) explain the protective effects of outdoor activity against myopia? Ophthalmic Physiol Opt 2013;33:368–372.

How to cite this article: Howell CM, McCullough SJ, Doyle L, Murphy MH, Saunders KJ. Reliability and validity of the Actiwatch and Clouclip for measuring illumination in real-world conditions. Ophthalmic Physiol Opt. 2021;41:1048–1059. https://doi.org/10.1111/opo.12860