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ORIGINAL ARTICLE

Utility of the Actiwatch Spectrum Plus for detecting the outdoor environment and physical activity in children

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Abstract
Purpose: To describe the performance of the Actiwatch Spectrum Plus (Philips, Respironics) for determining real world indoor and outdoor environments and physical activity in children.
Methods: Children wore the device while performing 10 different activities, ranging from sedentary to vigorous physical-activity, and under different indoor and outdoor conditions. Repeated measures ANOVA was implemented via mixed effects modeling to determine illuminance (lux) and physical activity (counts per 15 s, CP15) across conditions. Receiver operator characteristics (ROC) analysis assessed the accuracy to detect indoor versus outdoor settings.
Results: Illuminance was found to be statistically different across indoor (793 $\pm$ 348 lux) and outdoor (4,413 $\pm$ 518 lux) conditions (P<.0001), with excellent diagnostic accuracy to detect indoor versus outdoor settings (Area under the ROC Curve, AUC 0.94); 1088 lux was identified as the optimal threshold for outdoor illuminance (sensitivity: 93.0%; specificity: 85.0%). Using published activity ranges, we found that when children were sitting, 94% of the physical-activity readings were classified as sedentary or light. When children were walking, 88% of readings were classified as light, and when children were running, 77% of readings were classified as moderate or vigorous.
Conclusion: The Actiwatch Spectrum Plus performed well during real world activities in children, showing excellent diagnostic accuracy at 1088 lux as a threshold to detect indoor versus outdoor environments and in categorizing physical activity.

Introduction

The Actiwatch is a wrist-worn device consisting of an accelerometer and light sensor and has been used extensively in studies of circadian phase, sleep,[1,2] physical activity,[3] and

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light exposure.[4] Vision researchers have utilized various models of the Actiwatch to study associations between light exposure and physical activity with myopia.[5-8] The Actiwatch is unobtrusive and offers continuous, objective measurement. This is more appealing than other more cumbersome wearable sensors, such as the Hobo sensor that hangs around the neck or mounts on an arm band,[9] and more precise than subjective methods such as questionnaires, which suffer from recall bias.[10,11]

Accumulating evidence has emerged over the past 20 years that decreased time outdoors is an important factor in the development of refractive error.[12] More time outdoors during childhood has been strongly and consistently associated with less myopia according to meta-analyses.[13,14] Early studies relied on questionnaires, but this topic has more recently been addressed with wearable light sensors.[5,7,15] Objective wearable sensors have the capability to precisely quantify factors that questionnaires cannot, such as determining the exact amount of time outdoors and absolute intensity of light required for protection against myopia onset and progression in children. When measured objectively using wearable light sensors, time outdoors is traditionally defined as minutes per day exposed to greater than 1000 lux.[5,7,16] However, each instrument must be tested for reliability and validity in laboratory conditions, in natural light, and while being worn by the participants of interest, in this case, children.

Previous validation studies were primarily on the ActiGraph GT3X+[17] or older versions of the actiwatch, such as the Actiwatch 2[18-21] or the Actiwatch-4 (Cambridge Neurotechnology Ltd., Cambridge, UK).[22] However, there are limited studies on the validity of the light sensor and accelerometer of the Actiwatch Spectrum Plus, which has a different type of light sensor and accelerometer. The Actiwatch Spectrum Plus has only been assessed for validity in laboratory lighting conditions[23-25] and for light measurements in adults.[23,26] The manufacturer described a threshold for outdoor light at 1000 lux, but this has not been validated. Since this device is being used as a tool to measure light exposure and physical activity in many different reasearch settings, it is essential to assess it in real world situations in children. Therefore, the purpose of this study was to firstly to identify a lux threshold that accurately discriminates between indoor and outdoor lighting when the Actiwatch Spectrum Plus is worn by children. Secondly, we sought to establish activity count ranges and thresholds for different physical activities in children. With this, we characterized the performance of the Actiwatch Spectrum Plus for light and physical activity in children during real world applications. The results of this study will be of interest to scientists in vision research, circadian rhythm, health and obesity, psychology and depression, and in many other fields where objective measurements of environment and behaviors are important.

Materials and methods

Instrumentation

The Actiwatch Spectrum Plus (Philips Respironics, Bend, OR, USA) is a wrist-worn watch-like device that measures ambient illumination and physical activity continuously at 32 Hz. The light sensor in the Actiwatch Spectrum consists of light sensitive photodiodes that measure illuminance from 400 to 700 nanometers in units of lux. The range according to the manufacturer is 0.1−35,000 lux. Physical activity is measured via a MEMS-type accelerometer and is expressed in counts per minute, a dimensionless measure of motion that is designed to remove the effects of gravity, transportation, and other types of acceleration that do not indicate subjects' physical activity.[27] The accelerometer detects vertical accelerations between 0.5 and 2.0 g with a frequency response range of 0.35−7.5 Hz. The degree and speed of motion is integrated, the signal is amplified and digitized by the on-board circuit, and the data are stored in the memory of the device as activity counts per epoch. The device displays the time and date, and a sensor detects "off-wrist" time to monitor subject compliance. For the current experiments, the epoch was set to 15 s.[22]

To test the inter-device reliability of the light sensor of the devices used in this study, the eighteen Actiwatches were configured as above, mounted on a stand and tested in various outdoor and indoor conditions. From these data, Chronbach's alpha was found to be 0.912, suggesting excellent inter-device reliability.

Real world performance in children

Participants were healthy boys and girls, ages 9−13 years, who could perform various physical activity tasks. Only children who had been fully vaccinated for or recovered from COVID-19 were invited to participate, and masks were worn for all indoor activities. Informed consent was obtained from parents and informed assent was obtained from children. The study was approved by the Ethics Committee. Children wore short sleeve shirts to ensure that the light sensor of the Actiwatch was not obscured. Data were collected in August 2021 on a cloudless summer day. Sunrise and sunset were approximately 6:10 AM and 7:11 PM, respectively.

Children were asked to perform a total of ten different activities, each lasting six minutes (Fig. 1). All children performed the same activities at the same time, on the same day and the time was recorded by three observers. Activities were selected to match vigorous (running), low (walking), sedentary (sitting) physical activity ranges[28,29] along with four game activities (Simon Says, Catch-me, playing ball, and free play). The games Simon Says and Catch-me involved mostly standing or sitting with intermittent activity. Playing ball had more running and activity than Simon Says and Catch-me. For free play, children were free to choose their activities, which ranged from sedentary to vigorous activity. Between the activities, there was a transition period (rest) of approximately four minutes each, during which the children could do whatever they wanted. The first five activities (walking, running, playing Simon says, playing ball, and singing) took place outside. Walking, running, and playing ball took place in direct sun, Simon says took place under the canopy of a tree, and singing took place in the shade of a veranda of a building whose roof blocked direct sunlight. The children then moved indoors to a social hall with fluorescent lights and performed five more activities (playing ball, playing a Catch-me, sitting with lights on and lights off, and

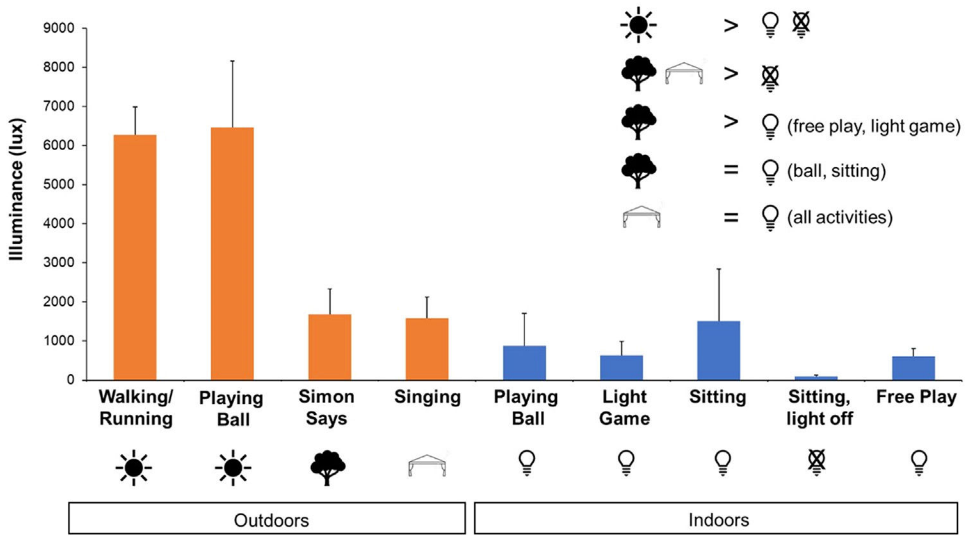

Fig. 1 Actiwatch-measured illuminance for various activities and environments. Illuminance (mean ± SD lux) while children were wearing the Actiwatch for indoor and outdoor conditions. Orange bars represents illuminance during outdoor activities and blue bars represent illuminance during indoor activities. The insert represents post-hoc comparisons for illumination between environments.

free play). The social hall was a large rectangular space (15 m by 16 m) with two walls completely made of windows. For each indoor and outdoor environment, illumination was measured with a lux meter (LX1330B; Dr. Meter, Union City, CA, USA). The light meter was placed on the floor with the sensor facing up. Illumination in the social hall was measured at several places and reported.

Analysis

Data were downloaded from each watch into Excel using the Actiware Software (Actiware 6.1.1.3, Philips, Respironics, Inc.). The software provides illumination in lux and physical activity in counts per 15 second epoch. Means and standard deviations are reported by condition.

Upon downloading and examining the data, anomalous data points were noted for light exposure. Therefore, data that fell into one of the following conditions for lux was considered “implausible” and were excluded: 1) a lux reading of NaN (not a number), 2) >35,000 lux (falling outside the range of the light sensor), and 3) 0 lux, when the light was known to be on or the watch was outdoors in sun.

For each task and lighting condition, the first and last 30 s were not used in the analysis to accommodate transition periods. Repeated-measures ANOVA was implemented via mixed effects modeling to determine differences in outdoor illumination in lux collected from the Actiwatch across conditions. Additionally, an analysis was conducted utilizing the two-factor condition of indoor versus outdoor aggregated across conditions. Post hoc pairwise comparisons were made across all conditions in the presence of a significant main effect, and Bonferroni adjustment was applied for multiple comparisons. Receiver operator characteristics (ROC) analysis was conducted to determine the diagnostic accuracy of the Actiwatch to detect indoor versus outdoor settings utilizing measures of sensitivity and specificity. The area under the curve and estimated 95% confidence intervals were computed to quantify the diagnostic accuracy. Standard errors were adjusted for clusters or repeated observations. An Area under the ROC Curve (AUC) of above 90% was considered to have good diagnostic accuracy. Sensitivity and specificity were computed for all possible lux values. The optimal discriminating lux threshold to detect indoor versus outdoor activity was determined based on the lux value which resulted in the highest proportion of accurate classifications and which provided the maximum sum of sensitivity and specificity measures.

Average physical activity counts for each condition which met the inclusion criteria (based on illuminance data) were used in the analysis. Repeated-measures ANOVA was implemented via mixed effects modeling to determine differences in physical activity measured as counts per 15 second epochs (CP15). Post hoc pairwise comparisons were made across all conditions in the presence of a significant main effect and Bonferroni adjustment was applied for multiple comparisons. Two activities, sitting and playing ball, were performed both indoors and outdoors. We performed mean comparison tests to determine whether indoor and outdoor activities can be combined for these two conditions.

Physical activity classifications of sedentary (<80 CP15), light (80 to <262 CP15), moderate (262 to <406) and vigorous (>406 CP15), as reported in the literature,[22] were applied to the observed data. Frequency of physical activity conditions and classifications were computed. Further, the distribution of activity in CP15 among each classification for each activity condition was computed.

Results

Eighteen children (6 female:12 male, mean age 12.3 ± 1.3 years, range 9−13 years) participated. While children were wearing the Actiwatch, the majority of the data (96.5%) were plausible. Most of the implausible data were

Table 1 Illuminance (lux) as measured with the Actiwatch and a lux meter while children were wearing the Actiwatch for various indoor and outdoor activities.

Environment	Actiwatch Illuminance Mean ± SD (lux)	Lux Meter (lux)
Outdoors		
Walking/running,* sun	6276 ± 710	6500
Playing ball, sun	6453 ± 1701	9500
Simon Says, dappled sun under tree	1681 ± 658	4500
Singing, shade	1582 ± 546	2700
Indoors, lights on		
Playing ball	883 ± 825	533–2500**
Catch-me	640 ± 352	
Sitting	1517 ± 1330	
Free play activity	614 ± 197	
Indoors, lights off		
Sitting	97 ± 36	99–1800**

* Conditions Running in Sun and Walking in sun were combined for this analysis.
** Varied with proximity to window.

recorded indoors with the lights on due to recordings of 0 lux, with a small proportion of recording of NaN and >35,000 lux.

Illuminance

The average illuminance indoors (793 ± 348 lux) was found to be statistically lower than the average illuminance outdoors (4413 ± 518 lux, $P<.0001$). Table 1 shows the average illuminance measured for each activity and environment, as measured while the children were wearing the Actiwatch and compared to the lux meter. Outdoor activities took place in the sun or in shade, while indoor activities were either with the light on or off and. The children spread across the social with varying distance from the windows. All outdoor activities in the sun resulted in at least a 1000 lux difference in magnitude compared with indoor activities (Fig. 1). However, this was not the case for outdoor conditions in the shade, where in some cases there was not a 1000 lux differences between outdoors in the shade compared to indoors. When comparing the average lux for each activity and illuminance condition, there was an observed statistically significant difference between conditions (f = 1.36; $P<.001$). Post hoc comparison with Bonferroni correction (table S1), showed that illuminance for all outdoor conditions that took place in the sun were significantly higher than all indoor condition (Fig. 1, $P<.05$). However, when comparing outdoor shade to indoors, not all conditions emerged as statistically significantly different. Illuminance measured under a tree and in the shade was significantly higher than indoor activities with the light off ($P<.0001$ for both). Illuminance under the tree was significantly higher than free play indoors with the light on and Catch-me indoors with the light on (P=.02 and P=.04, respectively). There were no statistically significant differences in illuminance between singing in the shade and the following indoor activities: free play, Catch-me, playing ball, and sitting; nor were there differences in outdoor sitting under the tree relative to the following indoor activities: playing ball inside or sitting. This finding is likely due to proximity of the children to the large walls of windows while indoors.

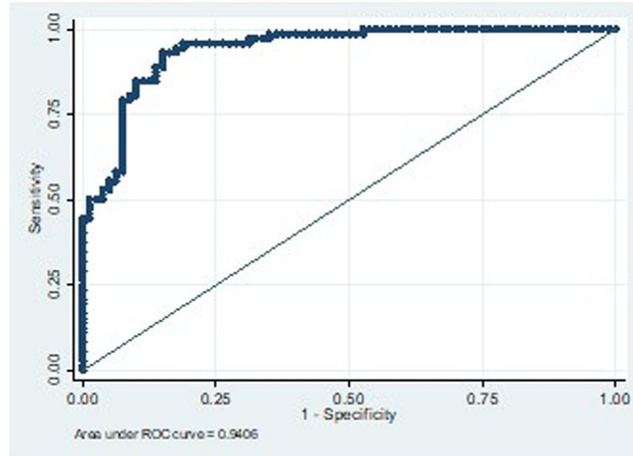

Fig. 2 **Receiver operating characteristic curve**. ROC analysis indicating diagnostic accuracy of Actiwatch light sensor to detect indoor versus outdoor activity.

A ROC for Actiwatch-measured illuminance provided excellent diagnostic accuracy to detect inside versus outside activity (AUC: 0.941, 95% CI: 0.911 to 0.970, Fig. 2). Based on criteria of optimal sensitivity and specificity, a threshold of 1088 lux was identified as the optimal threshold for discriminating between indoor and outdoor light (sensitivity: 93.0%; specificity: 85.0%; classification accuracy: 88.8%). Upon applying a threshold of 1088 lux to the 15-second interval dataset, 86.2% were correctly classified, with 86.4% correctly classified as indoor and 86.1% correctly classified as outdoor.

Physical activity

All activities among the 18 children were included in the analysis. Two activities were performed both outdoors and indoors (with light on and off): sitting and playing ball. No statistically significant differences were observed for physical activity between sitting outdoors (82 ± 38 CP15) and indoors (99 ± 26 CP15, P=.13), thus these conditions were combined. Similarly, no significant differences were observed for physical activity between playing ball outdoors (447 ± 151 CP15) and indoors (442 ± 160 CP15, P=.41), thus these conditions were combined.

Table 2 and Fig. 3 show physical activity for the different activities. Running resulted in the highest activity (534 ± 174 CP15), followed by the free activity (499 ± 126 CP15). Sitting resulted in the lowest activity (93 ± 22 CP15). When comparing across activities, there was a statistically significant main effect of activity on CP15 (f = 72.1, $P<.001$). Post hoc comparison with Bonferroni correction found that running, free activity, and playing ball were similar to each other but significantly higher than all other activities (table S2). Physical activity during Simon Says, Catch-me, walking, and sitting were not statistically different from each other.

Table 2 Actiwatch-measured physical activity. Physical activity in counts per 15 s (CP15) for different activities, with the percentage of time in that activity classified as sedentary, light, moderate, or vigorous activity, as defined by Ekblom et al.[22]

Activity	Activity Mean ± SD (CP15)	Sedentary ≤80 CP15 (%)	Light >80 to ≤262 CP15 (%)	Moderate >262 to ≤406 CP15 (%)	Vigorous >406 CP15 (%)
Running	534 ± 174	6	17	8	69
Free Activity	499 ± 126	3	23	16	57
Playing Ball	435 ± 145	5	23	22	50
Catch-me	188 ± 76	32	42	13	12
Walking	162 ± 34	4	88	7	0
Simon Says	109 ± 41	44	50	5	0
Sitting	93 ± 22	57	37	4	1

Physical activity was classified using previously published definitions of sedentary, light, moderate, and vigorous activities.[22] Free activity, running, and playing ball resulted in a high proportion of vigorous activity (57.0%, 69%, and 50%, respectively). In contrast, playing Simon says and sitting resulted in a high proportion of sedentary activity (44% and 50%). For three activities, running, walking and sitting, children's behavior was relatively uniform, as was the percent of measurements in the corresponding categories. For running, 77% of the readings were moderate to vigorous, for walking 88% were light and for sitting 94% were sedentary or light. All other activities included diverse behaviors and subsequently diverse types of physical activity readings. For example, when the children were playing ball, some were running after the ball while others were stationary waiting for the ball.

Discussion

Objective and precise quantification of time spent outdoors and physical activity is critical for numerous research areas. This is especially true in myopia research, in which the influence of behavioral factors in eye growth is not yet fully characterized. This study examined the diagnostic accuracy Actiwatch Spectrum Plus for determining indoor and outdoor environments and physical activity in children. Findings showed that the Actiwatch Spectrum Plus performed well during real world activities in children, with excellent diagnostic accuracy to detect indoor versus outdoor settings and classification of physical activity from sedentary to vigorous levels. While some limitations were noted, as discussed below, the Actiwatch performed well and provides advantages over traditionally used subjective quantification of time outdoors and physical activity in children.

We sought to determine the ability of the Actiwatch Spectrum Plus to accurately discriminate between indoor and outdoor settings while being worn by children. Accumulating evidence shows that time outdoors is effective in preventing myopia onset and, in some studies, slowing myopia progression.[8,14,30-35] Most studies rely on parent questionnaires to determine children's time outdoors. Parent questionnaires are inherently biased by recall and perceptions, and parents are generally unaware of how much time is spent outdoors during the school day.[10,11] Additionally, questionnaires suffer from low resolution and low temporal quantification of time outdoors, and absolute lux levels cannot be determined. These limitations contribute to variable and

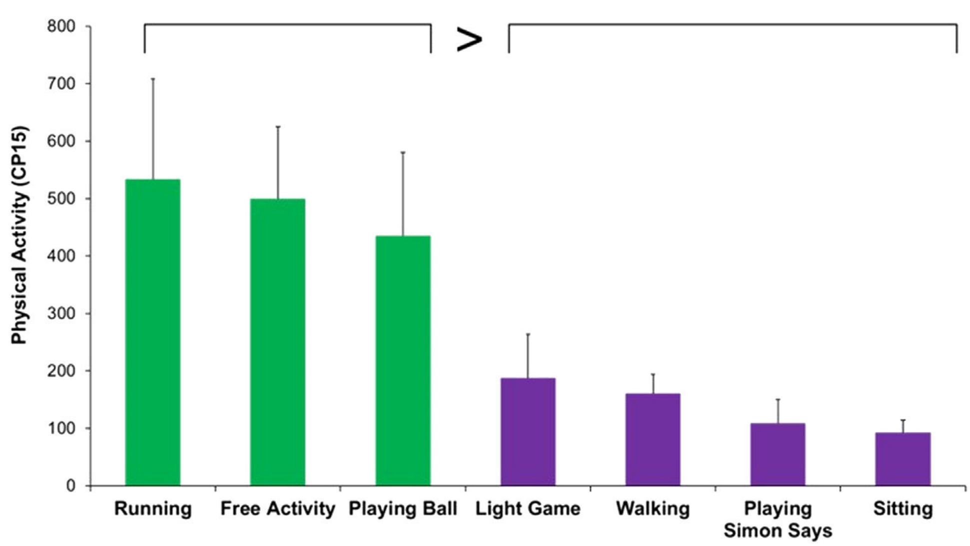

Fig. 3 Actiwatch-measured physical activity. Physical activity in counts per 15s (CP15) while children performed various activities wearing the Actiwatch. Green bars represent activities with CP15 that was significantly higher than activities shown in purple bars.

conflicting findings in the literature. Objective wearable sensors have the potential to overcome these limitations with continuous, objective illuminance measurement at high resolution. We found that the Actiwatch Spectrum Plus can discriminate between indoor and outdoor settings with high sensitivity and specificity when worn by children. Furthermore, an illuminance of 1088 lux was found to be the optimal threshold for discriminating between indoor and outdoor activity, which is in close agreement with the literature that uses 1000 lux as the threshold.[5,7,8,16,30,36,37] As with any threshold value, there may be misclassifcations in some cases for determining indoor and outdoor levels at an individual level.

Previous studies report that daytime outdoor illuminance in ranges from 10,000 to 175,000 lux.[7,38] A previous version of the Actiwatch, the Actiwatch 2, which has been previously tested against a calibrated photometer,[21] reports a measurement range of 5 to 100,000 lux. However, the reported range of the Actiwatch Spectrum Plus is 0.1 to 35,000 lux. The more limited range of the Actiwatch Spectum Plus therefore results in a ceiling effect in illuminance when children are wearing the Actiwatch outdoors. It is important to note that recordings >35,000 in the raw data are outside the range of the instrument and therefore anomalous. Despite the upper limit of the device, the results of the current study show that the Actiwatch can reliably detect indoor versus outdoor environments. We observed a large variability in illuminance readings across devices in the various environments tested. Several factors may have contributed to this variability. First, the devices were tested in real world environments while children were wearing the device on their wrist. While outdoors, children were moving in and out of shade and while indoors, moving closer and farther from windows and overhead light sources. Second, the children's arms in different directions relative to the light source. Finally, there is likely inherent variablity between devices. However, given that illuminance spans well over a 6 log range across environments, the variability represented a small proportion of total light exposure and the devices as a whole performed well in determining indoors versus outdoor environments.

Children wore the Actiwatch while carrying out prescribed activities ranging from sedentary to vigorous activity in different indoor and outdoor settings. The majority of illuminance data were plausible in outdoor conditions (99%). However, upon examining the Actiwatch-measured illuminance data, we noted that a small percentage (3.5%) of anomalous data points were observed, when the children were wearing the watches indoors under fluorescent light, almost entirely due to readings of 0 lux. A previous validation study noted similar anomalous data under indoor fluorescent lighting. The authors speculated that, specifically for the fluorescent light sources, which are "discharge light sources," the emission lies between 570 and 600 nm to which the Actiwatch Spectrum is almost completely insensitive.[23] Consequently, illuminance measurements of some indoor light sources may be systematically biased with the Actiwatch Spectrum.[23] Therefore, whether being used indoors or outdoors, it is necessary to carefully inspect raw data to examine and remove implausible data.

Previous studies have shown some inconsistencies in Actiwatch-measured illuminance compared to other light sensors. For example, the Actiwatch Spectrum was found to overestimate illuminance compared to calibrated photometers and to Daysimeter devices.[23] In another study, the Actiwatch Spectrum underestimated illuminance compared to the Actiwatch 2.[20] The Actiwatch Spectrum has color sensitive photodiodes, while the Actiwatch 2 has a silicon photodiode. The different light sensors may explain the variation in under-and over-estimation of illuminance when compared to photometer light sensors.[20] Another source of variability may be the position of the sensors in the Actiwatch Spectrum. As reported by Price et al., the three sensors of the Actiwatch Spectrum are placed along the major axis of a shallow depression.[25] Thus, depending upon the measurement plane, parallel or perpendicular to the major axis, the sides of the shallow depression can shadow incident light reaching a photosensor element[23] and thus may lead to variations (20%) in illuminance[25] between different instruments, and even across Actiwatches.

The Actiwatch Spectrum Plus performed well in differentiating between activities in which the children had relatively uniform behavior: sitting, walking and running. As expected, when playing games in which behavior varied, so did the physical activity readings. A previous study reported physical activity thresholds for sedentary, light, moderate and vigorous activity for a different Actiwatch model, based on calorimetry.[22] The current study shows that these thresholds can be applied to the Actiwatch Spectrum Plus for children.

This study was subject to the following limitations. The children were only in a limited number of outdoor conditions and only in one indoor condition. This was due to COVID-19 social distancing restrictions which limited gatherings in smaller indoor venues. For testing physical activity, we did not compare measurements to direct calorimetry. An alternative way of determining thresholds for physical activity would be having the participants walk or run on a treadmill with a known speed. This study was less formal and indeed, the children behaved differently from one another in many of the tasks. However, for three tasks in which children were observed to demonstrate relatively uniform behaviors (sitting, walking, and running), the activity counts corresponded well with a previous study using a different actigraph and compared the measurements to calorimetry.[22] Thus, the ranges found here can be used in future studies with the Actiwatch Spectrum Plus. The optimal posititioning is immediately adjacent to the Actiwatch. However, this is not possible with children who are performing physical activities in a space. Another limitation with wrist-worn sensors, such as the Actiwatch, is the potential for the sensor to become obstructed by clothing. This was not a concern in the current study because all participants wore short sleeve shirts. However, investigators using the device must take care to explain to participants that the sensors must not be covered by clothing. Lastly, the sample size was not based on an a priori calculation. However, the sample size in this study was similar or larger to previous reports.[17,20-24]

Conclusions

In conclusion, we found that the Actiwatch Spectrum Plus performed well during real world activities in children for discriminating indoor and outdoor environments with a threshold of 1088 lux, having high sensitivity and specificity, and for categorizing physical activity as sedentary, light, moderate, and vigorous. While limitations exist, the Actiwatch provides advantages over traditionally used subjective quantification and represents a valuable tool to investigate environmental and behavioral factors that may contribute to the rising prevalence of myopia in children.

Declaration of Competing Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Hadassah Academic College (protocol code 218, approved Aug. 21th 2021).

Informed Consent Statement

Informed consent was obtained from all participants involved in the study.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.optom.2023.100483.

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