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Wearable Light-and-Motion Dataloggers for Sleep/Wake Research: A Review

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Abstract: Long-term recording of a person's activity (actimetry or actigraphy) using devices typically worn on the wrist is increasingly applied in sleep/wake, chronobiological, and clinical research to estimate parameters of sleep and sleep-wake cycles. With the recognition of the importance of light in influencing these parameters and with the development of technological capabilities, light sensors have been introduced into devices to correlate physiological and environmental changes. Over the past two decades, many such new devices have appeared from different manufacturers. One of the aims of this review is to help researchers and clinicians choose the data logger that best fits their research goals. Seventeen currently available light-and-motion recorders entered the analysis. They were reviewed for appearance, dimensions, weight, mounting, battery, sensors, features, communication interface, and software. We found that all devices differed from each other in several features. In particular, six devices are equipped with a light sensor that can measure blue light. It is noteworthy that blue light most profoundly influences the physiology and behavior of mammals. As the wearables market is growing rapidly, this review helps guide future developments and needs to be updated every few years.

Keywords: human; actimetry; motion; ambient light

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1. Introduction

Actimetry (actigraphy) is a measurement of a person's physical activity using a wearable device (typically worn on the wrist) that is widely used in sleep/wake research. In using a built-in accelerometer, the actimeter captures and counts body movements, which can be converted into a representation of activity levels over many hours and days. This allows for relatively unobtrusive estimations of sleep and sleep-wake rhythm characteristics, such as sleep quantity, quality, timing, the amplitude of the day-night activity, and day-to-day variability of these parameters. Although the embedded algorithms tend to overestimate sleep, especially in clinical populations (according to the comparative studies using "gold standard" polysomnography [1]), actimetry is particularly helpful in diagnostics of circadian rhythm sleep disorders, hyper-, hyposomnia, sleep misperception, narcolepsy [2], and also some disorders beyond sleep domain such as movement disorders [3,4] and epilepsy [5]. Wrist-worn actimetry is widely used in human chronobiological research.

With growing evidence of the influence of ambient light on human physiology and behavior (e.g., [6,7]) and to meet the requirements of many investigators, actimeters became additionally equipped with light sensors that capture photons in the visible part of the electromagnetic spectrum. The gathered light exposure data are not only useful for correlating the dynamics of light and activity but also for a better distinction of episodes of time spent indoors and outdoors, with sleep and without sleep, wearing and not wearing a device. The first devices having both an accelerometer and light sensor appeared in the late 1990s. For example, the Actiwatch-L (invented by Cambridge Neurotechnology, Fenstanton, Cambridgeshire, UK, marketed together with Minimitter, Bend, OR, USA, with the subsequent sale of the trade rights to Philips Respironics, Bend, OR, USA) was launched in ~1998 [8]. Furthermore, with the discovery of melanopsin-based photoreception in the eye in 2000, which mediates a variety of physiological reactions to light [9], an importance emerged to measure specifically blue light as these photoreceptors are sensitive to the light wavelength ~480 nm [10]. Several existing light-and-motion dataloggers already provide such an opportunity.

To our knowledge, many investigators wonder which datalogger is best for their research. The family of research-grade stand-alone devices has been expanded over the past two decades, and an abundant amount of consumer-grade smart devices have been developed in recent years to track activity or light. The present study is aimed at reviewing existing dataloggers that simultaneously measure human activity and ambient light for their basic differentiating characteristics—appearance, dimensions, weight, mounting, battery, sensors, features, communication interface, and software.

2. Methods

Sources for the dataloggers selection for this review were existing practical knowledge of the authors on several research-grade dataloggers, an author's (K.D.) database of the articles on chronobiological studies, and the PubMed library. The search in PubMed was performed using word string (actimet* OR actigraph* OR accelerometer) AND ("light sensor" OR "ambient light" OR "illumination") and filter "Humans"; 65 records were retrieved. Several review articles were also analyzed (e.g., [1,11–13], others). The selection criteria were as follows: (1) currently available wearable devices; (2) that continuously record the levels of both human motion and ambient light; (3) the recorded data available for later computational analysis.

According to the first criterion, the review did not consider devices that are (or were/remained) in the development, pre-commercialization stage. They include either zero-cycle-developed prototypes (e.g., Eco-Mini [14,15], closed project [16]; an unnamed device [17]) or predecessor-based upgrading dataloggers (e.g., Sleep Watch 2.0 instead of Motionlogger Watch announced by Ambulatory Monitoring, Ardsley, NY, USA [18]; Speck instead of Daysimeter-D under joint development by Light and Health Research Center, New York, NY, USA and Blue Iris Labs, Fairfax, CA, USA [19,20]). There is one more device not included by the first criterion—AC10, or "Tempatilumi" (Guarulhos, São Paulo, Brasil) [21] because there is no evidence for its current production (existence of a manufacturer) and use in recent studies. The vast majority of existing dataloggers—mainly contemporary, smartphone-compatible—did not meet the second criterion: they do not record either human motion (e.g., LYS button, Lido) or ambient light (light sensor that they have is used exclusively to adjust the screen brightness: Oura Ring, Apple Watch, Fitbit, Withings devices, others).

In the result of the search, 17 dataloggers produced by 14 manufacturers were chosen for this review. The sources to collect their technical and functional characteristics for comparison were the authors' practical knowledge of several devices, manufacturers' websites (descriptions of device specifications, pdf instructions to users), and email communication with the manufacturers. The authors have experience with five reviewed devices: Actiwatch 2 [22], MotionWatch 8 [23], LightWatcher [24], Daqtometer 2.4 [25,26], ActTrust 2 (ongoing "Light-Arctic" project [27])—each produced by different manufacturers. An email request to specify some features of the devices was sent to 10 manufacturers (and one researcher—in the case of the ActiTrac device), and all responded, providing almost all necessary information.

3. Review

3.1. Devices and Manufacturers

The characteristics of the 17 dataloggers produced by 14 manufacturers are presented in Table 1. Twelve of these manufacturers are currently active, and their actual devices are being reviewed, while two developers (Daqtix, Oetzen, Germany; IM Systems, Baltimore, MD, USA) who have recently ceased their years of marketing are presented with their latest devices, as they are still in use by some research groups. In three cases in which dataloggers have versions that differ slightly from each other (by including additional feature(s)), these versions make up a single table entry (ActTrust/ActTrust 2, Actiwatch spectrum Plus/PRO; Axivity AX3/AX6). In one more case, where a standard datalogger (MSR145) has two additional variants, and each can be additionally configured to a custom version, the table mentioned only those two variants.

Almost all dataloggers are made specifically for scientific research and healthcare (some are even licensed as medical devices). As an exception, the dataloggers manufactured by Electronics GmbH (Seuzach, Switzerland) are designed primarily for transport needs (for monitoring environmental conditions in transported goods). Almost all dataloggers are designed for autonomous data acquisition for many days in a row (at least a week) for subsequent data processing on a computer. As an exception, the mini-loggers manufactured by Mbientlab (San Francisco, CA, USA) are mainly intended for real-time data recording on smartphones since the logger's internal memory is limited to a couple of days of data gathering (Table 1).

Almost all dataloggers have been used in scientific studies, the amount of which varies across the devices, partly due to a difference in the manufacturer's marketing time and activity in the field. Selected references to the scientific publications, links to the manufacturer's websites, and light-and-motion predecessors are indicated in Supplementary Table S1 (as a continuation of Table 1; includes references [7,22–26,28–53]).

3.2. Appearance and Mounting

The reviewed dataloggers typically look like wrist-worn devices (Figure 1). Three of them have a digital display with watch functions, which makes them even more watch-like. The dimensions of the devices vary greatly—from 50–55 mm (on the long side of the device) to 20–27 mm (on the short side or in diameter) (with the exclusion of Daysimeter-S; Table 1). The size partly depends on the number of features. For example, a compact and lightweight MotionWatch 8 ($36 \times 28 \times 9$ mm and 9 g) measures only photopic light and motion.

Several manufacturers made sure that the unit is easily disposable from the strap or sleeve band to be worn with a belt or other means in other locations (arm, leg, chest, etc.). To correctly measure light received through the eyes, some wearables can be placed close to the eyes: one device is made in the form of an ear headset (Daysimeter-S), two devices can be mounted on the frame of glasses (with sensors in the direction of gaze; Daysimeter-S, LightWatcher) or, like the other two devices (MetaMotionC, MetaMotionS), located in proximity to the head (for example, clipped at the collar edge). LightWatcher is supplemented with several fixing accessories (eyeglasses, headset, badge, necklace) in one transport box. Certainly, the placement on/at the head is less comfortable for the wearer in comparison to the wrist. Although studies show that eye-level and wrist-based light readings are highly correlated (e.g., [46]), correlations are only possible in case the covering of wrist-worn devices from sleeves is mostly prevented.

Table 1. Light-and-motion dataloggers for human research (as of October 2022).

N	Device (and Manufacturer)	Digital Display +/−; Mounting	Dimensions and Weight	Battery Recharge (+/−), Type. Low Battery Warning from Unit	Runtime. [1] Delayed Start +/−	Light Bands; Lux Range [2]	Other Sensors/Features	Communi-cation with PC	Software Name, Features. Operational System
1	ActTrust, ActTrust 2 (Condor, São Paulo, Brazil)	−, + [3] wrist band	47 × 31 × 12 mm 38 g (with band), 39 × 30 × 12 mm 35 g (with band) [2]	(+) Lipo charged via dock. Audible warning	90 days −	R,G,B, IR, total, plus UV [3]; 0.02–17,000	Skin temperature External temperature Event marker with audible feedback Watch (time) [3]	Dock → USB cable	ActStudio: circadian and sleep scoring. Windows, OS
2	Kronowise KW6 (Kronohealth SL, Murcia, Spain)	− wrist band	52 × 40 × 12 mm 64 g (with band)	(+) Lipo charged via USB cable to PC. Charge 4-LED indicator, work status indicator	21 (for 30 s storing) +	B, IR, photopic; 0.01–43,000	Skin temperature Body position Event marker	USB cable	Kronoware: circadian and sleep scoring Raw data accessible. Windows
3–4	Actiwatch 2 (Philips Respironics, Bend, USA)	− wrist band	43 × 23 × 10 mm 16 g (with band)	(+) Lipo charged via dock for 12–24 h. No warning	30 days +	photopic; range: NIA	Event marker /accelerometer is uniaxial/	Dock → USB cable	Actiware: circadian and sleep scoring. Windows
	Actiwatch spectrum Plus (or PRO) (−//−)	+ wrist band	48 × 37 × 15 mm 31 g (with band)	(+) Lipo CLB2032 charged via USB cable to PC. Battery status icon	60 (or 50 [3]) days +	R,G,B, photopic; range: NIA	Event marker with visual feedback Audible off-wrist reminder 4 subjective scores daily with alarm reminder [3] Watch (date, time) /accelerometer is uniaxial/	USB cable	
5	MotionWatch 8 (CamnTech, Fenstanton, UK)	− wrist band	36 × 28 × 9 mm 9 g (without band)	(–) CR2032. Work status red LED	90–180 days +	photopic; 0–64,000	Event marker with visual feedback	USB cable	MotionWare: circadian and sleep scoring. Windows
6	Motionlogger Micro Watch [4] (Ambulatory Monitoring, Ardsley, USA)	+ wrist band	48 × 36 × 10 mm 37 g (with band)	(−) CR2430. Work status indicator	30 days +	photopic; 0–1200	External temperature Event marking with visual feedback Off-wrist detection Watch (time, date)	Wireless via USB IrDA adapter	Operational software: to initialize and download data. Action4: circadian scoring. ActionW-2: sleep scoring. Windows

Table 1. *Cont.*

N	Device (and Manufacturer)	Digital Display +/−; Mounting	Dimensions and Weight	Battery Recharge (+/−), Type. Low Battery Warning from Unit	Runtime. [1] Delayed Start +/−	Light Bands; Lux Range [2]	Other Sensors/Features	Communi-cation with PC	Software Name, Features. Operational System
7	GENEActiv (Activinsights Ltd., Kimbolton, UK)	− wrist band, other locations	43 × 40 × 13 mm 16 g (without band)	(+) Lipo charged via 4-up charger cradle. No warning	30 days (for 20 s storing) +	photopic; 0–3000	External temperature Event marker Charge LED indicator (works when not in record mode)	Dock → USB cable	GENEActiv: graphing, sleep scoring. Windows
8	ActiGraph wGT3X-BT (ActiGraph, Pensacola, USA)	− wrist strap, other locations (belt not supplied)	46 × 33 × 15 mm 19 g (without strap)	(+) Lipo charged via USB cable to PC or multiple charger (optional). LED indicator will flash red 2 times	25 days +	photopic; 0–1500	Wear time sensor Body position, steps (for waist- or thigh-worn device) Heart rate (optional, via Bluetooth connection with Polar belt monitor)	USB cable, Bluetooth LE	Actilife: sleep scoring, row data analysis in the in-built template. Windows, OS. Android, iOS (do not work with Actilife).
9	Daqtometer 2.4 (Daqtix, Oetzen, Germany)	− wrist strap	44 × 40 × 12 mm 21 g (without strap)	(−) CR2032. Work status red LED	1 year −	photopic; (no conversion to lux)	/accelerometer is biaxial/	Wireless via USB IrDA adapter	Operational software. Export data in row units. Windows, Linux
10	ActiTrac (IM Systems, Baltimore, USA)	− wrist strap, other locations	55 × 37 × 12 mm 23 g	(+) Lipo charged via USB cable to PC No warning	44 days +	photopic; 800–8000	Event marker /accelerometer is biaxial/	USB cable	ActoScore: data graphing and analysis. Windows
11	Axivity AX3 or AX6 (Axivity Ltd., Newcastle upon Tyne, UK)	− sleeve band (optional)	35 × 24 × 9 mm, 11 g	(+) Lipo charged via USB cable to PC or USB hub. LED brief flash before and at stopping	>30 days (for 0.08 s storing (12.5 Hz))	photopic; (3–1000 lux at sensor level) [6]	External temperature Body position [3] /accelerometer is 6-axis [3]/	USB cable	OmGUI: operational software, view and export row units data. Windows

Table 1. *Cont.*

N	Device (and Manufacturer)	Digital Display +/−; Mounting	Dimensions and Weight	Battery Recharge (+/−), Type. Low Battery Warning from Unit	Runtime. [1] Delayed Start +/−	Light Bands; Lux Range [2]	Other Sensors/Features	Communi-cation with PC	Software Name, Features. Operational System
12–13	Daysimeter-S (Lighting Research Center, Troy, USA)	− ear headset	75 × 5 × 5 mm (sensors unit) +72 × 48 × 11 mm (control unit), weight: NIA	(−) CR2032. No warning	≥7 days −	R, G, B, total; IR; 0.2–65,000	/not waterproof/	USB cable	Two software: operational and data decoding. Python (works on Windows, OS, Linux)
	Daysimeter-D (–//–)	− different locations [5]	20 mm in diameter, weight: NIA	(−) CR2032, non-replaceable (epoxy encapsulated). No warning	11 days −	–//–		Dock (optical sensing) → USB cable	
14	LightWatcher (Object-Tracker, Perchtoldsdorf, Austria)	− eyeglasses, headset, badge, necklace	50 × 20 × 10 mm 12 g (without mount)	(+) Lipo charged via USB cable to PC. 1-sec long sound after recording stopped	6 weeks +	IR, R, G, B, UV, photopic; 0–100,000	Event marker with LED & sound feedback External temperature Barometric pressure Relative humidity	USB cable	OT-Sensor: data graphing. Windows
15	MSR145 (Electronics GmbH, Seuzach, Switzerland)	− velcro strap (by request)	53 × 27 × 16 mm (at minimum) ~20 g (without band)	(+) Lipo charged via USB cable to PC or 7-up USB hub (optional) Charge LED indicator	8 weeks +	photopic; 0–65,000	External temperature, relative humidity, air pressure, fluid pressure /the set may be configured individually by the manufacturer/	USB cable [7]	MSR Dashboard: operational software. MSR ReportGenerator: a compact report, graphing. Windows

Table 1. *Cont.*

N	Device (and Manufacturer)	Digital Display +/−; Mounting	Dimensions and Weight	Battery Recharge (+/−), Type. Low Battery Warning from Unit	Runtime. [1] Delayed Start +/−	Light Bands; Lux Range [2]	Other Sensors/Features	Communi-cation with PC	Software Name, Features. Operational System
16–17	MetaMotionC MMC (Mbientlab, San Francisco, USA)	− sleeve band, clip, adhesion	27 mm in diameter ×8 mm, 8 g	(−) CR2032 Charge status in app	<2 days (by memory) 1–2 weeks (by battery) −	photopic; 0.01–64,000	External temperature Barometer, Pressure, Altimeter Magnetometer BLE for daily data transfer /accelerometer is 6-axis/	Bluetooth LE to smartphone, hub, tablet, computer	MetaBase: operational software. No software for raw data analysis. iPAD, iPhone, Android, Windows
	MetaMotionS MMS (–//–)	–//–	36 × 27 × 10 mm 9 g	(+) Lipo charged via USB cable to PC Charge status in app	<2 days (by memory) 3–5 weeks (by battery) −	–//–	–//–	–//–	

[1] for 1-min storing (unless otherwise specified); [2] a range of the measured light illuminance (in lux) is indicated for the photopic light band; [3] this feature is attributable to the second version of the device; [4] also known as Micro Motionlogger Watch; [5] using pin, wristband, pendant, badge, or glasses clip; [6] the function is limited (see Section 3.4 for explanation); [7] plus wireless connection to smartphone or Cloud in the device versions MSR145WD and MSR145W2D. N—row number; Lipo—lithium-ion polymer battery; PC—personal computer; LED—light emitting diode; IR, R, G, B, UV—infrared, red, green, blue, ultraviolet light, respectively; IrDA—infrared adapter; BLE—Bluetooth low energy connection; –//—–same as in the cell above; NIA—no information available.

Figure 1. Reviewed dataloggers (pictures taken from manufacturers' websites or scientific articles (mentioned in Table S1)).

An important issue is the material from which the strap is made (vinyl, polyurethane resin, silicone, plastic, etc.), as there are cases of skin irritation (e.g., [22]). To cope with this problem, the GENEActiv, for example, is offered with straps in different materials to accommodate allergies. Otherwise, a cotton sublayer may be individually prepared for such wearer to be attached under the strap.

3.3. Battery

The battery is a critical aspect for reliable performance, related to the problems of temporal unavailability of the device (no charged battery at the moment) or accidentally missing data (due to energy depletion during the recording). Two kinds of batteries of coin-type are used in the devices—rechargeable (lithium-ion polymer battery, nine devices) and non-rechargeable (eight devices). The former are not intended to be replaced by the user, while the latter are user-replaceable (except Daysimeter-D) (Table 1).

It is usually battery life and not device memory that limits recording time. Although recording time is commonly declared to be as long as 21–90 days (only in four cases is the duration less; Table 1), 7–14 days is considered a safe period. A warning from the device on low battery is a useful important feature. The devices vary greatly with respect to this feature: no warning, stop flashing of the work status indicator, audible warning right after the recording stopped, flashing or audible warning somewhat before the recording will stop, constantly working charge level indicator (Table 1). Only the latter two features provide sufficient time for the datalogger wearer and researcher to plan an extraordinary meeting for the battery (or device) replacement to prevent impending data loss.

Current battery charge (in volts or % of the maximal voltage) and sometimes the predicted runtime (e.g., in MSR145) can be checked with the supplied software. The check can be done at any time during the data acquisition, as this does not normally stop the recording. Unfortunately, the voltage does not basically reflect the energy capacity of the battery, so the actual operating time may appear to be significantly less than estimated. Generally, the runtime of a rechargeable battery is more difficult to predict than a non-rechargeable battery. For a rechargeable battery, it depends on how many charge/re-charge cycles the battery underwent previously, whether it has been well maintained when the device was not in run mode (a full charge is recommended after each use and every 2–6 months thereafter, as zero-energy battery live short), and the expected overall battery life (when kept unused from the beginning).

A disadvantage of the rechargeable battery is that the recharge usually takes ~3 h, and if there is no other pre-charged datalogger to immediately continue the recording in a subject who came to an interim visit to the investigator, this can turn into a waiting time inconvenient for both persons. A further disadvantage is a need to send the device to the manufacturer to replace the battery after every 2–3 years of use. One more disadvantage concerns wearables, which require a docking station for charging (three devices, Table 1)—any intermediate technical element increases the risk of arising an additional problem, such as poor contact of the datalogger to a docking station or unavailability of the dock at the right time.

The situations in which a researcher should suspect a faulty battery also include a very short charging time (for rechargeable battery) and unreliable light or motion levels appearing gradually on the analyzed actogram. A delayed start at a defined time helps to save battery power, and many devices are provided by this software mode (Table 1). Optimal operating temperature ranges between 5–40 °C; lower or higher temperatures will shorten the battery life and reduce the battery capacity, especially outside the range $-20 \div 60$ °C. Nevertheless, even when the battery is exhausted, the recorded data remains in the unit's memory—they are non-volatile.

3.4. Sensors and Features

The majority of the dataloggers are equipped with a triaxial accelerometer for motion capture; four have uni- or biaxial accelerometer and two have 6-axis accelerometer (Table 1). Devices with more axes are more sensitive to movements than devices with fewer axes. However, the absolute movement counts do not influence the accuracy of distinction of episodes of greater or lesser activity to a large extent. The in-built software algorithm for assigning these episodes to wake or sleep plays a bigger role. Nevertheless, there is no consensus on algorithms across devices as of now (for more information and references, see for example, [45,54–56]).

All dataloggers have a built-in light sensor (s) to measure ambient light. This can typically be distinguished by the presence of a small window on the front of the device into which light can enter (Figure 1). Four devices feature a top-half translucent housing to capture more incident light from a wider range of directions (ActiGraph wGT3X-BT, Daqtometer, Daysimeter-D, MSR145). One exception is the Axivity AX3 unit, which has neither the window nor translucent puck casing and is therefore limited to detecting only the changes/trends in ambient light levels, especially when the unit is covered by placement on the inside of the sleeve band offered by the manufacturer. Like the Axivity device, another device, the Daqtometer, provides users with row-unit data only, not converted to specific light values.

All other dataloggers provide light values generally comparable to those measured by professional devices. Eleven devices only provide integrated illuminance values (lux) in the photopic range, and six have sensors for specific spectra, including red, green, and/or blue light (R, G, B), measured in irradiance (i.e., W/m^2 or photons/s/m^2) (Table 1). These devices are useful in studies where it is important to assess the contribution of blue light due to melanopsin-based photoreception (see Section 1). Nine devices measure a wide range of illuminance from $\leq$0.2 to 17,000–100,000 lux (Table 1).

Dataloggers differ in the type of light sensors they are equipped with. The optical performance characteristics of some dataloggers were investigated and reported by Price et al., 2017 [12] (Actiwatch 2, Actiwatch spectrum Plus/PRO, MotionWatch 8, GENEActiv, Daysimeter-D/-S), Figueiro et al., 2013 [46] (Actiwatch spectrum Plus, Daysimeter-D/-S), Arguelles-Prieto et al., 2019 [33] (Kronowise). The within-device variation in the light measurement may also exist, raising the issue of calibration. The published work suggests using the same-ID device on the same subject throughout the study [12,46,57].

In addition to light and motion sensors, ten dataloggers have other sensors, such as temperature sensors (nine devices). ActTrust/ActTrust 2 and Kronowise can measure wrist temperature, for which the thermistor is located as close as possible to the inner surface of the device in contact with the skin. In other cases, the thermistor is located centrally or close to the front of the device, recording neither a true skin nor a true ambient temperature (denoted as "External temperature" in Table 1). In addition to the external temperature, four devices (LightWatcher, MSR145, MMC and MMS) can measure other environmental parameters (Table 1). ActiGraph wGT3X-BT can record heart rate via Bluetooth connection with a Polar chest belt monitor. Three devices—Actiwatch spectrum Plus/PRO, Micro Motionlogger Watch, and ActiGraph wGT3X-BT—have a wear time sensor (capacitive touch technology) that can help distinguish, for example, whether the subject has been sleeping during daytime or has just removed the device, which is important in research. ActiGraph wGT3X-BT, Kronowise and Axivity (AX6 version) can additionally determine the position of the body using a gyroscopic inclinometer sensor. Usually, researchers can program which sensory channel is enabled for recording, but some dataloggers do not have this option (not specified in Table 1).

Actiwatch spectrum PRO, a device with a digital display, offers an option to enter several psychometric scores into the device's memory. All devices (except Daysimeter-S) are claimed to be waterproof, meaning water resistancy for at least 30 min at a depth of 1 m; that is, they do not need to be removed while taking a shower. A useful feature is an event marker button, which the subject may be asked to press at a specific time (usually to indicate the sleep onset (eyes closed) and sleep offset time). Nine devices have this marker button, and some give audible and/or visual feedback (Table 1) to confirm that the event has been recorded, adding usability.

3.5. Communication Interface and Software

All dataloggers have computer (PC) software that allows researchers to program the device to record data offline and download it after the recording. On MMC and MMS, this can also be done using a smartphone application (where data is sent live). The way of communication with PC varies among units (Table 1). A simple and secure direct connection via USB cable is available for devices having a USB port (N = 9). Four devices have metal contacts on them (ActTrust/ActTrust2, Actiwatch 2, GENEActive) or infrared optical contacts (Daysimeter-D), requiring an intermediate docking station (cradle, base, hub, reader—through which these devices are also charged) to communicate with a PC. The remaining four devices have exclusively wireless connection: using an infrared adapter plugged into a PC (N = 2) or Bluetooth (N = 2). The readout usually takes less than a minute. The collected data remains saved on the device until it is reinitialized.

The software of nine devices provide both graphical and analytical reports—actogram and circadian and/or sleep indices. An actogram is a 24-h graphical representation of motion, light values, event markers, and program-defined marks for the sleep onset and offset (Figure 2). The circadian and sleep indices are calculated using built-in algorithms selected by manufacturers to analyze activity score dynamics. The list of sleep indices may include sleep latency, onset, offset, duration, fragmentation, efficiency, and the list of circadian indices may include relative amplitude, interdaily stability, intradaily variability (e.g., [58]). Some of these analytics integrated into the software (for example, Actiware, MotionWare) give researchers the possibility to drag the event markers that outline the sleep episode to the appropriate positions on the actogram with automatic recalculation of the output measures, which is very convenient for researchers. Researchers may want to redefine the sleep onset/offset times based on the subject's sleep log data, event marker's position, and light levels at that time. As the built-in algorithms may vary across devices, the calculated values may also vary.

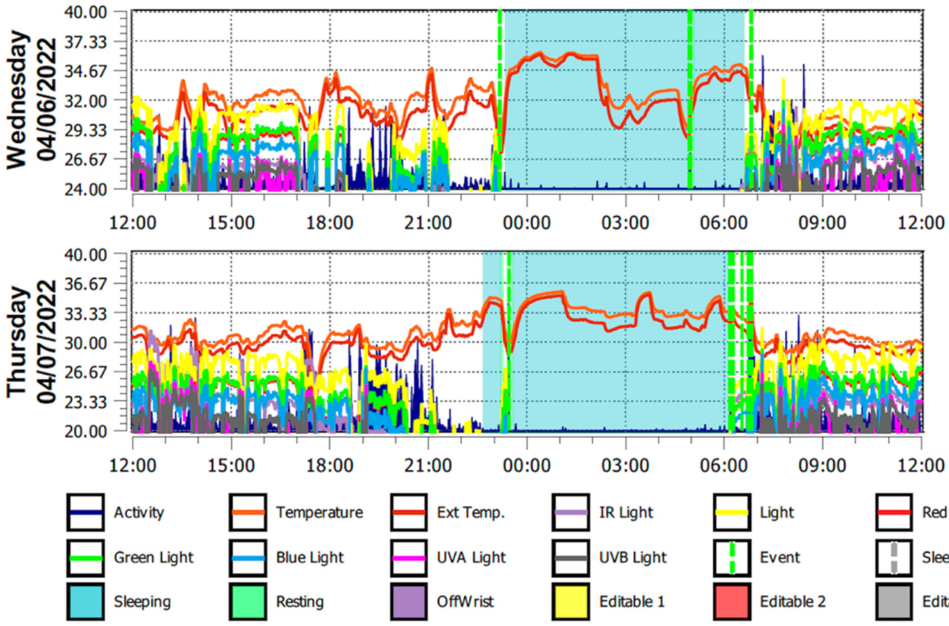

Figure 2. Actogram (example from the authors' study exploring ActTrust 2 device and ActStudio software).

The software of the other eight devices do not provide circadian or sleep analysis. They execute only operational actions (programming the device run and reading the recorded data), graphical display of data (not all devices), and access/export of data.

Most of the software (applications) provide the opportunity to freely export original data either in converted units (e.g., lux) or row units (specified partly in Table 1). Various software exist that can compute circadian, sleep and other rhythmic variables from the imported data, sometimes obtained using different types of devices and large populations. Many such tools are based on the cosinor method [59] and use non-traditional packages such as Python [60,61]. Some computational methods and software tools are presented in Supplementary Table S2 (includes references [59–69]).

4. Discussion

This review presented the basic features of seventeen wearable light-and-motion dataloggers. We found that all dataloggers differ from each other in several features. This review can thus help investigators to choose a device in accordance with the research needs. Some of these features are also important for test subjects to know in order to wear the device and record data properly, and they can be reflected in user instructions (see example in Supplementary Figure S1).

This review has a limitation in that it does not describe all characteristics of the wearables that may influence the researchers' choice of a particular datalogger in specific cases. This may particularly concern the performance characteristics of motion and light sensors and software peculiarities. Some relevant links to other articles describing the sensors' features have been provided in Section 3.4 of this review. It is also to be noted that some of the statements partially reflect the views of the authors (based on their own practice of working with dataloggers), which may not coincide with the opinions of other researchers. A more comprehensive, objective, and updated review is required in the future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app122211794/s1, Figure S1: Instructions for wearing ActTrust 2 datalogger (used in one of the authors' study). Translated from Russian. Table S1: Light-and-motion dataloggers for human research (as of October 2022; continuation of Table 1). Table S2: Computational methods and some software tools currently available for analyzing of the raw actimetry data.

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