

Illuminance measurement by mobile devices with a diffuser dome: a comparative analysis of different platforms and applications

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Received: 1 February 2021 / Accepted: 23 August 2021

Abstract. Studies in the literature suggest that smartphone-based applications are not suitable for measuring illuminance levels. The measurement of this photometric quantity is useful in several sectors, including monitoring the adequacy of lighting conditions in workplaces. This work investigates the contribution of attaching a diffuser dome to the embedded light sensors of smartphones and tablets associated with different applications on their performance for measuring illuminance. Two experimental arrangements were developed using an LED lamp (294.84 lx, 475.58 lx, 880.39 lx) and a xenon arc lamp (607.94 lx, 1013.72 lx, 4012.26 lx, 23933.33 lx). In the comparative analysis, the impact of using diffusion dome attachment was evidenced, indicating its potential to enable some of the device/application combinations to achieve adequate performance for being applied in the daily assessment of illuminance.

Keywords: Metrology / illuminance measurement / luxmeter / smartphone and tablet applications / metrological reliability

1 Introduction

Luxmeters are commonly used to measure the illuminance of environments in industries, offices, hospitals, residences, schools, restaurants, and other spaces. The International Technical Standard ISO 8995-1: 2002 [1] and the European Technical Standard EN 12464-1:2011 [2] provide guidelines on appropriate lighting characteristics according to the type of activity being carried out and recommend average illuminance values for performing visual tasks in working environments. For instance, for reception desks of offices, restaurants, or hotels, 300 lx is specified, while 500 lx is required for their kitchens. This same illuminance level is recommended for laboratories in industry or educational buildings, office rooms for writing, typing, reading, or data processing. In turn, higher levels of 1000 lx are associated with operating theatre of health care facilities and leather industry rooms for quality control or color inspection. In dental clinics, the required illuminance varies from 500 lx, 1000 lx, and 5000 lx, respectively, for general lighting, the illuminance at the patient, and the operating cavity.

The Luxmeter consists of a milliamperimeter and a photoelectric cell, made up of light-sensitive semiconductor

material. When the light falls on the photocell, it generates a current in the semiconductor, which, after amplification, is measured with the ammeter using a properly graduated scale to detect the incident level of illuminance at the measurement site. This measuring instrument shall comply with the international standard ISO/CIE 19476:2014 [3].

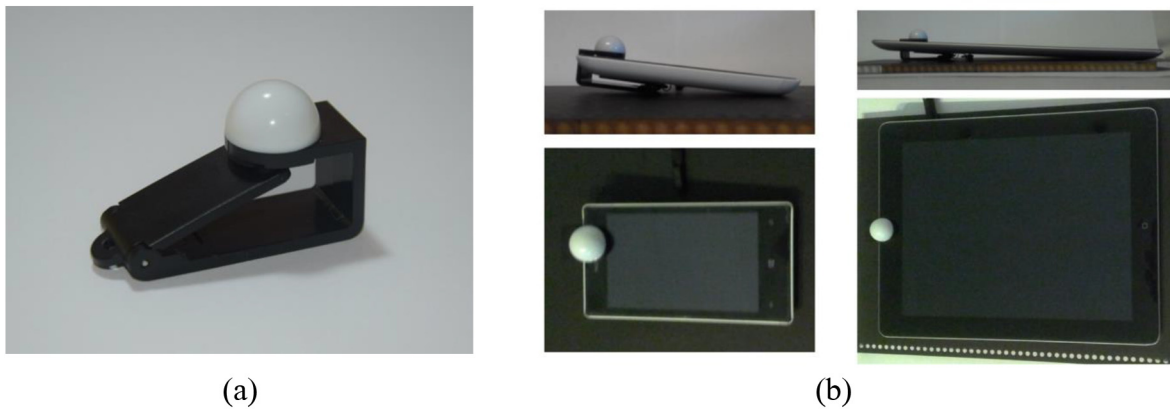
The possibility that existing sensors in mobile devices can perform illuminance measurements would make it feasible to use them in multiple everyday applications without needing a digital luxmeter.

Some studies have analyzed the performance of various combinations of smartphones with illuminance measurement applications in the literature, comparing them to measurement results using a digital luxmeter [4–11]. These studies indicated the limitations of the devices and applications evaluated to perform the illuminance measurement [8–11]. On the other hand, there are diffuser domes available on the market, at low cost, designed to increase the light absorption region of mobile devices' cameras. In the literature, none of the studies evaluates the performance of smartphones using these domes for illuminance measurements. However, an appropriate combination of application and sensor connected to a diffuser dome may contribute to making possible the use of mobile devices to measure illuminance.

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Table 1. Codes for the digital luxmeter measurements and each association of apps and operating systems of mobile devices employed in the study.

| Code | Application | Operating system |
|-----------|------------------|----------------------------|
| D_{REF} | Digital Luxmeter | |
| DA_1 | Dr. Led | iPad [IOS] |
| DA_2 | Lux Light Meter | iPad [IOS] |
| DA_3 | Lux Câmera | iPad [IOS] |
| DA_4 | Luxi | iPad [IOS] |
| DA_5 | Dr. Led | Motorola [Android] |
| DA_6 | Ourolux | Motorola [Android] |
| DA_7 | Light Meter | Motorola [Android] |
| DA_8 | Luxmetro | Motorola [Android] |
| DA_9 | Luxi | Motorola [Android] |
| DA_{10} | Luxmetro | Nokia Lumia 520 [W. Phone] |
| DA_{11} | Light Scales | Nokia Lumia 520 [W. Phone] |
| DA_{12} | Lux-O-Meter | Nokia Lumia 520 [W. Phone] |

**Fig. 1.** (a) Device used as a light diffuser (Luxi for all). (b) Mobile devices: Nokia (left) and Ipad (right) with the diffuser dome attached.

The present work evaluates mobile smartphones and tablets' performance for illuminance measurement, combined with different applications, also investigating the contribution of a diffuser dome attached to the devices.

2 Material and methods

Volunteers provided the smartphones/tablet samples for testing. The three models evaluated were: a tablet iPad (model A1395) running the iOS Apple platform; a Motorola smartphone (model Moto G XT1032), with an Android operating system; and a Nokia smartphone Lumia 520, with Windows Phone operating system. Ten free luxmeter applications (apps) were selected. However, none of the software applications could be installed on all the models of devices.

Table 1 shows codes used in this work for the employed combinations between apps and mobile devices (DA_1 to DA_{12}), and the digital luxmeter (D_{REF}).

Experimental setups and measuring procedures have been developed using a light emitting diode (LED) lamp and a xenon arc lamp. The latter simulates the light radiation emitted by the Sun. All measurements took place in a dark chamber aiming to minimize light reflection and avoid other light sources' interference than those under test. For each device/app combination, measurements were performed in two measuring conditions: with or without the smartphone's front-facing camera attached to a light diffuser dome (Luxi for all) [12], shown in more detail in Figure 1a. Figure 1b shows Nokia and Ipad mobile devices, respectively, with the "Luxi for all" dome attached and positioned towards the front camera. For all the sensor/app combinations, at each experimental condition, 31 repeated measurements were performed.

Figure 2 shows the experimental setup using a LED lamp. Different illuminance levels were achieved with the LED light source by changing distances between the light source and the smartphone's light sensor (640 mm,

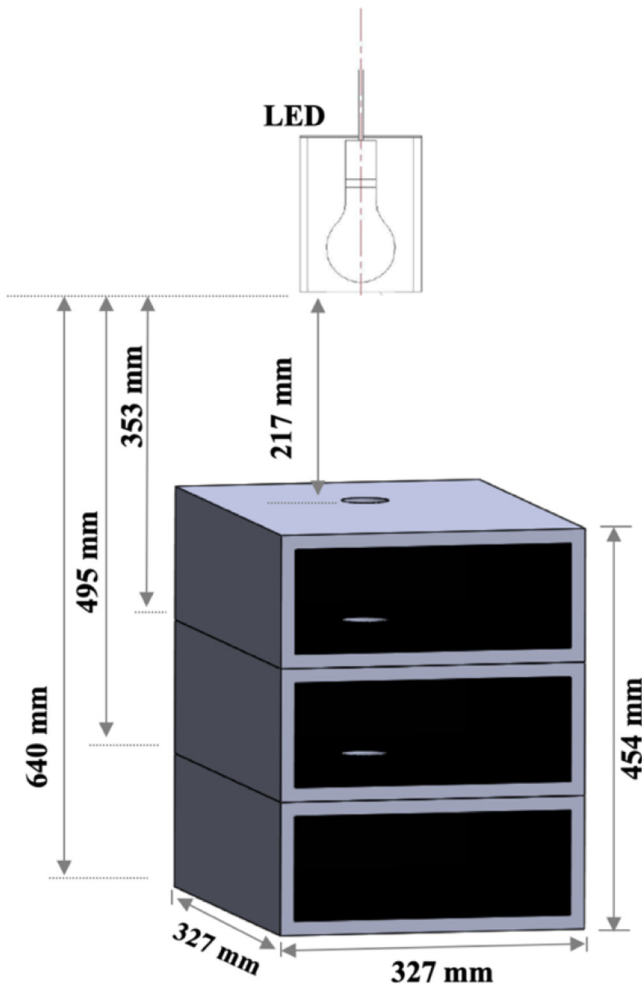


Fig. 2. Experimental setup using an LED source.

495 mm, 353 mm). This procedure provided values of 294.84 lx, 475.58 lx, and 880.39 lx illuminance levels. Each device was positioned on the horizontal surface of each level. Through a hole with a diameter of 50 mm, the light was directed to the sensor area of the device where the diffuser dome was attached.

Figure 3 shows the experimental setup using a xenon arc lamp as the light source. It employs a Small Collimated Beam Solar Simulator, 300 W, Class AAA (SF-300-A). The solar simulator (SF-300-A) includes Ushio Xenon short arc lamp (UXL-302-0), power supply, Air Mass AM1.5G Filter, and a beam turning assembly in the output port. This latter redirects the light downwards onto a horizontal surface. In this setup, the distance between the light source and the device was fixed. Three different illuminance levels were obtained by adapting an iris to the light output of the solar simulator, with three different opening diameters. Iris's opening diameters of 3 mm, 4.5 mm, and 7 mm provided illuminance intensities of 607.94 lx, 1013.72 lx, and 4012.26 lx.

The reference value for the measured illuminance was obtained using a portable digital luxmeter Minipa MLM-1011 (D_{REF}), covering the range of 1 lx to 100 000 lx. The

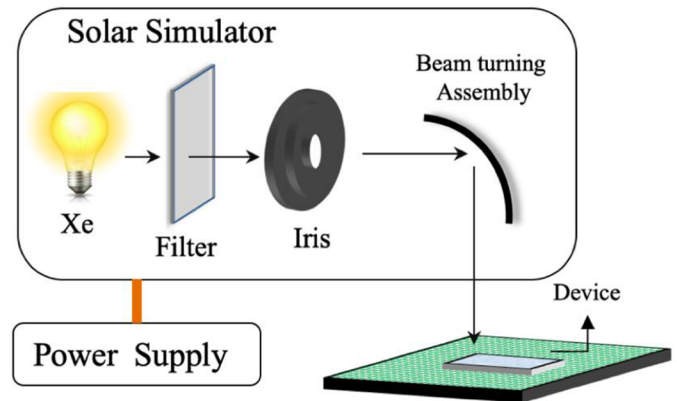


Fig. 3. Experimental setup using the solar simulator (SF300A) with xenon lamp.

mean reference values for the illuminance provided by the digital luxmeter readings for LED lamp and xenon arc lamp measurements are shown in Figure 4a and 4b, respectively.

The data analysis was accomplished by comparing the illuminance measurement results obtained by each of the 12 device/app combinations with reference values provided by the luxmeter. The relative difference expressed as a percentage (Δ_{RD}) between the illuminance measurement results obtained by mobile devices to the reference values was calculated using equation (1):

$$\Delta_{RD} = \left[\frac{(\bar{x}_{app} - \bar{x}_{lux})}{\bar{x}_{lux}} \right] \times 1 \quad (1)$$

where \bar{x}_{app} is the mean value of the application illuminance readings (lx) and \bar{x}_{lux} is the mean value of illuminance measurement results (lx) provided by the digital luxmeter (D_{REF}).

Measurement precision was estimated for each measuring series of 31 repeated illuminance measurements by estimating the relative repeatability (0.9545 coverage probability; $k=2.087$), calculated from the product of the selected coverage factor (k) and the standard uncertainty obtained from a Type A evaluation. The relative repeatability (RR) was then expressed as a percentage of the mean value of the application illuminance readings (\bar{x}_{lux}).

3 Results

We considered a 10 % limit for defining appropriate discrepancies between illuminance values obtained by each combination of apps and operating systems of mobile devices, listed in Table 1, and the reference illuminance value. The chosen limit was based on tolerances regarding the disparity between the calculated prediction and the measured performance of a lighting installation, described in ISO 8995-1 [1].

Table 2 shows the relative percentage difference (Δ_{RD}) between the reference illuminance values and the means of measurement results from each device/app combination.

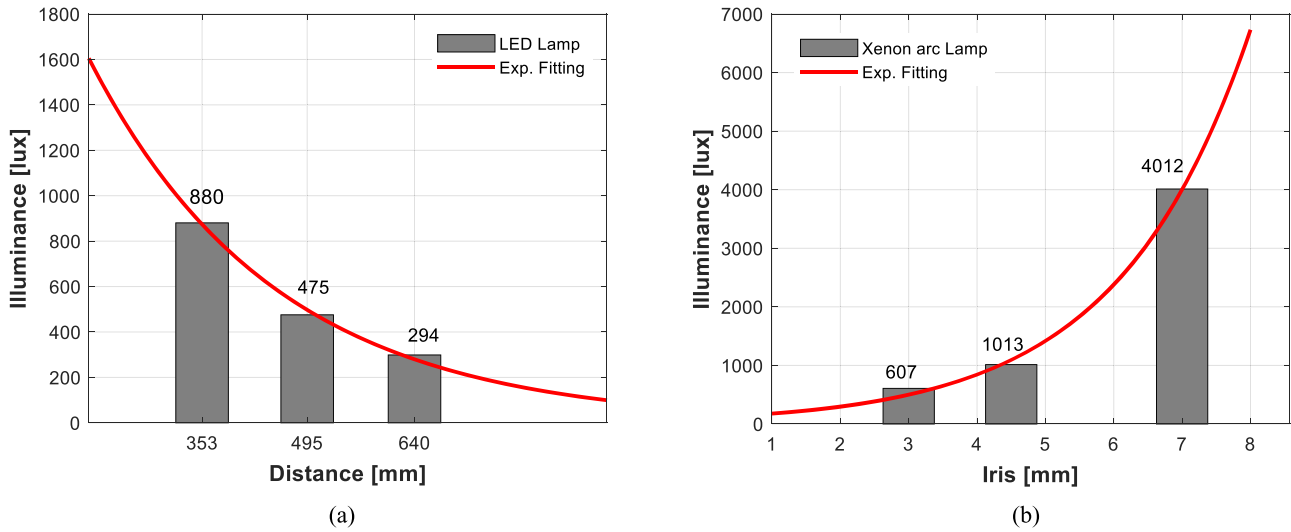


Fig. 4. Illuminance reference mean values, measured by the digital luxmeter, for each of the two light source assemblies: LED Lamp, in (a), and Xenon arc lamp, in (b).

Table 2. Relative percentage difference (Δ_{RD}) between mean values of the mobile's results and the reference value for the three illuminance levels at each sensor-light source distance.

| Code | Distance Sensor-Source | | Distance Sensor-Source | | Distance Sensor-Source | |
|-----------|------------------------|------------------|------------------------|------------------|------------------------|------------------|
| | 640 mm | | 495 mm | | 353 mm | |
| D_{REF} | 294.84 lx | | 475.58 lx | | 880.39 lx | |
| | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} |
| | With Diffuser | Without Diffuser | With Diffuser | Without Diffuser | With Diffuser | Without Diffuser |
| DA_1 | 5 % | 59 % | 0 % | 57 % | 3 % | 50 % |
| DA_2 | 54 % | – | 44 % | | | |
| DA_3 | 51 % | – | 42 % | | | |
| DA_4 | 15 % | – | 18 % | | | |
| DA_5 | 38 % | 33 % | 11 % | 40 % | 46 % | 51 % |
| DA_6 | 47 % | 55 % | 4 % | 6 % | 0 % | 3 % |
| DA_7 | 59 % | 55 % | 26 % | 7 % | 3 % | 3 % |
| DA_8 | 59 % | 56 % | 28 % | 6 % | 4 % | 3 % |
| DA_9 | 177 % | 193 % | 288 % | 368 % | 367 % | 392 % |
| DA_{10} | 87 % | 59 % | 87 % | – | 88 % | – |
| DA_{11} | 87 % | 60 % | 88 % | – | 88 % | – |
| DA_{12} | 87 % | 61 % | 88 % | 55 % | 88 % | 43 % |

The results are presented for situations where the diffuser dome is attached to the device or not. The three illuminance levels were obtained by varying the sensor's distance to an LED light source (640 mm, 495 mm, 353 mm).

When using the diffuser dome attached to the camera, the mobile device iPad obtained mean illuminance values close to those of the reference D_{REF} (294.84 lx) in its configuration DA_1 (Dr. Led – 279.00 lx) and DA_4

(Luxi – 249.32 lx). However, only the measurement using the iPad/Dr. Led application (DA_1) presented a performance within the 10 % limit.

The Motorola device did not perform well for the lowest illuminance level (294.84 lx); Nevertheless, when associated with some of the applications, their results met the 10 % (Δ_{RD}) limit for higher illuminance levels (475.58 and 880.39 lx). For the higher illuminance (880.39 lx), Motorola's association with three of the applications

Table 3. Relative percentage difference (Δ_{RD}) between mean values of device/app combination illuminance results and the reference illuminance for three illuminance levels at distinct opening diameters of an iris.

| Code | Iris diameter | | Iris diameter | | Iris diameter | |
|-----------|---------------|------------------|---------------|------------------|---------------|------------------|
| | 3 mm | | 4.5 mm | | 7 mm | |
| D_{REF} | 607.94 lx | | 1013.72 lx | | 4012.26 lx | |
| | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} | Δ_{RD} |
| | With Diffuser | Without Diffuser | With Diffuser | Without Diffuser | With Diffuser | Without Diffuser |
| DA_1 | 11 % | 2155 % | 22 % | 659 % | 103 % | 255 % |
| DA_2 | 56 % | 1072 % | 40 % | 287 % | 0 % | 84 % |
| DA_3 | 55 % | 976 % | 39 % | 283 % | 3 % | 81 % |
| DA_4 | 6 % | – | – | – | 34 % | – |
| DA_5 | – | – | – | – | – | – |
| DA_6 | – | – | – | – | – | – |
| DA_7 | – | – | – | – | – | – |
| DA_8 | – | – | – | – | – | – |
| DA_9 | 54 % | 54 % | 72 % | 72 % | 93 % | 93 % |
| DA_{10} | 93 % | 1932 % | 93 % | 1122 % | 94 % | 242 % |
| DA_{11} | 93 % | 1926 % | 93 % | 1087 % | 93 % | 239 % |
| DA_{12} | 93 % | 1778 % | 93 % | 1015 % | 93 % | 238 % |

(DA_6 , DA_7 , DA_8) made it possible to obtain satisfactory performance regardless of the diffuser dome use. In particular, the Motorola/Ourolux association (DA_6) presented adequate performance irrespective of the use or not of the diffuser dome for the two highest levels of illuminance provided by measurements using the LED Lamp.

The relative repeatability (RR) for the mobile device iPad (DA_1) using the diffuser dome attached to the camera was null for the three levels of illuminance using the LED lamp source. Without the dome, the relative repeatability eventually increased but reaching values under 3%. The great majority of RR results for the illuminance measurements with the LED lamp source were inferior to 1%, with no impact on the conclusions obtained by (Δ_{RD}) analysis.

Table 3 presents the (Δ_{RD}) values obtained in the measurements performed with the experimental arrangement using the xenon lamp as the light source. Results are presented for three illuminance levels obtained at distinct opening diameters of an iris (3 mm, 4.5 mm, and 7 mm).

In measurements using the xenon lamp (Tab. 3), much higher (Δ_{RD}) values were observed, particularly in measurements without the dome. In this condition of very high illuminance, only four configurations of iPad devices using the dome met the limit [1]. Table 3 indicates the four appropriate results stressed in bold.

Despite the discrepancies observed in (Δ_{RD}) results for Xenon lamp measurements (Tab. 3), the relative repeatability was generally under 2%, except for measurements with the 3 mm iris diameter (607.94 lx), with RR from 48 to 336%. Relative repeatability estimates did not impact conclusions regarding adequate performance based on (Δ_{RD}) results. The four iPad configurations stressed in

Table 3 were associated with low RR results, varying from null (DA_1) to 2.56% (DA_3) of the mean value of the application illuminance readings (\bar{x}_{app}).

4 Discussion

In the literature, a study in which seven mobile phones running on distinct operating systems (three IOS, three Android, and one Windows Phone), tested for three different illuminance levels (100 lx, 500 lx, and 1000 lx), concluded that the evaluated technologies are not suitable for illuminance measurements [8]. Similarly, an even broader study [9], covering nine mobile devices, three operating systems, 14 applications, for four illuminance levels (300 lx, 500 lx, 750 lx, and 1000 lx), indicated that smartphones have significant limitations to estimate illuminance levels, being unsuitable for use in occupational lighting assessments [9].

In contrast, the use of diffuser dome attached to the mobile devices in our study, allowed some of the device/app combinations to properly perform the illuminance measurement. On the other hand, corroborating with [9], the configurations using Nokia did not perform well in any of the present study arrangements. The diffusing dome made it possible to bring the Nokia results closer to the reference value, but not enough to reach a satisfactory performance.

In turn, a study employing Motorola[®] XT 1068 and AndroidTM, without diffuser dome, has shown this combination's suitability for measuring illuminance values to assess laryngoscopes' adequacy [11]. The study considered the illuminance measurements required by the

international standard ISO 7376 for evaluating laryngoscopes for tracheal intubation, which establishes a minimum of 500 lx for curved blade laryngoscopes in specified measurement conditions [13]. The evaluation described in [11] indicated no significant difference between the smartphone outcome and the reference values obtained with a digital luxmeter. Our study evidenced good results in measurements with the Motorola[®] smartphone, without using the diffuser dome, for 475 and 880 lx illuminances with the LED source; therefore, corroborating with the device's adequacy described in [11].

The studies analyzing the performance of combinations of smartphones with illuminance measurement applications, described in the literature [4–11], are based on discrepancies associated with systematic errors. Similarly, our results evaluated by (Δ_{RD}) represented the dominant aspect defining the suitability of the measuring devices [4–11]. Random errors evaluated by the relative repeatability associated with the mean value of the application illuminance readings were more elevated only for the measurement arrangement performed without diffuser dome, specifically with the xenon lamp with a 3 mm opening diameter of the iris. The more intense light beam provided by the xenon lamp impacted the sensor/app combinations' performance. For measurements with a setup employing this latter illumination, only some of the iPad/app combinations attached to a light diffuser dome reached proper results. It was observed that, despite the very low values of the relative repeatability associated with the luxmeter measurements, the measuring instrument providing the illuminance reference values, their RR percent were higher for xenon lamp measurements (between 0.069 % and 0.152 %) than those obtained with an LED source illumination (between 0.005 % and 0.008 %).

5 Conclusions

This work analyzes the light sensors' performance in smartphones and tablets associated with different applications for measuring illuminance, using or not a diffuser dome attached to the devices. Two experimental arrangements were developed. One of them uses an LED light source, in which different levels of illuminance were provided by changing the distance between the sensor and the light source. The other arrangement uses a xenon lamp light source for higher illuminance levels, varying the sensor exposition with a predefined iris aperture diameter. The measurements performed had a digital luxmeter as a reference for comparing the results.

Using the LED lamp setup (294.84 lx, 475.58 lx, 880.39 lx), the only devices with less than 10 % difference from the nominal value measured by the digital luxmeter were the iPad and Motorola. In tests with the LED light source, the dome enabled the iPad device with the Dr. Led application to present acceptable performance in the three levels of illuminance analyzed. In turn, for measurements made with the xenon lamp (607.94 lx, 1013.72 lx, 4012.26 lx,

23933.33 lx), the iPad with the dome-shaped diffuser was the only condition that provided results close to the reference value.

Thus, the comparative analysis performed in this study characterized a potential contribution of the use of diffusion dome attachment for the front-facing camera in the performance for illuminance measurements using the evaluated mobile devices. The diffuser attachment enabled some of the device/application combinations to achieve adequate performance for being applied in the daily assessment of illuminance.

Future research should investigate other mobile devices of different brands and models associated with other light sensor modalities, also incorporating other light radiation sources in the study setup. Furthermore, as the present study considered only free applications, paid applications shell also be included in the following performance evaluations.

Conflict of interests

The authors declare that they have no conflict of interest.

The authors acknowledge the financial support provided by the Brazilian Agencies CNPq, FINEP, FAPERJ, and CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) – Brazil – Financing Code 001.

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Cite this article as: Viviane Godinho Vaz, Roberta Dutra de Oliveira Pinto, Daniel Ramos Louzada, Elisabeth Costa Monteiro, Illuminance measurement by mobile devices with a diffuser dome: a comparative analysis of different platforms and applications, *Int. J. Metrol. Qual. Eng.* **12**, 23 (2021)