Optimizing Camera Exposure Control Settings for Remote Vital Sign Measurements in Low-Light Environments

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Abstract

Remote photoplethysmography (rPPG) is an optical technique that enables both non-invasive and efficient measurement of vital signs from facial videos. However, the quality of rPPG measurements can be adversely affected by improper camera exposure control and bad lighting conditions. In this paper, we present a systematic study of camera exposure control settings, specifically gain and exposure time, in low-light environments. Our results indicate that manual adjustment of gain and exposure time can significantly improve the quality of rPPG measurements, enabling accurate vital sign measurement even in environments with illuminance levels as low as 25 lux. Furthermore, we demonstrate that the optimal brightness range for rPPG-based vital sign measurement depends on the sensitivity of the vital sign to the shape and peaks of the rPPG signal. These findings have important practical implications for the use of rPPG in healthcare and remote monitoring applications.

1. Introduction

Remote photoplethysmography (rPPG) is an innovative technique for remotely measuring physiological signals by analyzing blood volume changes under the skin from camera videos. The rPPG technique provides a low-cost and effective approach to extract vital physiological signs such as heart rate (HR) [8, 16], heart rate variability (HRV) [6], and blood pressure (BP) [19]. In particular, heart rate and heart rate variability derived from an rPPG signal have been used in patient, sleep, and neonate monitoring, as well as wellness applications [3, 4, 17, 22].

Different measurement conditions can greatly affect rPPG results and may be detrimental to the quality of detected physiological signals [9, 14, 21, 23]. In low-light environments, it has been observed that insufficient lighting results in the loss of facial details and a decrease in the amplitude of pulsatile signals leading to a low signal-to-noise ratio [21]. Proper exposure control could alleviate such an impact by adjusting related camera parameters such as the analog gain and exposure time. Analog gain is the electronic amplification applied to the voltage of the detected light, while exposure time measures the duration of light reaching the sensor.

Exposure control methods have been studied primarily for producing aesthetic images and boosting performances for computer vision and robotics tasks [5, 12, 13, 18]. Research has highlighted that camera parameters such as exposure time and gain greatly affect the results of tasks involving information retrieval from images. Furthermore, using existing Auto-Exposure (AE) algorithms or setting fixed camera parameters manually do not always achieve optimal image quality for different tasks. Therefore, various metrics to evaluate the 'well-exposed' quality are defined, and exposure control algorithms based on these metrics were proposed and tested.

Previous research has mainly focused on improving computer vision tasks unrelated to rPPG extraction. Other studies have been carried out to investigate the effect of camera exposure control on remote vital sign measurement. For example, Laurie et al., [5] examined total noise and quantization noise under different gain and exposure time levels. They observed that increasing gain did not reduce total noise after some critical points, while increasing exposure time, on the contrary, reduced total noise. An exposure time control algorithm maximizing rPPG Signal-to-Noise Ratio was then proposed and tested under fluorescent lighting. Their method improved HR assessment, demonstrating the potential of improving rPPG results under different lighting conditions with camera exposure control. Van Esch et al., [15] also investigated the effect of exposure time on HR measurement under different lighting conditions. Their research concluded that camera exposure control is unnecessary beyond avoiding saturation, thereby conflicting with the results of Laurie et. al. [5]

However, both Van Esch et al., [15] and Laurie et al., [5]

limited their research and experiments solely to the heart rate and did not consider sensitive vital signs that depend on peak localization and shape of the rPPG signal. Furthermore, these studies were conducted in well-lit environments and the number of participants involved in related experiments was limited to 4-5 people. Therefore, our focus in this paper was to study the effect of camera settings under low-light scenarios. Our contributions can be summarized as follows:

1. We present a systematic study of camera exposure control settings, specifically camera exposure time and gain, for rPPG extraction in various illumination environments.

2. We propose a novel metric to assess the feasibility of rPPG extraction based on the perceived brightness of the subject's face.

3. We show that the optimal brightness of facial videos for remote vital sign measurement depends on the vital sign that is being measured. The range is much smaller for vital signs that are sensitive to the rPPG signal's shape, such as heart rate variability and blood pressure.

4. We demonstrate that controlled exposure outperforms auto exposure for HR estimation in low-light scenarios.

2. Theory

There are many factors that can impact the brightness and the quality of an image. The relationship between these factors can be summarized in the following equation [11]:

$$IB \propto gain * ET * AA * SI * C_1 \tag{1}$$

where IB stands for Image Brightness, $gain$ is analog gain also known as ISO sensitivity, ET is exposure time, AA is aperture area, SI is scene illumination and C_1 is a constant. C_1 in this equation represents factors that are difficult to control such as the reflectivity of an object. The aperture area, in optics, is the opening through which light passes. It is adjustable in industrial cameras or dedicated photographic cameras. However, the aperture area is fixed in most webcams and smartphone cameras, and therefore, equation 1 can be re-written as:

$$IB \propto gain * ET * SI * C_2 \tag{2}$$

where C_2 is constant for the factors that are difficult to adjust.

$gain$ in equation 2 is an electronic amplification of the detected voltage. A higher gain increases image brightness, but an excessive gain may also lead to strong salt-and-pepper noise [13]. The gain is usually given in decibels (dB) as follows [1]:

$$gain(dB) = 20 \log_{10} \frac{V_{out}}{V_{in}} \tag{3}$$

where V_{out} is output voltage that is mapped to pixels, V_{in} is input voltage or detected voltage.

Exposure time (ET), in Equation 2, is the duration that the digital sensor of the camera is exposed to light. Larger exposure time leads to greater brightness of the image, while an excessive amount may cause motion-blur effects. Finally, scene illumination (SI) is the magnitude of light per unit area calculated in units of lux.

3. Experimental Setup

3.1. Dataset

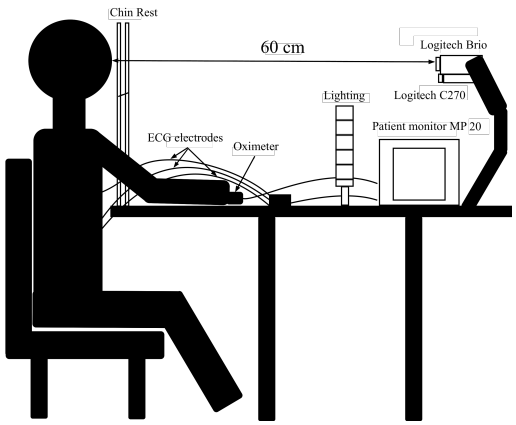


Figure 1. Illustration of the experimental setup. The participant is seated 60 cm away from Logitech cameras.

A total of 12 participants, consisting of 8 males and 4 females aged 22 to 56 years with diverse skin tones, took part in our experiment. The experimental setup included two cameras, a Logitech Brio, and a Logitech C270, mounted on a stand. An adjustable lighting device was used to control the ambient environment's luminosity, and an HPCS-320 spectrometer was used to measure luminosity by placing it directly in front of the subject's face and pointing it toward the light source and cameras. To minimize measurement errors, we took three measurements for each luminosity setting. The MP 370 patient monitor and an oximeter were used as reference devices for benchmarking purposes.

During the data collection, each participant was assigned an ID to ensure anonymity and was asked to sit on a chair and rest for 5 minutes to achieve a stable physiological state. They were then invited to look at the two cameras from 60 cm while seated and with their faces positioned on a chin rest (see Figure 1). A total of 72 uncompressed video recordings of 30 seconds were collected for each participant from each camera, with a frame rate of 15 frames per second at a resolution of 480×640 pixels. Of these recordings, 60 consisted of various conditions, including four illuminations (25, 50, 75, 100 lux), five gain controls (0, 6, 12, 18, 24 dB), and three exposure times (1/16, 1/32, 1/64 s). The

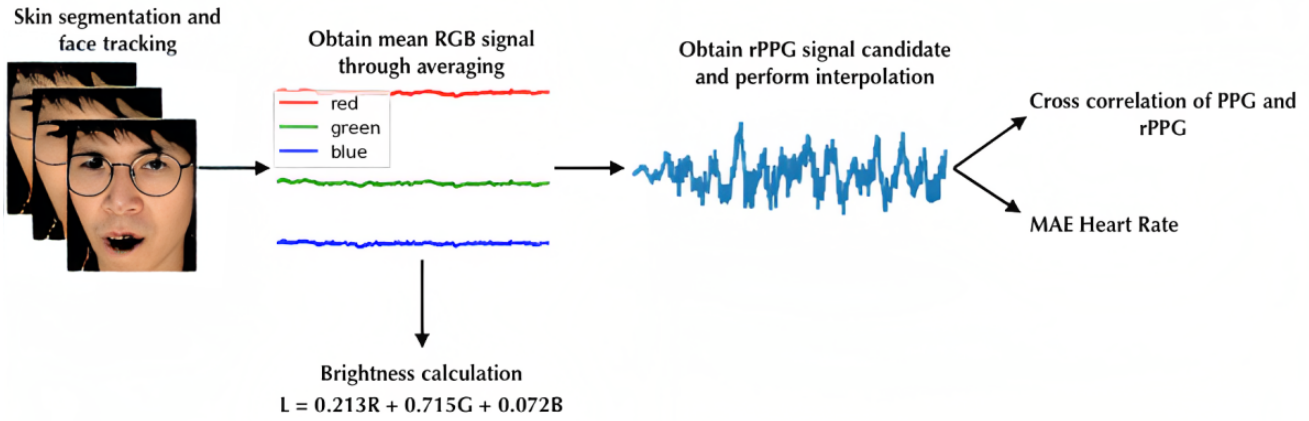


Figure 2. Flowchart illustrating the data processing pipeline of the study.

remaining 12 recordings were taken with auto-exposure, in which the cameras set the gain and exposure time automatically, for three repetitions under each of the four illuminations.

3.2. Data Processing

The recorded videos were processed with the pipeline as shown in Figure 2. The face of each participant was detected and tracked by MediaPipe FaceMesh [7]. Skin segmentation was applied to mask out nonskin regions. The spatial mean of face pixels was then taken and temporarily concatenated to acquire a mean RGB signal over time. The Plane Orthogonal to Skin (POS) [20] algorithm was utilized to map the mean RGB signal to the rPPG signal. The Butterworth bandpass filter with band size 0.7- 3Hz was applied to reduce noise. Finally, the heart rate mean absolute error and the cross-correlation of PPG and rPPG (both defined in Section 3.3) were used to evaluate the performance of vital sign extraction with different video recordings.

To facilitate our study, $brightness$ was defined as the mean brightness of the face, and it was utilized for further analysis of the effects of camera gain and camera exposure time on rPPG quality. The calculation of $brightness$ is shown in the formula below [2]:

$$L = 0.213R + 0.715G + 0.072B \tag{4}$$

where R is the red channel, G is the green channel, B is the blue channel and L stands for Luma, the perceived lightness dimension of an image in HSL space.

3.3. Metrics

During the experiment, the PPG and rPPG signals were obtained from the oximeter and cameras, respectively. The former served as the ground truth, while the latter served as an estimation. To assess the accuracy and reliability of the rPPG signal, it was compared to the PPG and evaluated based on two metrics: heart rate mean absolute error (MAE) and cross-correlation of the two signals.

For cross-correlation, the sampling frequency of the rPPG signal, originally at 15 Hz, is first increased to 125 Hz to match the sampling frequency of the PPG using first-order linear interpolation. Then the cross-correlation operation in 1-D can be performed through the dot product of PPG and rPPG signal, given by the equation below [10]:

$$F \circ I(x) = \sum_{i=-N}^{N} F(i)I(x+i) \tag{5}$$

Here, F and I represent the PPG and rPPG signals, respectively, and x is the time lag between the two signals. Both signals have $2N + 1$ elements/data points.

4. Results and Analysis

The result of MAE heart rate against gain and exposure time for different illumination values is given in Figure 3 for Logitech C270 and Figure 4 for Logitech Brio. It can be noted that the accuracy of the heart rate estimation was strongly dependent on $brightness$. When the images were under-exposed ($brightness < 50$), increasing brightness by either increasing gain or exposure time, decreased heart rate MAE. Furthermore, from Figures 3b, 3c and 3d, it can be observed that when the frames were over-exposed ($brightness > 200$) the heart rate MAE increased. Finally, when $brightness \in [50, 200]$, MAE heart rate was less than 5bpm for both cameras under various combinations of exposure time, gain, and scene illumination. Hence, it

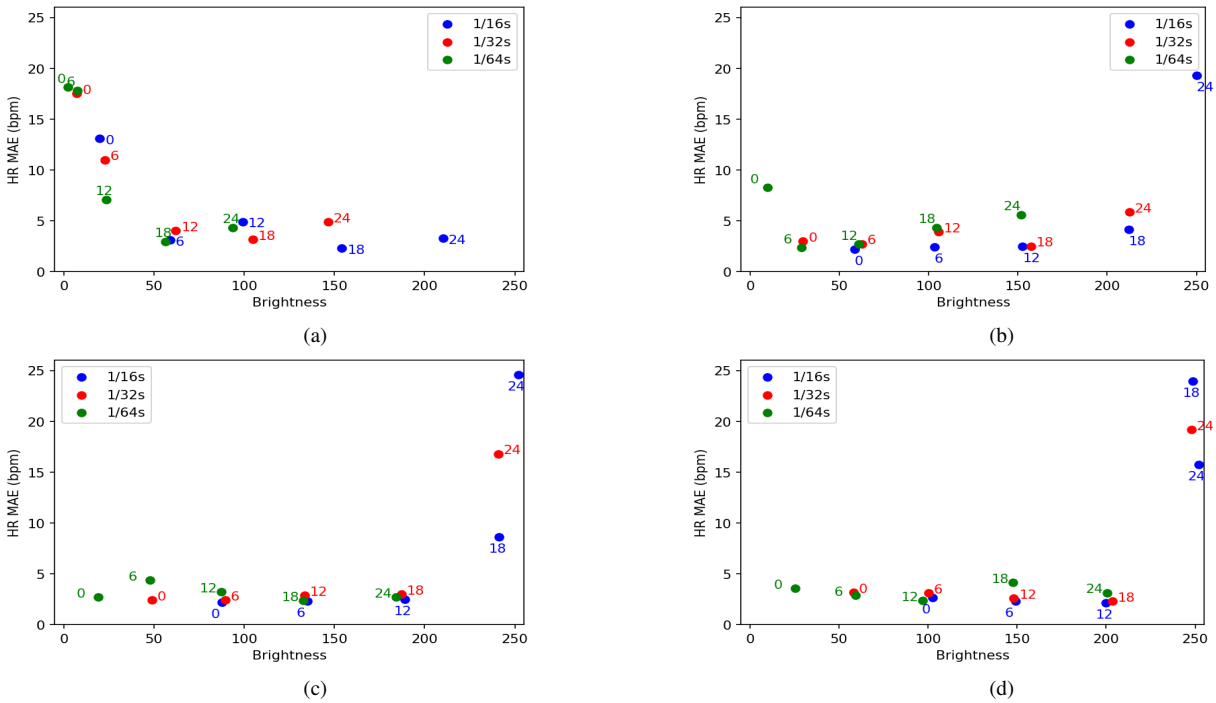


Figure 3. Average MAE of heart rate (bpm) across all subjects versus brightness, gain, and the exposure time of C270 webcam for different illuminations: (a) 25 lux, (b) 50 lux, (c) 75 lux, and (d) 100 lux. The number on each data point represents the corresponding gain from 0 to 24 decibels (dB). The color of each data point represents exposure time (1/64, 1/32, 1/16) in units of seconds.

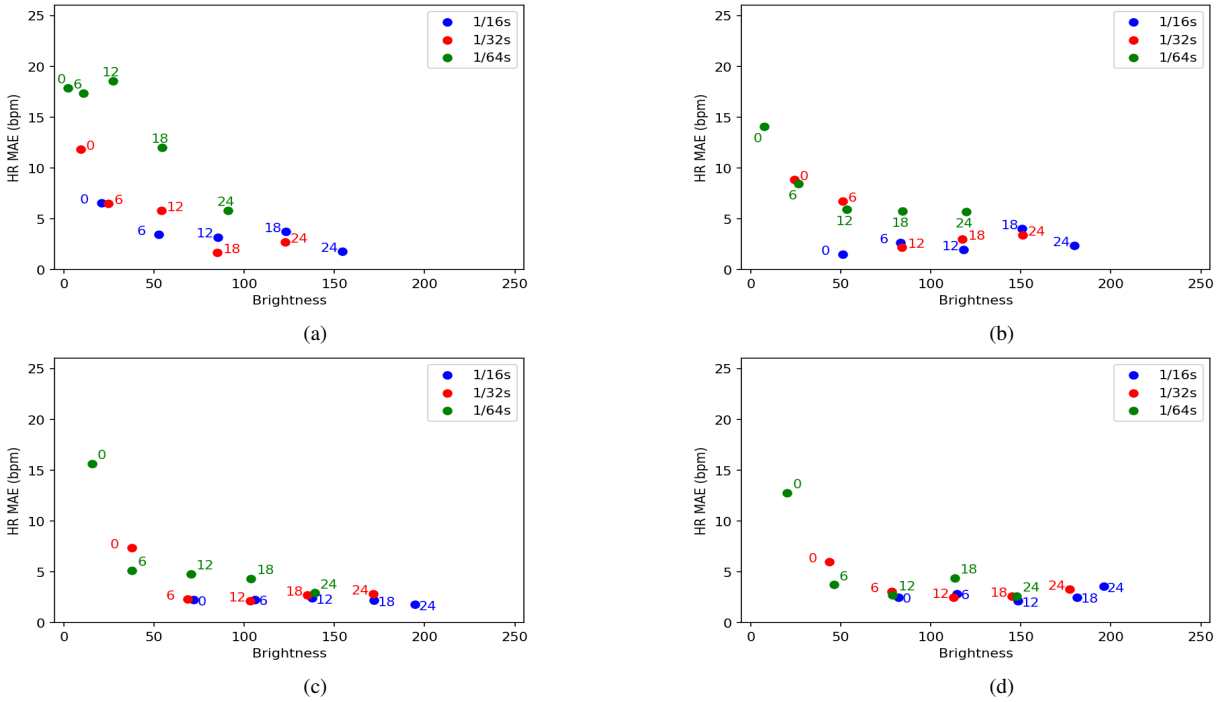


Figure 4. Average MAE of heart rate (bpm) across all subjects versus brightness, gain, and the exposure time of Brio webcam for different illuminations: (a) 25 lux, (b) 50 lux, (c) 75 lux, and (d) 100 lux. The number on each data point represents the corresponding gain from 0 to 24 decibels (dB). The color of each data point represents exposure time (1/64, 1/32, 1/16) in units of seconds.

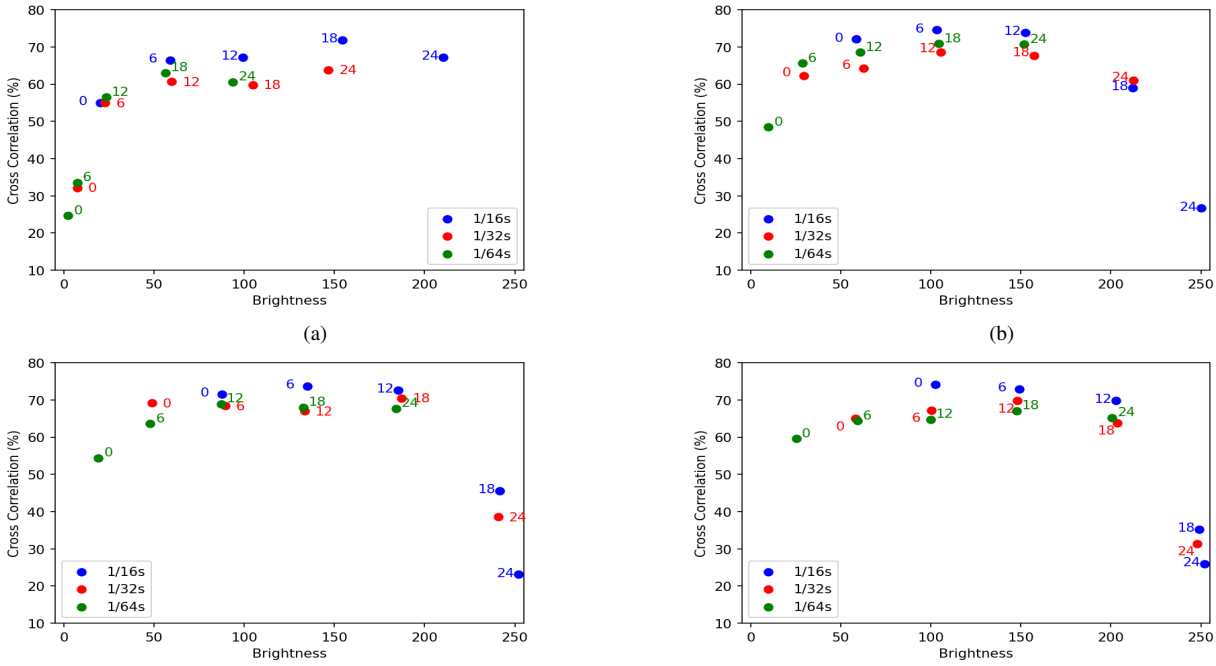


Figure 5. Cross-correlation of the contact PPG signal and interpolated rPPG signal versus brightness, gain, and the exposure time of C270 webcam for different illuminations: (a) 25 lux, (b) 50 lux, (c) 75 lux, and (d) 100 lux. The number on each data point represents the corresponding gain from 0 to 24 decibels (dB). The color of each data point represents exposure time (1/64, 1/32, 1/16) in units of seconds.

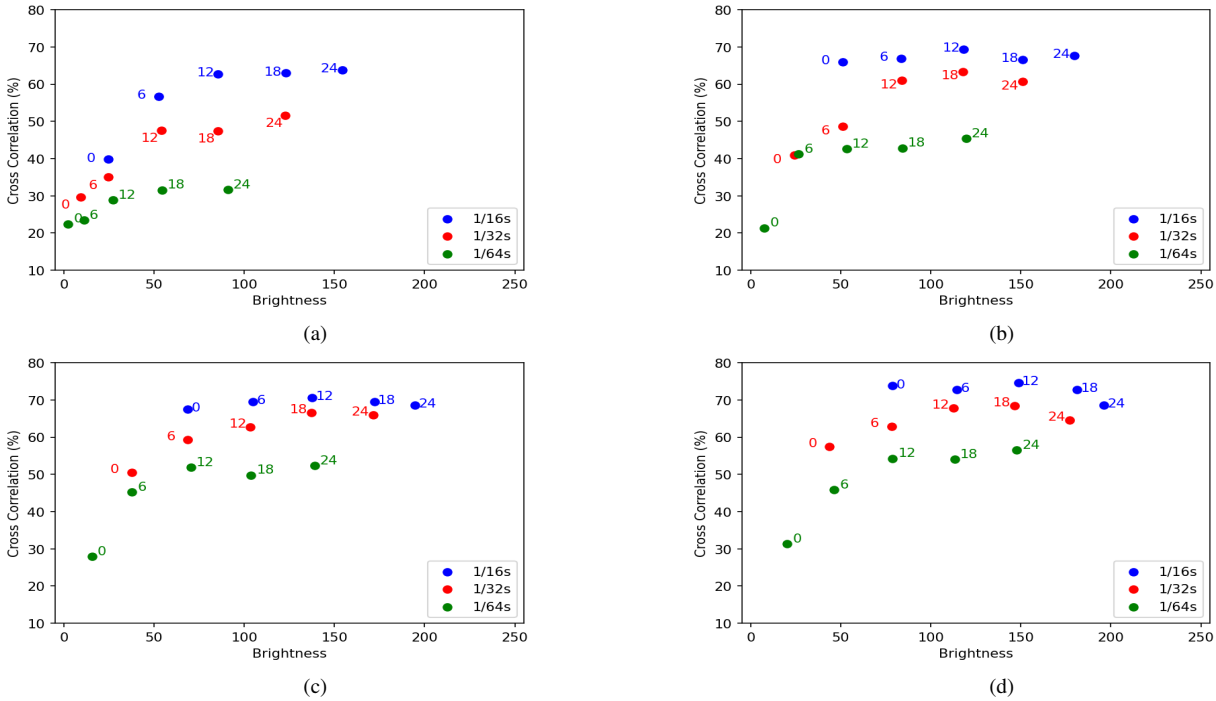
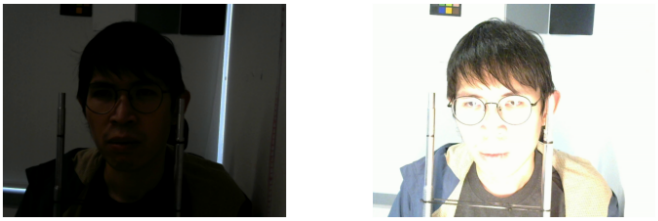


Figure 6. Cross-correlation of the contact PPG signal and interpolated rPPG signal versus brightness, gain, and the exposure time of Brio webcam for different illuminations: (a) 25 lux, (b) 50 lux, (c) 75 lux, and (d) 100 lux. The number on each data point represents the corresponding gain from 0 to 24 decibels (dB). The color of each data point represents exposure time (1/64, 1/32, 1/16) in units of seconds.

can be concluded that when the image is not under or over-exposed, increasing the brightness of the video does not decrease the MAE heart rate by a significant margin. This is consistent with the findings of this paper [15] that suggest controlling exposure time is not important beyond avoiding saturation. Examples of under-exposed and over-exposed faces are illustrated in Figure 7.



(a) (b)

Figure 7. (a) Under-exposed face; (b) overexposed face, both recorded by Logitech C270. (a) 25lux, exposure time: 1/32s, gain: 0dB, average face brightness: 11; (b) 75lux, exposure time: 1/16s, gain: 18dB, average face brightness: 251

However, this conclusion is only limited to heart rate. From Figures 5 and 6 it can be noticed that unless the face pixels are oversaturated ($brightness > 200$) longer exposure times consistently yield a higher cross-correlation between contact PPG signal and rPPG signal than shorter exposure times. For instance, in Figure 6d by looking at $gain = 18dB$, where different exposure times are represented by different colors, it can be observed that increasing exposure time from 1/64s to 1/16s increased the correlation between rPPG and contact PPG signals by 20%. This implies that more sensitive metrics such as HRV and blood pressure, which are dependent on the position of the peaks and shape of the rPPG, are significantly influenced by a change in exposure time.

Furthermore, both MAE and correlation plots show that increasing gain does not always improve the quality of vital sign measurement significantly. Figures 3 and 4 demonstrate that when $brightness \in [50, 200]$, increasing brightness by increasing gain did not reduce MAE heart rate or reduced MAE by 1bpm. A similar trend can be observed from correlation plots. For example, in Figure 6d it can be noticed that for a fixed $exposure\ time = 1/16s$, increasing gain did not improve the cross-correlation between contact PPG signal and rPPG signal. Lastly, Figure 6d reveals that increasing exposure time is more effective than increasing gain to achieve the same brightness level.

Figures 5 and 6 also illustrate the relationship between the feasibility of rPPG extraction and the brightness of the face. From these figures, it can be noticed that when $brightness < 200$, increasing the brightness of the face improves the cross-correlation between rPPG and contact PPG signals, reaching the maximum value at $brightness \approx 175 - 200$. However, when $brightness > 200$, increasing brightness reduces cross-correlation. This implies that even before calculating human vital signs, by looking at the brightness of the face, one can estimate the quality of the rPPG signal and the feasibility of vital sign extraction. Moreover, it can be concluded from the figures that the range of optimal brightness is strongly dependent on the vital sign. For less sensitive metrics like heart rate, as depicted in Figures 3 and 4, $brightness \in [50, 200]$ gave MAE $<$ 5bpm. However, the range was different for other metrics that are dependent on the location peaks and structure of rPPG such as cross-correlation, as illustrated in Figure 5, 6. These figures demonstrate that the cross-correlation between contact PPG and rPPG signals reached the maximum value when $brightness \in [150, 200]$. Therefore, the range of optimal brightness is unique and distinct for each vital sign.

Illumination	CE Brio MAE±SD	AE Brio MAE±SD	CE C270 MAE±SD	AE C270 MAE±SD
25 lux	**1.8± 1.2** 24dB, 1/16s	2.1± 2.1	**2.3 ± 2.0** 18dB, 1/16s	3.8 ± 5.5
50 lux	**1.5 ± 0.9** 0dB, 1/16s	2.2±2.5	**2.2 ± 2.8** 0dB, 1/16s	2.9 ± 2.3
75 lux	**1.8 ± 1.0** 24dB, 1/16s	2.0 ± 1.0	2.2±1.4 0dB, 1/16s	2.2± 1.0
100 lux	**2.1 ± 2.1** 12dB, 1/16s	2.8 ± 1.5	**2.1±2.7** 12dB, 1/16s	3.4±2.1

Table 1. Comparison between heart rate MAE Auto Exposure (AE) and Controlled Exposure (CE) of different cameras and illumination values. Superior performance is highlighted in **bold**. The settings to obtain optimal heart rate are given below the MAE values

Finally, from Table 1, it can be seen that controlled exposure consistently outperformed or was on par with auto exposure set by the camera. This phenomenon was also observed by Laurie et al., [5]. The rationale behind this phenomenon is that the camera adjusts its auto exposure setting based on the entire frame for aesthetic purposes, rather than for an rPPG measurement. Furthermore, it can be noted that optimal heart rate estimation was always achieved by the $exposure\ time = 1/16s$. This indicates that greater exposure time is associated with a higher correlation between contact PPG and rPPG under low-light scenarios.

5. Conclusion

In this paper, we conducted a systematic study of camera exposure control settings, specifically gain and exposure time, in a range of low-light conditions for rPPG-based vital sign measurement. We found that the effect of gain on the quality and accuracy of rPPG-based vital sign measurements is significant when the face is under-exposed, and increasing exposure time improves the quality of the rPPG

signal unless the face pixels are oversaturated. The ability to accurately measure vital signs using rPPG in low-light environments is critical for its widespread adoption in clinical and remote monitoring settings. Our study provides important insights into the impact of camera exposure control settings on rPPG measurements and can inform the development of more robust and accurate rPPG-based vital sign monitoring systems. We also demonstrate that the optimal brightness range for rPPG-based vital sign measurement varies depending on the sensitivity of the vital sign to the shape and peaks of the rPPG signal. Future research should explore the effects of sensor size on rPPG and investigate camera exposure properties under changing lighting conditions and various motion scenarios.

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