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Modified Camera Setups for Day-and-Night Pulse-rate Monitoring

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Abstract— **Camera systems have been studied as a means for ubiquitous remote photoplethysmography. It was first considered for daytime applications using ambient light. However, main applications for continuous monitoring are in dark or low-light conditions (e.g. sleep monitoring) and, more recently, suitable light sources and simple camera adaptations have been considered for infrared-based solutions. This paper explores suitable camera configurations for pulse-rate monitoring during both day and night (24/7). Various configurations differing in the recorded spectral range are defined, i.e. straight-forward adaptations of a standard RGB camera by choosing proper optical filters. These systems have been studied in a benchmark involving day and night monitoring with various degrees of motion disturbances. The results indicate that, for the 24/7 monitoring, it is best to deploy the full spectral band of an RGB camera, and this can be done without compromising the monitoring performance at night.**

I. Introduction

Contactless pulse-rate monitoring by camera-based remote photoplethysmography (remote-PPG) has been researched for many years and now found its ways into products for patient monitoring or personal health care (e.g. Vital Signs Camera APP). The typical application scenario of remote-PPG is in the daylight monitoring with an RGB camera, as RGB cameras are ubiquitous and widely accessible (e.g. mobile phone camera or webcam). But RGB camera sensors are not sensitive in darkness and this fundamentally limits the application range to the day time. Therefore, Near-Infrared (NIR) remote-PPG that uses a multi-wavelength/monochrome camera sensitive in the NIR range and an active infrared light source has been proposed. It promises attractive applications that require long-term continuous monitoring over day and night (24/7), such as patient/neonatal monitoring in hospital care units [1]–[3] and driver monitoring in automotive [4].

Regarding NIR-PPG, progress has been made on camera sensors and light sources separately. Multi-wavelength NIR cameras have been particularly studied as multi-wavelength channels can be used to significantly reduce non-cardiac disturbances like motion [5]. Typical options are multi-camera systems (multiple monochrome cameras with different IR-cut optical filters, but with parallax) and RGB2NIR cameras (single RGB camera adapted to a NIR camera by replacing the IR block filter by a visible-light block filter) [6]. Various options of light sources that provide infrared energy for NIR-PPG have been explored [7], such as fluorescent lamps (including visible light that is obtrusive to the eye), time-multiplexed infrared LEDs (multiple narrow-band infrared LED with time sequential activation, i.e. non-homogeneous spectrum), broad-band phosphor LED (single LED source with a continuous and homogeneous spectrum). A recent study [7] suggested that the combination of RGB2NIR and phosphor LED light source constitutes a good candidate for pulse-rate monitoring in darkness as it shows motion-robust performance and the required camera modifications are minimal.

TABLE I: Feasibility of (modified) RGB cameras for pulse-rate monitoring during day and night.

Scenario	RGB-only	IR-band	Long-pass	Full-band
Wavel. (nm)	400-650	660-1000	530-1000	400-1000
Daytime	✓	✓	✓	✓
Nighttime	×	✓	✓	✓

Though the NIR-PPG solution (RGB2NIR + phosphor LED) from [7] supports continuous monitoring over day and night, we feel its performance in the daylight monitoring can be further improved. The rationale is that daylight provides additional information for highly accurate PPG extraction, where especially the green component is important as the (de-)oxygenated hemoglobin has high absorption in this range. Therefore, we advocate to further extend the NIR-PPG camera to a long-pass (green + NIR) or even a full-band RGB camera that is sensitive in both the visible and infrared parts, which means that (i) in the daytime, we use a combination of visible and infrared spectra to measure PPG (from environmental light and active IR source); (ii) in the nighttime, we only use the infrared part (by active IR source). Our research question for this paper is therefore clear: can we improve the IR-band camera (i.e. the latest concept of RGB2NIR) by extending its sensitivity to long-pass or full-band range?

We first select our study candidates (see Table I): we considered four camera options where RGB-only and IR-band RGB are known solutions; long-pass RGB and full-band RGB[1] are our new proposals, representing combinations of two known extreme cases. Since the RGB-only setup cannot work in darkness, it was excluded from our benchmark. We built a synchronized monitoring setup consisting of three RGB cameras with different modifications: IR-band, long-pass and full-band (see band definitions in Table I). Using

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[1] The full-band RGB camera presented in this study is essentially different from a broad-band monochrome camera, as full-band RGB is multi-spectral during day and night.

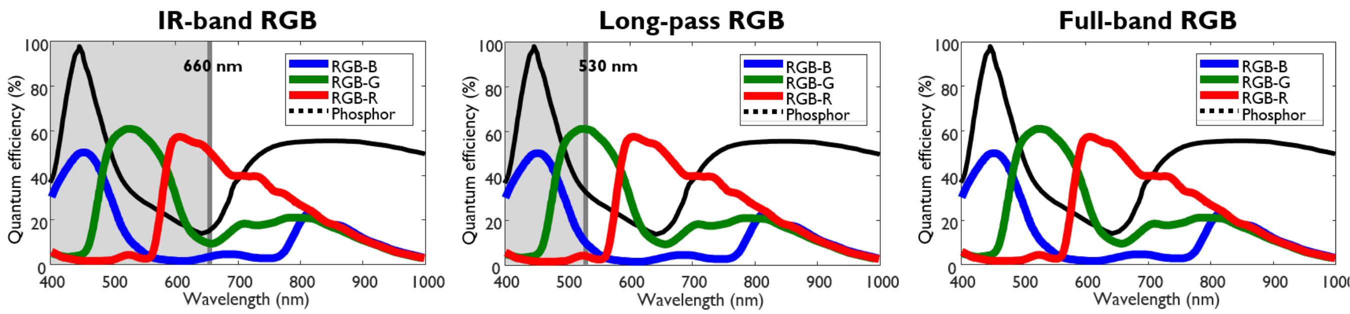

Fig. 1: Optical responses of the phosphor LED and the three modified RGB cameras used in the test (see Table I). The shaded area denotes the blocked part of the spectrum.

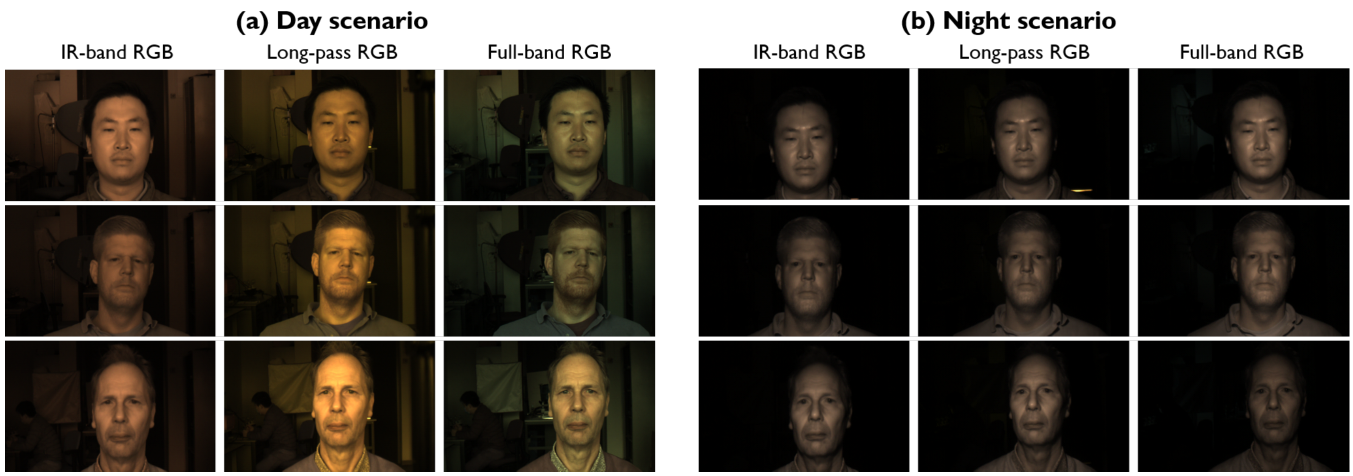

Fig. 2: Snapshots from three cameras in two lighting conditions for a visual comparison of the skin DC-level.

the same phosphor LED source as in [7], we created a large benchmark dataset with 17 adult volunteers in two lighting conditions: day and night (full darkness). The subjects follow a protocol including significant head motions for verifying the motion robustness of different camera configurations. The videos were processed by the remote-PPG extraction framework proposed in [7]. Based on the thorough evaluation, we conclude that long-pass and full-band RGB cameras significantly improve the existing IR-band RGB camera in the daylight condition while their performance in darkness is similar (as we expected based on modeling). In view of the general performance over these two lighting conditions, we conclude the full-band RGB camera as a favorable solution for continuous pulse-rate monitoring over day and night.

II. Methods and Measurements

To address the research question whether long-pass/full-band RGB cameras are better than IR-band RGB cameras for day and night monitoring, we built a synchronized triple camera setup with different modified optics as shown in Fig. 1:

- IR-band RGB camera (660-1000 nm): a visible-block filter is used to attenuate the visible part [7]. The [R, G, B] channels become three IR channels with band overlap/cross-talk.
- Long-pass RGB camera (530-1000 nm): a cut filter is used to block the blue part, as blue light is considered unable to penetrate deep into the skin issue to interact with arterial blood [8]. The [R, G, B] channels become [R+IR, G+IR, IR] channels.
- Full-band RGB camera (400-1000 nm): no block filter is used in the RGB camera. It is sensitive to the whole spectral range of the image sensor. The [R, G, B] channels become [R+IR, G+IR, B+IR] channels.

We take the full-band RGB camera as an example to illustrate how it works in the day and night mode separately. In the daylight scenario, since the phosphor LED [7] is on and daylight has infrared content, the camera measures [R+IR, G+IR, B+IR]. In the darkness scenario, it measures three IR channels only, similar to the IR-band camera. If the camera is in an indoor lighting condition (e.g. with ceiling fluorescent lamp that does not have infrared content) while the phosphor LED is off, it measures [R, G, B]. We stress that final results are not extremely sensitive to the exact wavelength modifications made in this study based on our pilot measurement, i.e. for the IR-band RGB, we exclude the visible part by putting the low-band limit to 660 nm but it can also be, for example, 680 nm.

Based on the synchronized triple RGB cameras (for fair comparison, all use the same model: IDS UI-3860-C-HQ) and in-house designed phosphor LED source [7], we created a large benchmark dataset including 17 adult volunteers with skin types I to VI according to the Fitzpatrick scale.

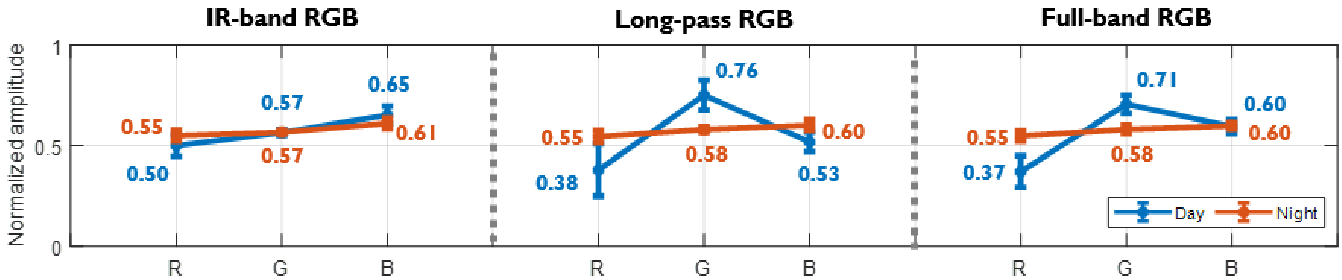

Fig. 3: The pulsatile signatures measured by three cameras from 17 subjects (in their stationary phases) in two lighting conditions (day and night). The solid lines denote average signatures, the vertical bars the standard deviation.

The camera and light source setup were placed on a tripod that was around 1 m in front of the subject sitting on a chair to mimic the automotive use case, i.e. one of the typical scenario requiring continuous monitoring over day and night. The videos were recorded in an uncompressed format (with 968×548 pixels, 8 bit depth) at the constant frame rate of 15 frames per second. All auto-adjustment functions of the camera were switched off during the recording. The experimental protocol from [7] was adopted to facilitate comparison between these studies. The protocol creates repetitive stationary and motion phases (see motion intensity signals in Fig. 5 for an impression of the recording protocol). In the motion phase, the subject was instructed to perform significant head motions with a mixture of rotation, translation, scaling and talking. In the last non-motion phase, the illumination level was fluctuating in a non-controlled manner. Each recording is around 8 minutes long. A finger-based transmissive pulse oximeter (Model: Philips IntelliVue X2) was used as the reference to collect the ground-truth. We note that the use of pulse oximeter might be contaminated by motion and thus reference PPG signal were manually inspected before benchmarking. This study has been approved by Philips Intellectual Property & Standards, and written informed consent has been obtained from each participant.

The DC images recorded by three cameras in day and night scenarios are exemplified in Fig. 2. We can see that three cameras are mostly different in the day scenario, which is to be expected as the modification mainly differs in the visible part. In the night scenario, their images show rather similar DC levels as they all exploit the same spectrum of the IR light source. We also notice that the IR-band RGB gives similar DC images in day and night (i.e. in daylight the DC is a bit more reddish), which indicates that its PPG-extraction performance in day and night is not expected to be very different.

Different illumination spectra imply different pulsatile signatures to be used for PPG extraction [9]. We pre-defined them for three camera configurations based on the video recordings (stationary phase). The pulsatile signature is calculated as the (l_2-norm) normalized vector of AC/DC amplitudes of the 3-channel signals within the heart-rate band (0.6-3.0 Hz), representing relative pulsatile amplitudes between different wavelengths. If the contrast of this signature is large (less flat, more deviating from the $\mathbf{1}$-direction), it means easier separation with distortions like motion [5], i.e. motion-induced intensity changes are typically in $\mathbf{1}$-direction. Fig. 3 shows averaged pulsatile signatures of three cameras. It is obvious that long-pass and full-band RGB have steeper signatures (with G>B>R) than IR-band RGB in the daylight. Full-band RGB has less spread (i.e. inter-subject variation) than long-pass RGB, suggesting the full-band measurement may be more stable. In the night scenario, the three configurations show very similar and flat signatures (where on average B>G>R), which is in line with the observations on the DC-images. The signatures obtained by the IR-band RGB in day and night have slight variations but the direction remains the same. Based on this analysis, we expect the performance of long-pass/full-band RGB to be significantly different from IR-band RGB in daylight but the three configurations should perform similar at night.

To extract the pulse signals and rates from the videos for data analysis, we use the processing chain of [6], which is essentially a combination of spatial redundancy strategy [10] and core algorithm of DIS [11] (DIScriminative signature-based camera-PPG). We chose this method because it demonstrated motion-robust PPG measurement in infrared [6], [7], [11]. The measured pulsatile signatures (see Fig. 3) are used in DIS for pulse extraction.

We used two evaluation metrics to quantify the camera measurements: Mean Absolute Error (MAE) between camera pulse rates and reference pulse rates, and measurement coverage (i.e. percentage of valid camera measurements that are within 5 bpm range w.r.t. the reference).

III. Results and Discussion

We will discuss the performance by the statistical overview provided in Table II, PPG spectrograms overlayed with the reference data (Fig. 4) and a plot of the PPG-rate estimates, the reference and the movement intensity (Fig. 5). The statistical analysis includes a split of data according to the categories (stationary, motion and overall) defined in the protocol.

In the day scenario, long-pass and full-band RGB clearly outperform IR-band RGB (see Table II). The largest improvement is in the motion phase where the measurement coverage of IR-band RGB (45.1%) is nearly doubled by long-pass and full-band RGB (88.6% and 95.1%). From Fig. 5 (a) we see that the measurements of long-pass and

TABLE II: Evaluation metrics for the three camera configurations during day and night. Their performance are analyzed in categories of stationary, motion and overall. Bold entries denote the best option per category (row) in each lighting condition.

Evaluation metric	Category	Day			Night		
		IR-band	Long-pass	Full-band	IR-band	Long-pass	Full-band
MAE (bpm)	Stationary	1.26	0.61	**0.54**	1.81	1.92	**1.70**
	Motion	12.23	2.22	**1.19**	**9.24**	9.49	9.69
	Overall	5.53	1.23	**0.79**	**5.24**	5.38	5.33
Coverage (%)	Stationary	94.3	97.8	**98.4**	92.9	92.6	**93.2**
	Motion	45.1	88.6	**95.1**	48.3	**48.6**	48.1
	Overall	75.1	94.3	**97.1**	72.3	72.5	**72.7**

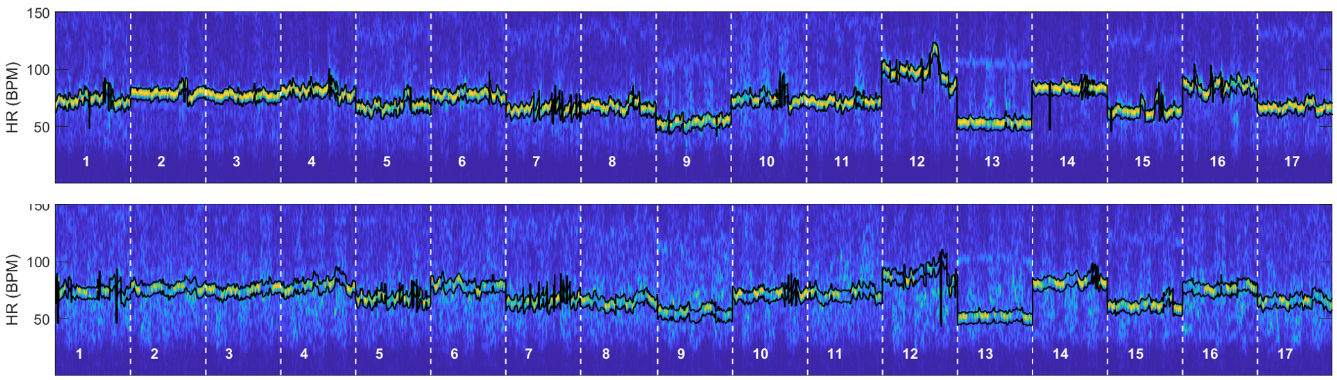

Fig. 4: Pulse spectrograms obtained by the full-band RGB camera from 17 subjects in the scenario of day (top row) and night (bottom row). Black line denotes the reference pulse-rate range ± 5 bpm.

full-band RGB are more consistent with the reference (i.e. much less outliers) as compared to that of IR-band RGB. This is due to the extra visible components (especially green) from daylight. Comparing the solutions of long-pass and full-band, we found that full-band RGB is slightly better for both the stationary and motion phases, suggesting that the blue wavelength contributes to motion-disturbance reduction. We suspect that this is caused by the fact that when turning the blue channel into an IR channel, it also modifies the spectral characteristics of specular variation direction (contrast to the diffuse reflection that includes pulsatile information), making it closer to the pulsatile signature direction that is more difficult to separate the specular and pulsatile components.

In the night scenario, all three cameras show rather similar performance in both the stationary and motion phases, i.e. the difference between their overall MAE and overall coverage are within 1 bpm and 1%, respectively. This is exactly what we expected: in full darkness, the spectral characteristics of camera configurations are fully determined by the active IR light source (phosphor LED), as all three cameras are sensitive to the spectrum of the IR light source. Their optical measurements, including DC-images (Fig. 2) and pulsatile signatures (Fig. 3), are very similar. Thus their PPG measurements will not deviate much. The qualitative comparison in Fig. 5 (b) suggests that three camera solutions perform equally well given the same IR light source in full darkness. Comparing the best candidate of full-band RGB in two lighting conditions, we confirm that its performance in daylight is still clearly better than in darkness (see Fig. 4), meaning that it is indeed valuable to extend its sensitivity to the visible spectrum in daylight conditions.

We summarize the results as follows: in the daylight, we favor the full-band RGB camera as it can profit from the visible spectra of daylight to further improve the motion robustness of measurement; in the night/darkness, three camera solutions do not show clear difference. Thus, considering the general performance over day and night (24/7), we recommend to use the full-band RGB camera. An extra benefit of full-band RGB camera is cost-effective as it does not need any band-cut filter as is the case for the other two camera solutions (with extra optics). The full-band configuration can be easily realized from almost any consumer-grade RGB camera: only the IR block filter needs to be removed.

IV. Conclusions

This study explored suitable camera configurations for long-term continuous pulse-rate monitoring during both day and night. The configurations are made by straightforward adaption of an RGB camera to different spectral ranges using optical filters. More specifically, we compared three camera configurations, i.e. IR-band, long-pass and full-band, in a benchmark on 17 test subjects performing large head movements in both daylight and darkness. The results indicate that for 24/7 continuous monitoring, it is best to deploy the full spectral band of an RGB camera, which significantly improves the daytime monitoring performance and this can be done without compromising the performance at night.

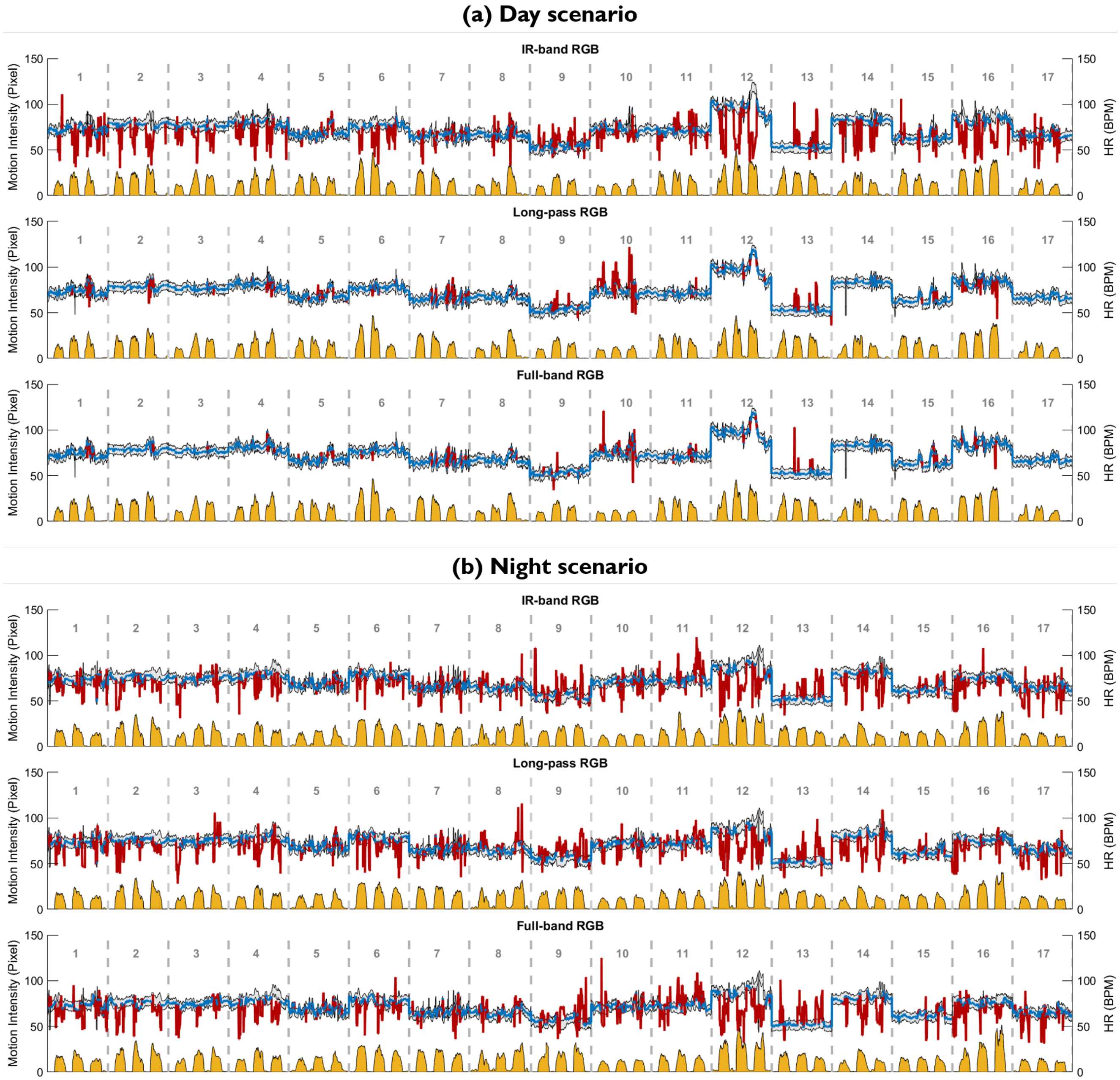

Fig. 5: Overview of camera pulse rates (outside reference±5 bpm are annotated as outliers), reference pulse rates and motion intensities of 17 subjects in the benchmark, in day and night separately. Yellow areas: motion intensity; gray lines: reference pulse rate ±5 bpm; blue line: camera pulse rate inside the range defined by reference; red: camera pulse rate outliers.

REFERENCES

[1] S. Rasche *et al.*, "Remote photoplethysmographic assessment of the peripheral circulation in critical care patients recovering from cardiac surgery," *Shock*, vol. 52, no. 2, pp. 174–182, 2019.

[2] S. Yeung *et al.*, "A computer vision system for deep learning-based detection of patient mobilization activities in the ICU," *NPJ Digital Medicine*, vol. 2, no. 1, pp. 1–5.

[3] J.-C. Cobos-Torres *et al.*, "Non-contact, simple neonatal monitoring by photoplethysmography," *Sensors*, vol. 18, no. 12, p. 4362, 2018.

[4] S. Leonhardt *et al.*, "Unobtrusive vital sign monitoring in automotive environments - a review," *Sensors*, vol. 18, no. 9, p. 3080, 2018.

[5] W. Wang *et al.*, "Algorithmic principles of remote PPG," *IEEE Trans. Biomed. Eng.*, vol. 64, no. 7, pp. 1479–1491, July 2017.

[6] W. Wang and A. C. den Brinker, "Modified RGB cameras for infrared remote-PPG," *IEEE Transactions on Biomedical Engineering*, vol. 67, no. 10, pp. 2893–2904, 2020.

[7] W. Wang, L. Vosters, and A. C. den Brinker, "Continuous-spectral infrared illuminator for camera-PPG in darkness," *Sensors*, vol. 20, no. 11, 2020.

[8] A. A. Kamshilin *et al.*, "A new look at the essence of the imaging photoplethysmography," *Scientific Reports*, vol. 5, p. 10494, 2015.

[9] G. de Haan and A. van Leest, "Improved motion robustness of remote-PPG by using the blood volume pulse signature," *Physiol. Meas.*, vol. 35, no. 9, pp. 1913–1922, Oct. 2014.

[10] W. Wang *et al.*, "Exploiting spatial redundancy of image sensor for motion robust rPPG," *IEEE Trans. Biomed. Eng.*, vol. 62, no. 2, pp. 415–425, Feb. 2015.

[11] W. Wang *et al.*, "Discriminative signatures for remote-PPG," *IEEE Trans. Biomed. Eng.*, vol. 67, no. 5, pp. 1462 – 1473, 2020.