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Development of a sleep disturbance protocol collecting simultaneous indoor and outdoor noise, motility and heart rate

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ABSTRACT

Within the Program for Innovation Procurement, the Flemish government is investing in innovative methods to answer numerous societal challenges. One project is focusing on noise and sleep and requests the development of a sleep monitoring protocol. This protocol will be rolled out in the Human Biomonitoring Program of the Flemish Government. In this manuscript we present an outline of the protocol. The main focus of the protocol is the user-friendliness and the use of non-invasive but accurate technology. It includes simultaneous indoor and outdoor noise monitoring to discriminate between indoor and outdoor noise (events) known to affect sleep quality. To detect potential arousals and awakenings, actimetry and heart rate are monitored on-body. At the start of a monitoring period, the subject completes a general questionnaire. After each monitored night (one week of data collection), a few questions on sleep quality are administered. The protocol goes beyond the current state-of-the-art by including multiple simultaneous physical components of relevance for sleep research: indoor noise, outdoor noise, body motility, heart rate and noise perception. The ambition is to roll out the protocol in the future in 300-400 subjects within the Flemish Human Biomonitoring Program (focusing on teenagers). Several chemical biomarkers are gathered by default in the Human Biomonitoring Program and the current sleep disturbance protocol will further enrich the existing data collection. The current paper reports on testing the protocol with 10-20 persons, showing that the sensor boxes can successfully be deployed without third party support using a simple set of instructions.

Keywords: Noise monitoring, Sleep, Actimetry, Noise annoyance, Heart rate, Protocol

INTRODUCTION

Historically, environmental noise evaluations in Flanders are performed within the overall environmental reporting MIRA, organized by a government organization managing water quality and air pollution. In 2019-2020, an extensive evaluation of the noise indicators in this environmental report was performed [2], and a trajectory was presented to improve the quality and sustainability of these long-term noise indicators. The implementation path is found in a program of the Flemish government aiming at investigating innovative methods to answer societal challenges (see https://www.innovatieveoverheidsopdrachten.be/en/projects, referred to as PIO).

This renewed momentum for noise exposure evaluation in Flanders resulted in an innovative PIO project called "Ambient noise in Flanders". The program started with a market consultation within the noise field and a preparatory stage listing potential projects, applications and general conditions for quality control. Two PIO projects are defined : (1) a sleep study protocol including indoor and outdoor measurements with on-body motility and (2) a population based noise exposure protocol based on citizen science approaches. This publication will focus on an ongoing sleep study protocol. Currently, the technical setup is in a final stage, but the conditions for the deployment of the protocol in an epidemiological study are not yet finalized.

The overall aim of this project is to monitor indoor and outdoor noise exposure in a real-life setting. In addition, a method has to be selected to evaluate the physical responses (arousals or awakenings) of the subject to disturbing outdoor events during sleep. The procedure has to be as simple as possible since it has to be performed by the subjects without local support of a technical crew. The second aim is the integration of the protocol into the existing human biomonitoring program of the Flemish Government (FLEHS) [1]. The fifth monitoring cycle will start in 2024. The main study population in this program are teenagers. The protocol is designed to match this preselected study population.

The PIO project partners are the Ghent University (UGent) and Provincial Institute of Hygiene (PIH). UGent is responsible for the technical components and PIH is responsible for the selection, communication and on-body monitoring of the subjects. PIH is the partner in the FLEHS projects responsible for this component in FLEHS since 2002, performing the surveys, bio-sampling and the administration of the cohorts.

The paper will describe the noise monitoring setup, the underlying data platform, the on-body actimetry, the subject instruction manual and a preliminary version of the post-processing method. The protocol will be illustrated with the first results from the first pilot, performed between January 16th and March 6th of 2023.

MATERIALS AND METHODS

Noise monitoring hardware

The goal of the noise monitoring is to collect simultaneous indoor and outdoor sound pressure levels. The noise monitoring unit is based on an open source development performed by Makerspace-Antwerpen with the project 'Klankentappers' by Imec [1]. The hardware components are a raspberry pi 3 and a MEMS (Infineon IM6D130). The software is available on github[2].

To provide simultaneous noise measurements and reduce the hardware cost, a wireless microphone is developed in the current project. The software from 'klankentappers' is extended to enable multi-microphone data acquisition. In addition, the software includes local file-based database storage of the measurements to allow 'on-edge' long-term indicator calculations. In the design process, the raspberry pi 3 and 4 proved to incapable for the task ahead. A different hardware platform namely Asus Tinkerboard S R2.0 – compatible with the Raspberry pi - was selected to improve functionality[3]. The Tinkerboard has native I^2S and is available with internal storage with higher read/write speeds and longer lifetime compared to the SD cards used in the Raspberry pi configuration.

The wireless microphone is equipped with a ESP32-WROOM-23E to connect over to a local WIFI access point provided by the indoor noise monitor (see Figure 2) . Matching software is developed in Arduino. The I^2S data stream is transmitted to the indoor unit and processed by the noise software running on the indoor unit. The design includes the option to use an analog microphone as well (ADC with I^2S output). This would allow replacing the MEMS microphone by more robust microphones [4] if the long-term durability of the MEMS would prove to be inadequate.

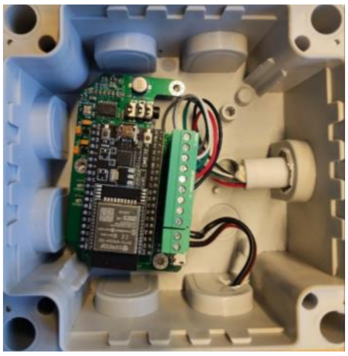

Figure 1: Wireless microphone (including two options - ADC or I^2S MEMS)

An additional feature of the Tinkerboard is the availability of an aluminum casing enabling efficient heat dissipation without including a fan, thus reducing the cost of boxing the measurement setup. A 3D printed housing is designed to mount the MEMS microphone (Figure 2 - left). No additional casing is required for the indoor

[1] https://www.imec.be/nl/articles/hackable-city-things-brengt-stadsgeluiden-kaart
[2] https://github.com/Makerspace-Antwerpen/klankentappers
[3] https://tinker-board.asus.com/product/tinker-board-s.html

unit. The outdoor unit is mounted with a similar 3D-print and is powered with a flexible cable (Figure 2 – right).

Figure 2: The indoor noise unit (left) and outdoor noise unit in an operational setting.

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Calibration and validation

The measurement accuracy of the noise monitors were tested in an anechoic room. The MEMS microphone is not accurate at both high (>10 kHz) and low frequencies (< 100Hz). A compensation filter is added in the noise processing software to accommodate for these deviations. The calibration value for each of the MEMS microphones is found by means of a ring test (see figure 3). The noise floor of the design is evaluated and results in typical values of 28 dBA (26 to 30 dBA).

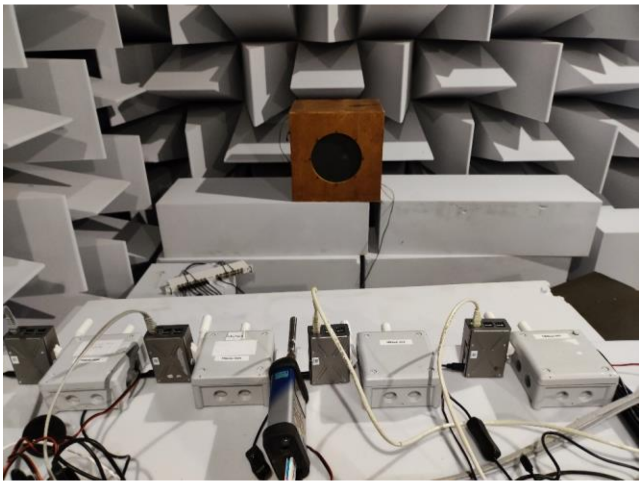

Figure 3: Ring test setup with four sets of indoor and outdoor units including type 1 reference unit.

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Actimetry

The physical impact of noise on human sleep will be assessed by ECG and accelerometry with the Bittium Faros[4] (formally known as eFaros) [3]. This device is easy to install, collects a full ECG, provides motion data though the accelerometer and measures heart rate variability. This device is commonly used in stress related research. In a recent review, the Faros was evaluated and compared with other commercial options. The quality of the ECG provided by the eFaros showed to be very high [53]. The internal clock of the eFaros is verified and proved to be accurate. When transferring the data, the clock is verified and synchronized with the computer. The eFaros data is stored as an '*.edf', i.e. European Data Format[5]. As a result, several open source processing options are available. Within this project, the python library 'hrvanalysis' is used[6],providing a large set of heart rate variability parameters and motility.

Noise surveys

Next to the physical exposure measurements, the subjects fill in a general noise related survey. This survey is aligned with the repeated questionnaires performed every five years by the Flemish Government over the whole region. This survey is also a fundamental component in the historical and revised noise indicator framework mentioned in the introduction [2]. In addition, the subjects get a short survey after each night. The survey is performed via an internet link. This operational choice fully aligns with the current practices in the FLEHS projects. During this pilot, the subjects also evaluate the protocol itself. The results were highly relevant to improve the instructions.

Data platform and workflow

The Flemish Government is currently activating a general purpose IoT data platform. One of the requirements of the project is to implement the data collection through the platform. The chosen technology is Thingsboard and the collected data is transferred to an underlying database for further reporting.

The noise monitor in the pilot setup is equipped with a network module (SIM-module) to provide network connectivity, to be replaced with a standard modem later on.

Both the ECG and motility data are graded as 'medical information' and are therefore only available at the PIH. The data flow is summarized below:

1. Noise measurement indoor is processed on the Tinkerboard, agent calculated a various set of indicators, including aggregations over 10 seconds and 15 minutes.
2. Noise measurement outdoor is transferred to the Tinkerboard over WIFI and processed in a similar way.

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[4] https://www.bittium.com/medical/bittium-faros
[5] https://en.wikipedia.org/wiki/European_Data_Format
[6] https://pypi.org/project/hrv-analysis/

3. The results are posted to the Thingsboard platform at the same rate of the aggregations. Every 10 seconds, the full dataset (third octave bands in 1/8 sec resolution) are uploaded to the Thingsboard platform. Each noise monitor has its matching dashboard. This dashboard is only used to verify the proper operation of the equipment.
4. PIH defines the measurement periods to match the equipment to the subject and provides this to the Thingsboard platform. This link uses a dummy identifier of the subjects to disable any link to the biomedical data. Only PIH can link measurement results to actual subjects.
5. The Thingsboard operators use the measurement periods to link the measurements to the dummy identifier of the subjects and provide the resulting exported files to PIH.
6. Automated processes merge the noise, ECG and motility data. In this first phase, the data alignment is performed at a 10 s and 15 minute resolution. The raw data stays available for detailed analysis when a full roll-out becomes available.
7. The 10 s and 15 minute data are aggregated to nightly indicators. The nightly indicators are aggregated to the subject level. Each of these dataset are aligned with the matching survey results.

Instructions manual

The success of implementing this protocol in a larger population is – apart from the technically robustness – the ease of use and the low support required to collect the data.

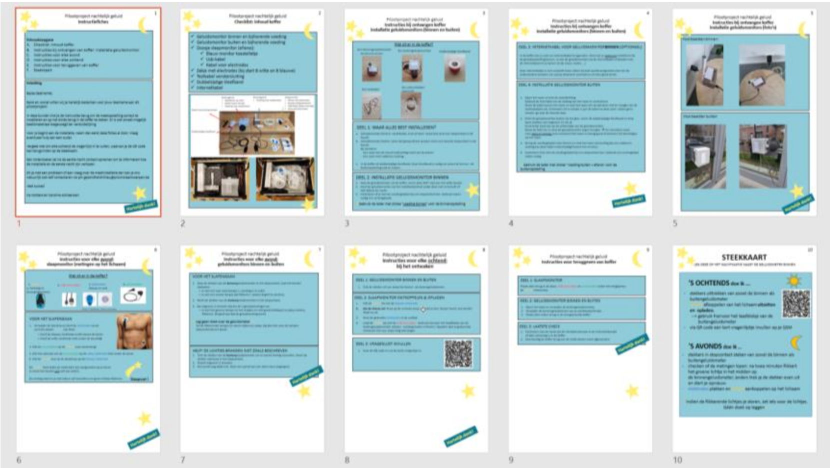

Figure 4: Instruction set for the study subject (developed for teenagers) (in Dutch)

The measurement box

The overview of hardware is presented in Figure 5. The picture shows, from left to right a test cable for the power supply of the outdoor box, mounting options and the outdoor unit itself; the indoor unit and communication hardware, the eFaros and consumables.

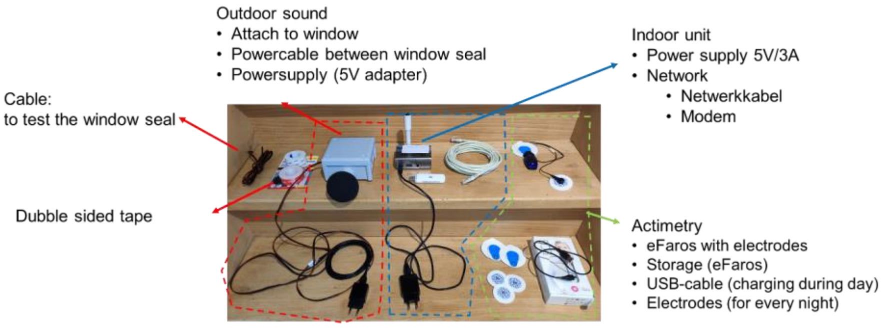

Figure 5: Overview of the hardware

The subjects receive this equipment in a measurement box (see Figure 6), including the instruction documents.

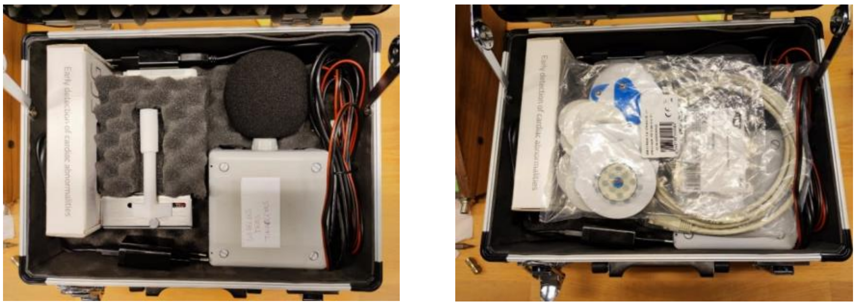

Figure 6: The measurement box: eFaros 90, Tinkerboard, wireless microphone), at the right the box including the consumables (electrodes, spare cables etc.).

RESULTS
Evaluation of the first pilot

The first pilot was performed without the online posting of the data to the Thingsboard platform but used local storage and manual uploads to a cloud service. Overall, it showed that most of the aims where reached. The subjects succeeded in installing the sensors and measuring the intended data. Most technical failures were hardware related (damaged cable of the outdoor unit, failed to start the eFaros, etc.). At the same time, the users reported some shortcomings. They asked for an on-line life check to verify if the equipment is working properly. Several people reported allergic skin reactions due to the electrodes. Adding a SIM-module and making the dashboards available for the subjects will solve most reported issues. The adaptations are implemented in the second pilot, planned in May 2023.

First quality check of the acquired data

The first analysis of the measured data shows the potential of the proposed protocol. In Figure 7, the $L_{Aeq,10sec}$, mean heart rate and mean acceleration are shown in their raw form. The main aim of the outdoor and indoor measurements is to be able to connect outdoor events to indoor events. Arousals or awakenings triggered by indoor events can then be evaluated separately. In this specific sample, the outdoor noise sources are local road traffic and a railway (at 30 m distance). Outdoor events can be easily visually linked to changes in both the heart rate and the motility. The heart rate reacts – as expected - more to the outdoor events than the motility, the latter showing a delay. This sample illustrates the quality and usefulness of the collected data for studying the effects of noise on human sleep.

Figure 7: Sample of the aligned data in the aggregated resolution of 10 seconds.

CONCLUSION

In this paper, a protocol is described for the deployment of a measurement campaign studying the effect of environmental noise on sleep in Flanders. The measurements go beyond the current state-of-the-art by including multiple bodily reactions potentially relevant for noise-induced sleep disturbance, and include measurements of both indoor and outdoor sound in the bedroom. For the latter, dedicated low-cost but still accurate equipment was developed, allowing for an easy installation by the test subjects themselves. This minimizes intervention cost for the government in case of a large scale deployment. The noise floor of the measurement chain was below 30 dBA making them suited for the planned measurement campaigns. Results from a first pilot at least suggest that heart rate and motility can be linked to noise events, giving confidence in both the technical developments and that the data gathered will be useful.

Acknowledgements

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