An approach for continuous sleep quality monitoring integrated in the SmartWork system

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***Abstract*—Sleep quality is an important factor highly impacting on quality of life, in particular in the case of older people who are still in the workforce and wish to remain professionally active, as it correlates to work efficiency and work ability. On one side, many self-reported sleep quality tools are used in the clinical practice, which are subject to the personal feelings of the individual about his/her sleep quality. On the other side, highly accurate and objective sleep assessment tools employed for diagnosis of sleep disorders are costly and can only be used for short periods of time in hospital setup. The aim of this paper is to present the SmartWork approach for continuous sleep quality assessment, which supports the triggering mechanisms for behavioral and lifestyle interventions in order to guide older people adopt healthier sleep habits and increase their sleep quality and satisfaction**

***Keywords*—Continuous sleep quality monitoring, self-reported sleep quality, wearable devices, work ability sustainability, older office workers**

I. Introduction

Good sleep is a health target difficult to achieve for many people and bad sleep can have many health implications and daily quality of life detriments that compound across months and years, reducing the quality of many aspects of health and life in various ways [1]. In the case of older adults who need less sleep and have shorter sleep schedules, any half-hour or hour reduction in sleep is larger in percentile sleep loss than for younger people. Past research has shown that sleep problems, especially in the case of older people can have very serious implications [2][3],beyond the feelings of tiredness, including chronic pathologic exhaustion and sleep disorders and potentially contributing to other health conditions (e.g. depression). Implications caused by bad sleep affect work efficiency, productivity or even work ability on the long term [4]. Not being able to work or succeed in work can produce even more implications for the emotional state and motivation of the person (e.g. stress, disappointment), creating a negative feedback loop on the quality of life and health of the individual [4] [5]. The interest of the research community in assessing sleep quality has been triggered long time now by the need of the medical practitioners to establish methods that can help in the diagnosis of sleep disorders, along with monitoring sleep quality in case of other chronic conditions, given the influence that sleep has on self-management a large number of other health conditions or it is being affected by such conditions (e.g. cough at night due to poor management of chronic respiratory conditions)[6][7]. Many self-reported sleep quality tools have been developed, among which the Pittsburgh Sleep Quality Index (PSQI) [8] is one of the most used, which however is limited to the subjective feelings of the individual. A large number of objective methods for assessing sleep quality are continuously being developed, being dedicated to in-hospital set-up in the case of sleep disorders (e.g. polysomnography) or to unobtrusive monitoring in-home set-ups using affordable wearable devices [9][10][11]. Among the most important parameters to be considered in the adoption of a certain approach are the comfort, the affordability and the unobtrusiveness [12]. For older people, it is also important to have an easy to use device and interface.

The work presented in this paper is being implemented in the context of the SmartWork project [13], which aims to provide sustainability of work ability in the case of older office workers, and give them a better chance in competing for jobs through improving their work performance and quality of life. There is a well-documented relation in the literature between sleep quality and work ability [14][15], demonstrating the correlation between bad health and work ability reduction, failure in the ability to acquire and sustain a steady job, perform well in demanding or even mundane tasks and in general be satisfied with the productivity of one's self. The aim of this paper is to present the on-going approach for continuous sleep quality assessment integrated in the SmartWork system, which supports the triggering mechanisms for behavioral and lifestyle interventions in order to guide older people adopt healthier sleep habits and increase their sleep quality and satisfaction.

II. Methods and Experimental Setup

A. The SmartWork System

The Worker-Centric AI System, built within the SmartWork project [13], integrates unobtrusive sensing and modelling of the worker state with a suite of novel services for context and worker-aware adaptive work support. The main user groups of the SmartWork system include the office workers, their employer (e.g. project manager) and their carers. The unobtrusive and pervasive monitoring of health, behaviour, cognitive and emotional status of the office worker enables the functional and cognitive decline risk assessment. The implementation of the SmartWork services integrates and shares on the various dimensions of the worker state aware work ability modelling, a series of transdisciplinary methods and technologies, to address the needs and requirements of the main user groups.

B. Background

The Pittsburgh Sleep Quality Index (PSQI) is one of the most used tests to assess sleep quality through a self-reported questionnaire [8] by the medical practitioners, which long-time now has demonstrated its value in comparison to other measures of sleep [16], as it can differentiate poor versus good sleep by considering seven domains, namely: subjective sleep quality, sleep latency, sleep duration, habitual sleep efficiency, sleep disturbances, use of sleep medication, and daytime dysfunction over the last month. However, its accuracy is influenced by a variety of factors and measures in a subjective way mainly the way the reporter feels about his sleep and not objectively the actual sleep quality. This has led to the development of many objective methods for assessing sleep quality, including costly methods dedicated to in-hospital set-up in the case of sleep disorders (e.g. polysomnography), or some less expensive dedicated to unobtrusive monitoring in-home set-ups in case of e-health applications requiring continuous assessment of sleep quality [17]. Important parameters to be considered in the adoption of a certain approach are the comfort, the affordability and the unobtrusiveness [12]. Wearable physiological monitoring devices, currently emerging on the markets, and reaching mass-usage (e.g. smart watches), allow for monitoring of sleep-related physiological signals over very long periods of time (months or even years) in an affordable and unobtrusive way.

Ear-ElectroEncephaloGraphy (EEG) has been recently investigated as a potential candidate for sleep quality monitoring in the home setup [12], its performance being assessed by comparing the manually scored hypnogram versus the predicted label based on the in-ear sensor data. In-home sleep and insomnia monitoring using radio signals is also an emerging approach, which monitors the user remotely by analyzing the radio signals that bounce off the user's body [18]. A large variety of consumer-grade sleep monitors for individual use has invaded the market, being mostly based on some smartwatch sensing solution and dedicated apps on smartphones [9][11]. Despite the popularity and the mass-usage of such devices, their full potential in supporting healthier lifestyles and improving quality of life on various domains (e.g. physical activity, sleep) has not been realized, due to the difficulty the user has to understand the provided sleep quality metrics (e.g. sleep stages), relate them to his/her own perceived sleep quality and understand which attitude/behaviour changes would result in a better sleep. An integrated approach, including both self-reported and quantitatively assessed sleep quality can improve the accuracy and information content of the assessment, and even predict potential problems (e.g. work efficiency) that might arise from the sleep patterns and behavior of a person.

C. Experimental set-up of the proposed approach

The design of the sleep quality assessment in SmartWork system (see Fig.1) is based on an approach integrating both self-reported PSQI and continuous sleep data collection using a smartwatch, and it is tailored around an asynchronous process that flags for start whenever new data are collected. This process is designed with scalability and optimization in mind, so that the server can manipulate big amounts of data without loss of efficiency. For the ubiquitous and continuous data collection we use commercially available smartwatch [11], from which we collect biometric data related to sleep, Heart Rate (HR) and physical activity. A preprocessing step is included in order to handle the potential unreliability of the device.

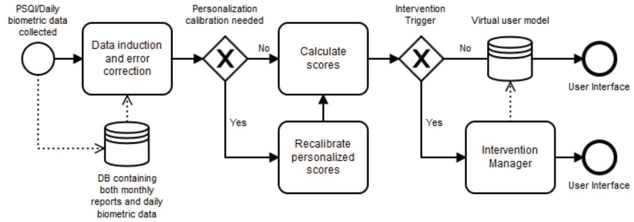

Fig. 1 Asynchronous process design for sleep data collection

D. User-perceived sleep quality

Sleep quality based on self-reported data is implemented in SmartWork project using the PSQI sleep assessment tool. In the questionnaire there are qualitative and quantitative questions about a user's sleep quality, which are then used as components to generate a general sleep quality score [8] (Global PSQI score). The index gives a score of 0 to 21, with 0 being the value for no sleep problems at all, while 5 or higher being a "poor" sleeper. This 0 to 21 score is the sum of 7 different 0 to 3 scores that are calculated by unique a formula of components for each one. The components and the scores (always ranging from 0 to 3, with 0 being best) calculated using the PSQI survey implemented as part of the user profile initialization interface in SmartWork are as follows:

PSQI_C1: Subjective sleep. This component is based on PSQI question #9 which directly links user's answers to a score from 0 to 3.

PSQI_C2: Sleep latency. This component is based on two questions of PSQI, namely, #2 and #5a. PSQI #2 is how many minutes it takes the user to fall asleep to which answer a discrete formula is applied to calculate the score (less than 15 score=0, between 16 and 30 score =1, between 31 and 60 score=2, more than 60 score=3). PSQI #5a refers to how often the user was unable to fall asleep within 30 minutes of lying in bed, quantified with 0 being not once in the past month (could always fall asleep within 30 minutes), 1 being less than once a week (had a hard time falling asleep), 2 being once or twice per week and 3 being three of more times a week. The final score for this component is the mean of the 2 questions, rounded up to the closest natural number.

PSQI_C3: Sleep duration. The user answers in how many hours of sleep he thinks he gets each night (PSQI #4) where 7 hours or more is score 0, 6-7 hours is score 1, 5-6 hours is score 2 and less than 5 hours is score 3.

PSQI_C4: Habitual sleep efficiency: This is calculated by using bedtime (PSQI #1) to wake time (PSQI #3) to calculate total hours in bed, then total hours of sleep (PSQI #4) to calculate total rest time. The percentile is:

$$\text{(hours of sleep)/(hours in bed)*100 \%} \qquad (2)$$

Then a discrete pattern is used to categorize the percentile into scores (>85% score=0, between 85% and 75% score =1, between 75% and 65% score =2, <65% score=3).

PSQI_C5: Sleep disturbance. This component is related to the number of sleep disturbances the user has during a week due to a number of factors (use the bathroom, feeling cold/hot, pain or bad dreams, not breathing well, cough/snore, waking up without a reason). Individual scores are assigned to each of the questions #5b to #55j, which are summed up to derive the final score for this component: 0 if sum of scores=0, 1 if sum of scores=1-9, 2 if sum of scores=10-18, 3 if sum of scores=19-27.

PSQI_C6: Use of sleep medication. The score for this component is obtained by assessing how often the user needs medication to fall asleep.

PSQI_C7: Daytime dysfunction. The user reports mid-day sleepiness (PSQI #7) and general enthusiasm about activities (PSQI #8). The score for this component is the mean score obtained from PSQI questions #7 and #8, rounded up to the closest natural number.

E. Automatic Sleep Scores Estimation

Sleep duration varies during the lifetime of a person, and it is highly influenced by the age group of the person. The implementation of guidance or intervention systems towards improving sleep quality are using internationally established recommendations, such as the Sleep Duration Recommendations established by the National Sleep Foundation [19]. In the case of SmartWork target end users (office workers aged between 50 and 65 years old) the expected normal sleep duration is between 7 to 9 hours, with 6 or 10 hours being also considered as acceptable. Sleep stages identified by the smartwatch are used to estimate daily the total hours of sleep and the actual hours of sleep, as well as the number and duration of sleep interruptions. Scores are assigned to the data gathered, in a similar approach as the one used by the user to self-report sleep quality using the PSQI tool.

Auto_C3: Daily sleep duration. For the computed daily sleep duration score, the recommended sleep duration is used as a ground truth [20]. The value comparisons are based on the recommendations for sleep duration by age group by medical professionals [20]. We define md as minutes deviation from recommended sleep duration for the age group to which the user belongs. The formula for scoring is similar to the calculation of PSQI_C3

```
md<=120 then score=md/60
md>120 then score=2+(md-120)/360
if score >3 then score=3
```

Auto_C4: Habitual sleep efficiency. (Auto_C4) For habitual sleep efficiency we define pr as percentile rest over time in bed. This formula is based on the PSQI_C4 formula though changed minimally to account for user misconceptions

```
pr>90% then score=0
pr>=60% and pr<=90% then score=3-(pr-60)/10
pr<60% then score=3
```

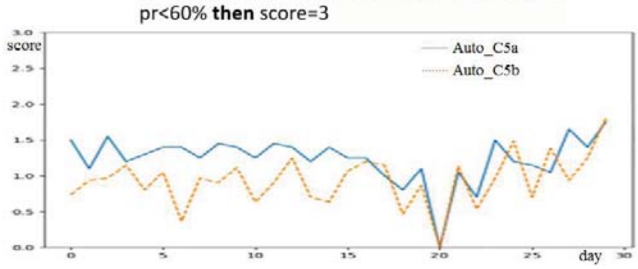

Fig. 2 Daily discrete interruptions (Auto_C5a) and total minutes of interruptions (Auto_C5b) over a month (June 2020) of monitoring

Auto_C5a: Daily sleep interruptions. (Auto_#5b in minutes) For sleep interruptions in minutes using the data collected by the smartwatch we define sim as minutes of sleep interruptions over nighttime rest. The formula is based on matching subject data to the score they reported that month (PSQI #5b) and may change with a bigger data sample and could be unique to each user. At the start matching exactly the PSQI #5b question we saw that the users severely under-report many minor or few major interruptions so the formula is changed linearly to align with user self-reports based on data comparisons.

```
sim<20 then score=0
sim>=20 and sim<40 then score=(sim-20)/20
sim>=40 then score=1+(sim-60)/60
if score>3 then score=3
```

Auto_C5b: Daily sleep interruptions. (Auto_#5b discrete) For absolute number of sleep interruptions using the data collected by the smartwatch we define si as the absolute number of sleep interruptions over nighttime rest. The formula is as Auto_C5a based on matching user-perception of sleep interruptions to results of automatically calculated based on his FitBit data.

```
si<10 then score=0
si>=10 and si<20 then score=(si-10)/10
si>=20 then score=1+(si-20)/20
if score>3 then score=3
```

Auto_C7: Daytime dysfunction. (Auto_C7) For out of bed, mid-day, sleepiness we define mds as the minutes of mid-day sleep events. These events are categorized as mid-day sleep events if they are small enough in duration and that are not categorized as actual secondary actual sleep in a day. The formula is based on aligning the daily data of users with the self-reports of users for question #7 (PSQI #7).

```
mds<=5 then score=mds/5
mds>5 and mds<=30 then score=1+(mds-5)/25
mds>30 then score=2+(mds-30)/30
if score>3 then score=3
```

Auto_C8: Daily Bedtime. There is no clear analogous in the PSQI for this score, thus we use the answers to question #1 (PSQI #1) for a "usual" time of reference. Regarding the time the user goes to bed (bedtime) we define bd as deviation in minutes from the usual bedtime of the user. The usual bedtime of a user is a composite mean of the last 5 days of sleeping with each day further from "today" counting less as a component.

```
bd<=240 then score=bd/120
bd>240 then score=2+(bd-240)/480
if score>3 then score=3
```

Auto_C1: Daily overall sleep quality. We calculate daily overall sleep quality as the mean score of Auto_C3, Auto_C4, Auto_C5, Auto_C7 and Auto_C8. We compare this component to the user's self-reported subjective sleep quality component of the PSQI (PSQI_C1) and not the Global PSQI score.

Automatically calculated monthly scores. The various scores calculated automatically on a daily basis are also used to derive the corresponding monthly scores, as mean values of the daily ones.

F. Test data set

The test data set is being collected from a group of volunteers, which although are office workers are not necessarily in the target age group (e.g. 50-65 years old). Data collection from this cohort is still on-going, with currently 4 users having collected data with the smartwatch for periods between 10 months and 5 years. However, only 1 of these users has also filled in the PSQI for a period of more than one year, and the data from this user is used in this exploratory study. This user is a female office worker, in the age group of 46-50, who has been diagnosed with mild asthma, allergic rhinitis and high cholesterol.

III. Results

Fig. 3 to Fig. 6 show automatically calculated sleep quality components in comparison to the PSQI components as self-reported by the user for duration of 13 months of data collection from one user. In Fig. 5 we can see the sleep interruption scoring, where when we take discrete number of interruptions the graph is a bit more normalized, more flattened which is less information content, where the one based on minutes of interruption has more variation.

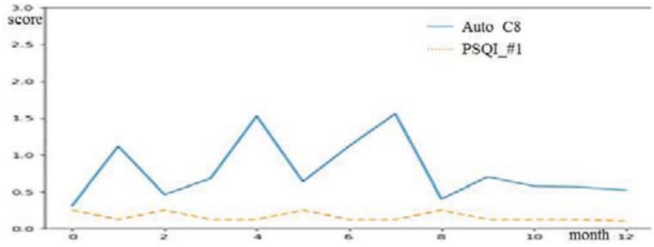

Fig. 3 Comparison of automatically calculated (Auto_C8) and self-reported (PSQI_#1) bedtime score for 13 months of 2019-2020.

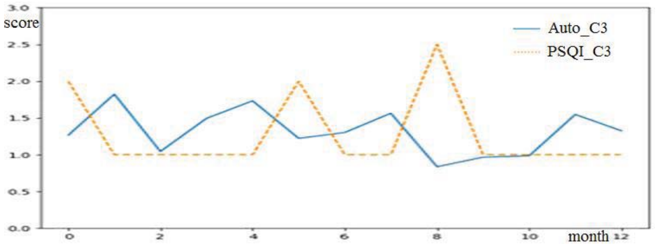

Fig. 4 Comparison of automatically calculated (Auto_C3) and self-reported (PSQI_C3) sleep duration score for 13 months of 2019-2020.

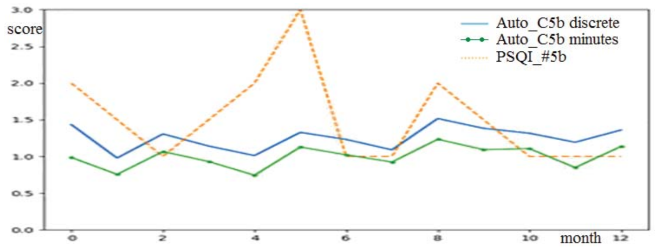

Fig 5 Comparison of monthly number (Auto_C5b discrete), minutes (Auto_C5b minutes) and self-reported (PSQI_#5b) sleep interruptions score for 13 months of 2019-2020.

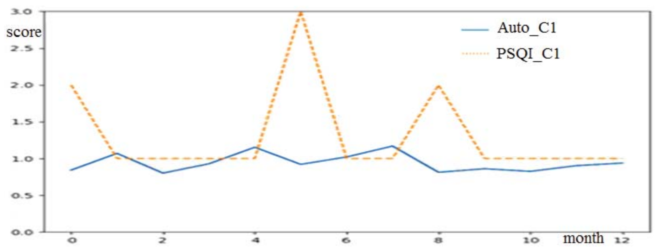

Fig. 6 Comparison of monthly automatically (Auto_C1) and self-reported (PSQI_C1) overall sleep score for 13 months of 2019-2020.

IV. Discussion and conclusion

An important limitation of the current analysis and results is inherited from the limited dataset used, as although collected over a long period of time, it is only from one user. The data collection is on-going, and the PSQI will be administered in parallel with the smartwatch-based data collection to all users participating in the research cohort, to validate and establish the value of our integrated approach. Additional data (e.g. number of steps and HR, chronic health condition status, self-reported contextual data, weather conditions) are considered in the further steps of this study to establish correlations between the individual scores and determine weighting factors for the total daily and monthly scores, in an attempt to personalize the interventions. The proposed approach for sleep quality assessment, through the comparison with the PSQI self-assessment of sleep quality, demonstrated that user's perception of sleep quality does not fully match the implemented objective quantification sleep quality, potentially due to the delay with which the user fills in the PSQI survey (e.g. the user is recalling best what happened during the last week) and due to the necessity to fine tune the reference values for the automatic scores calculation to each user (e.g. the recommended sleep duration). The results demonstrated an overall good correlation between the monthly automatically calculated scores and the self-reported sleep quality, thus the proposed approach providing a reliable quantitative method to assess sleep quality in the SmartWork system.

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