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A Tailored Internet of Things Lighting Solution to Support Circadian Rhythms and Wellbeing for People Living with Dementia

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Abstract: Light is a requirement for setting and maintaining the body's circadian rhythm, however our knowledge of the spectral content, timing and duration of lighting exposure for the indoors is not well defined. For people living with dementia, this knowledge gap is important to address since they experience more heavily disrupted circadian rhythms, which can heighten symptoms of sundowning, agitation, low mood and poor sleep quality. This paper focuses on the required design aspects for a dynamic lighting and sensing device tailored towards supporting the wellbeing of people living with dementia. The authors discuss the current understanding of lighting for health, identify the gaps to be addressed and propose the design and research protocol for an indoor lighting and sensing solution. The device is currently deployed within a care home and analysis of results is forthcoming.

1 INTRODUCTION

On a global scale, the ageing population is increasing at a rapid rate. Moreover, it is commonly reported that within these populations, the prevalence of dementia is more significant than in other age brackets (Livingston *et al.* 2020). This contributes to the fact that there are approximately 50 million people living with dementia at present, forecasted to more than triple by 2050.

The diagnosis itself is associated with certain behavioural and psychological symptoms which can contribute to decreased wellbeing (Finkel *et al.* 1997). Common of these symptoms are expressions of agitation and sundowning; the latter referring to the increase in neuropsychiatric symptoms which contribute to evening restlessness (Canevelli *et al.* 2016). As a result, this evening restlessness offsets the body's circadian rhythm; the 24-hour harmonic cycle responsible for many of the body's essential functions (Hastings *et al.* 2007). Of these essential functions, the circadian rhythm is dominantly responsible for controlling hormone balance (impacting mood), regulating the body temperature, regulating sleep-wake cycles, and influencing rest-activity patterns (Hastings *et al.* 2007). Therefore disproportionate influence over mood, agitation and sleep-wake cycles, as common in dementia, can put pressure on informal caregivers when looking after their close relations. This makes it more likely for admittance to care facilities (Fillit *et al.* 2021, Fishbein *et al.* 2021). As a result, it is estimated that the total cost of dementia to the global economy is $1 trillion (Livingston *et al.* 2020).

This combined social and economic strain of a dementia diagnosis can be attributed to the fact that to date there is no cure for dementia. Therefore, the best attempt to confront this challenge is to find optimal ways to alleviate symptoms in dementia. In turn, this will contribute to enhancing their wellbeing, and possibly reducing the rate of admissions to care facilities. A common solution to attenuating these symptoms is to use pharmaceuticals such as sedatives (ARUK, 2022). However, research has demonstrated that these solutions are indirectly targeting symptoms such as agitation and restless nights by prescribing a 'one size fits all' solution, and unnecessarily increasing drowsiness in favour of reduced agitation (ARUK, 2022). This can therefore lead to reduced wellbeing which counteracts any initial efforts made. In contrast, this paper focuses on devising a nonpharmaceutical solution to improve wellbeing for people living with dementia; the adoption of circadian lighting. This is ‘daylight-mimicking’ indoor lighting, designed to support the body’s circadian rhythm and positively impact activity metrics such as mood, agitation, sleep-wake cycles, hormone balance and social interactions. This paper represents a work in progress report which outlines the design of the technical architecture and summarizes the research protocol of the study.

2 OUTLINE OF OBJECTIVES

In order to address the research problem, several objectives have been formulated:

1. Design a novel digital health technology capable of both monitoring and improving wellbeing for people with dementia; consisting of circadian luminaires (actuators) and sensing devices.

2. Develop and evaluate algorithms acting on the raw sensor data, to produce relevant metrics on individual activity profiles, since this is expected to be impacted through the circadian lighting.

3. Deploy and evaluate the solution in a care home environment in order to observe the impacts of the lighting on activity for people living with dementia.

4. Make use of these observed changes in activity in order to better actuate/tailor the circadian lighting output to better align circadian rhythms.

5. Assess the impact to wellbeing/circadian rhythm through the sensor-generated activity profiles, from interviews and validated wellbeing questionnaires.

6. Assess the acceptability of the digital health solution for supporting wellbeing and circadian rhythms in dementia.

7. Generate a conclusion on the capacity for alleviation of symptoms of dementia and strain on care staff in order to remark on the initial research problem.

3 STATE OF THE ART

Circling briefly back to circadian rhythms, it is well established that the principle excitor for controlling this rhythm is light (Berson 2002). Due to consistent day/night intervals of light and dark, early human ancestors were subconsciously attuned to wake with the rising sun and sleep with the setting sun (Wright et al. 2013). This light/dark cycle has manifested itself into what is now known as the ‘typical’ circadian rhythm. This process occurs through receival of light signals in the retina, which prompts the brain to instantiate the controlled release of the hormones (melatonin and cortisol) that influence our mood, sleep-wake cycles and activity patterns mentioned earlier. Melatonin is known for inducing sleepiness and cortisol is known for inducing alertness (Sato et al. 2014). Therefore with a ‘typical’ circadian rhythm, these hormones are optimally balanced to lend itself to better sleep-wake cycles and fewer night time disturbances (Figueiro et al. 2020). However, with dementia, a more irregular rhythm means that these hormones are no longer synchronised with the circadian rhythm, and high levels of cortisol may dominate bed-times, creating a detrimental impact on sleep-wake cycles and mood. This contrast in typical and atypical circadian rhythms is demonstrated in Figure 1.

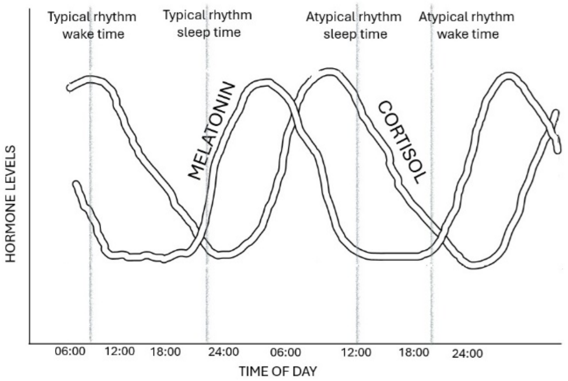

Figure 1: The difference between the hormone release of both typical and atypical circadian rhythms. Note how an irregular rhythm would result in poorer sleep/wake cycles (Sato *et al.* 2014).

Therefore exposing people living with dementia to circadian lighting is likely to alleviate their symptoms and improve their wellbeing. There are many studies which have conducted this type of research before, generating positive impact to wellbeing (Sust et al. 2012, van Lieushout-van Dal et al. 2019, Bromundt et al. 2019, Figueiro et al. 2020). However, common within this research area is the agreement on what is not yet known. This stems from the fact that the ‘typical’ circadian rhythm differs somewhat for every individual (Skeldon et al. 2017). An individual’s response to lighting will depend on many factors, such as age, chronotype, previous lighting exposures, gender, dementia type and state of progression, amongst others (Skeldon et al. 2017).

Therefore in order to provide a tailored lighting solution designed to optimise wellbeing for any individual, it is paramount to find a way to monitor the impact to both the circadian rhythm and wellbeing that the lighting is responsible for. It is also commonly reported that the parameters of the lighting for benefiting wellbeing are not fully understood. These parameters refer to the timings of lighting exposure, the duration of the exposure, the intensity of the lighting, and the colour temperature of the lighting (van Lieushout-van Dal et al. 2019, Brown et al. 2022).

As a result, this study has an initial focus on designing a novel technical architecture which can facilitate the collection of data which will help uncover these unknowns in the present literature. The overarching aim is that the architecture can generate the necessary health informatics to understand the circadian rhythm of each individual, while simultaneously actuating and monitoring the lighting output over time. Therefore along with the luminaire, the architecture makes use of an environmental sensing device designed to track the activity of an individual in an unobtrusive manner. This is essential within dementia cohorts since their vulnerable status makes enforcement of wearables unfeasible in the long-term (Harper et al. 2020). The sensor is capable of tracking the current location of an individual, their activity patterns, and their sleep-wake cycles. When initially trialling this technology, the added social wellbeing parameters such as mood and social interactions will be documented using the validated ‘QUALIDEM’ scale, to support the quantitative sensor data (Ettema, T.P. et al. 2007).

Lastly, this novel architecture will cater for the collection of lighting and circadian-related activity metrics in order to infer the relationship between them. The collection of demographic information through the mobile application will also help to draw any individual and group-based homogeneities to the lighting response. Once there is an accepted understanding of the circadian response to lighting over time, it becomes possible to make data-driven changes to the circadian lighting in order to best support any particular individual. This therefore creates a lighting/sensing feedback loop which outputs the optimal lighting based on the circadian health metrics of the individual. Due to the novel architecture, this feedback communication channel is built-in to the design; a concept not explored in this field to date. An outline of the main contributions to ‘state-of-the- art’ status are summarized in Table 1.

Table 1: Summary of the research problems and the devised solutions.

Research problem	Devised solution
No knowledge of exact timing, duration, intensity and colour temperature of lighting that individuals are exposed to (van Lieushout-van Dal *et al.* 2019, Brown *et al.* 2022).	The architecture supports networked luminaires and sensors with a scalable IoT design. Knowledge of an individual’s location and corresponding luminaire spectral output in relation to the height of an individual is possible. This is how we determine the lighting exposures throughout the day (Brown *et al. 2022*).
Vulnerable cohort status means collecting long-term data with wearables is difficult to implement and maintain (Harper *et al.* 2020).	Unobtrusive sensor design means that longitudinal data collection is possible. Mains connected device also removes burden associated with device recharge, calibration, and of becoming forgetful to use the device.
Limited knowledge of influence of dementia type and state of progression on lighting/circadian rhythms (Skeldon *et al.* 2017, van Lieushout-van Dal *et al.* 2019, Brown *et al.* 2022).	Long-term database collation with lighting/activity/ demographic information over time lends itself to pattern mining and new discoveries

The unique element of this research begins with the novel architecture. This data-driven feedback system allows for automated tailoring of circadian lighting based on an individual’s circadian-related activity over time. This design concept has not yet been developed for the research area of circadian rhythms.

In addition, the unobtrusive design (environmentally fixed) of the technology facilitates long-term data collection without the need for constant intervention to charge the device or re-calibrate it. This facilitates a better capacity for database growth. This enriched database with metrics on activity, mood, sleep-wake cycles, lighting exposures, and demographic information will therefore provide the fundamental building blocks to uncovering the largely unknown relationship between these above factors (Skeldon et al. 2017, van Lieushout-van Dal et al. 2019, Brown et al. 2022). This will therefore contribute to new knowledge in the field.

4 METHODOLOGY

The methodology focuses on trialling the lighting and sensing technologies within a care home over 16 weeks. This data collection will consist of validated wellbeing scales (QUALIDEM), interviews and sensor analytics in order to form an overall assessment of the circadian lighting for this cohort.

Therefore, conducting this research requires a real- life environment such as a care home to evaluate the digital health technology. This will take place in a care home in Belfast, Northern Ireland. This research proposal has undergone ethical review and been approved by the Office for Research Ethics Committees Northern Ireland (ORECNI). The initial project objective is to design and build the architecture. Preliminary work has been published on this by (Turley et al., 2021).

The unobtrusive digital health technology is deployed in a care home environment. The luminaires and sensors are in a mesh network where real-time sensor data is sent to a third party cloud server over a Bluetooth Low Energy (BLE) gateway. Luminaire output data is also transferred in this manner, but at a lower frequency (per 15 minutes). The processing, storage and application data are all managed from a local server. Real-time sensor data is filtered and transferred to an Influx database. At pre- defined intervals, the processing block will fetch data from this database and generate metrics to produce information on activity, sleep/wake cycles and location trajectories.

Again, at a specified time interval which is informed by known circadian rhythm adaptation times (van Lieushout-van Dal et al. 2019), the rule-based circadian logic will be invoked. This assesses if the circadian lighting is having a positive, negative, or null effect on wellbeing. Depending on the outcome, the lighting will remain as it is or be marginally tailored (in colour temperature and intensity). This occurs via REST API to the Bluetooth mesh network connecting the care home devices. It should be noted these lighting changes are informed by insights from the literature. For example, increased blue wavelength light during the day may alleviate disrupted sleep (Hanford et al. 2013), so if the sensor detects a resident who experiences frequent night-time disturbances, the blue component of the lighting may be increased during the day to try and help improve their sleep at night. This will be monitored over the next time interval and assessed for efficacy. As and when the circadian-related metrics are updated in Influx, they will be presented on a dashboard. This dashboard is integrated into an overall mobile application. This application then acts as an outlet which provides both client-side demographic information (stored separately) and the matching circadian-related metrics per individual. It will then act as a support to care staff when planning their daily or weekly routines. A summary of this architecture is seen in Figure 2.

As an aside, there is a preliminary ‘value-add’ feature of fall detection being trialled, which consumes real time sensor data and uses rule-based threshold techniques to determine if a fall has occurred, in order to alert the carer’s mobile application.

The participants will take part in 16 weeks of observation; 4 weeks of baseline measurements (static lighting output) preceding 12 weeks of a between-subjects experimental design. The experimental group will receive circadian lighting for 12 weeks and the control group will receive the existing lighting in the care home for 12 weeks. The circadian lighting will begin as a general profile, set in accordance with lighting parameters used in other literature using circadian lighting on these cohorts (Figueiro et al. 2020). It will gradually rise in intensity from early morning to afternoon and fall again by evening. The colour temperature will be cool from 09:00-14:30 to promote active days and gradually become warmer in the evenings to promote restful nights. Depending on the outcome of the circadian lighting logic outlined in Figure 2, the lighting will be tweaked according to the activity profile picked up by the sensor. Completion of QUALIDEM questionnaires will be required by care staff once a week, and short interviews with carers will be conducted four times throughout the study duration. At the end of the 16 weeks, individual and group analyses of the data will take place, in order to inform the relationship between circadian lighting, demographics, and activity profiles. A conclusive report supported by the data will then be shared with the care home team and researchers alike. This should state the demonstrated impact to wellbeing (if any), and outline future milestones for this research field. A flow schematic of the study protocol is summarized in Figure 3.

An overall assessment of wellbeing is deduced from combined analyses of qualitative (QUALIDEM/ interview originated) and quantitative (sensor originated) data.

A comparison of a week 4 (last control week for experimental group) to week 16 behaviour profile between those who have experienced static lighting and those who have experience circadian lighting will be conducted. Key indicators to explore will be the

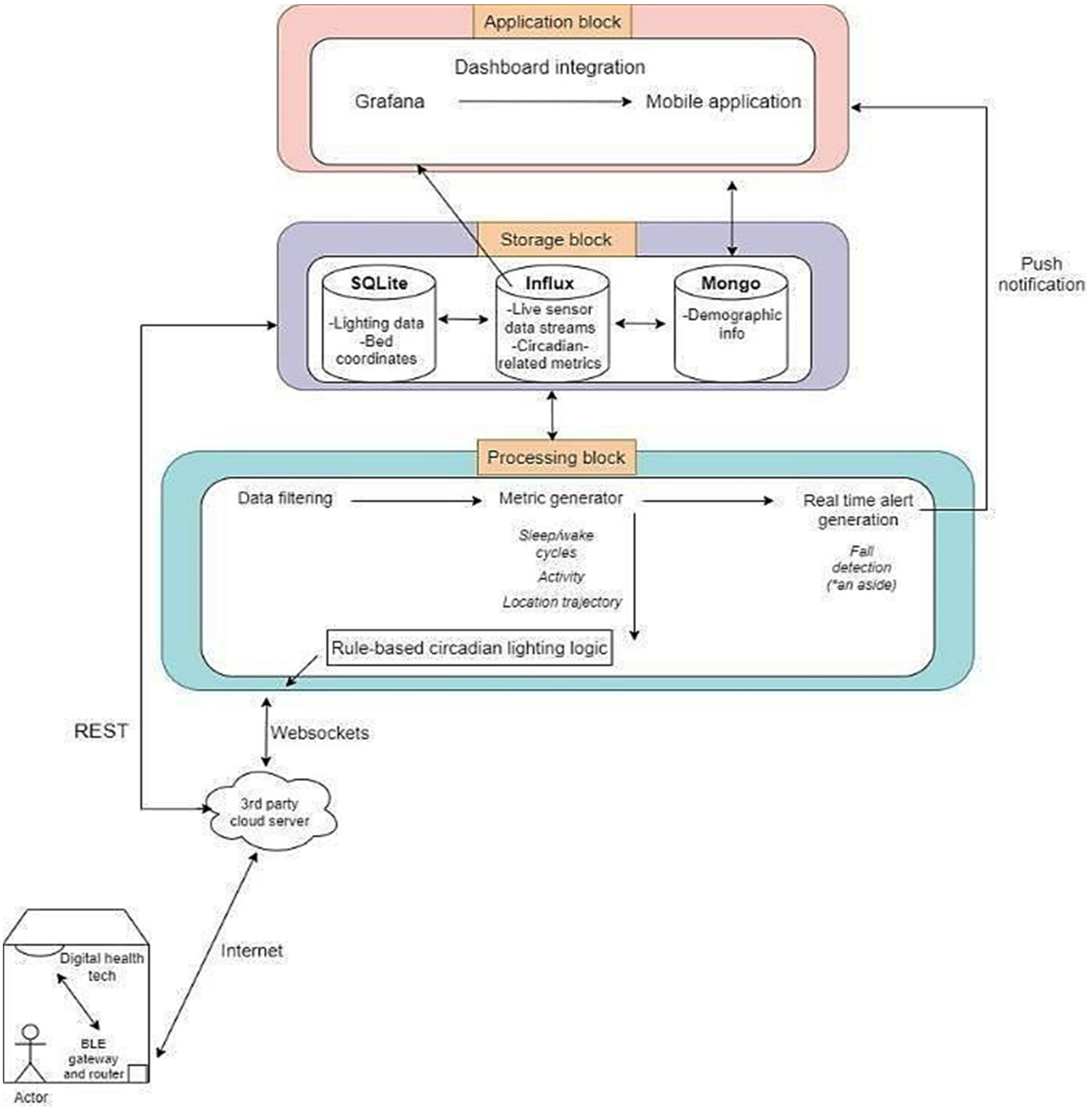

Figure 2: Overall IoT architecture of the digital health solution. Note that that processing, storage and application layers are all managed locally. Push-based actuation occurs both out to luminaires and to mobile application alerting panel.

frequency of night time disturbances, phase-advance or delay of sleep onset/wake times, duration of sleep, changes to mood and social interactions, amongst others. In unison, these wellbeing parameters will give an insight into the overall status or ‘wellbeing score’ at both the beginning and end of the study. In turn, this will give an insight into the initial efficacy of this digital health technology for its outlined purpose; supporting wellbeing for people living with dementia.

The acceptability of the digital health solution is supported by the fact that the research is conducted within a care facility environment. This makes it possible to access feedback from both people living with dementia making most use of the lighting, and also care staff making most use of the mobile application.

Feedback will be collected at multiple intervals throughout the study. This will be with people with dementia, care staff and family members/close relations. Subject areas such as perception of

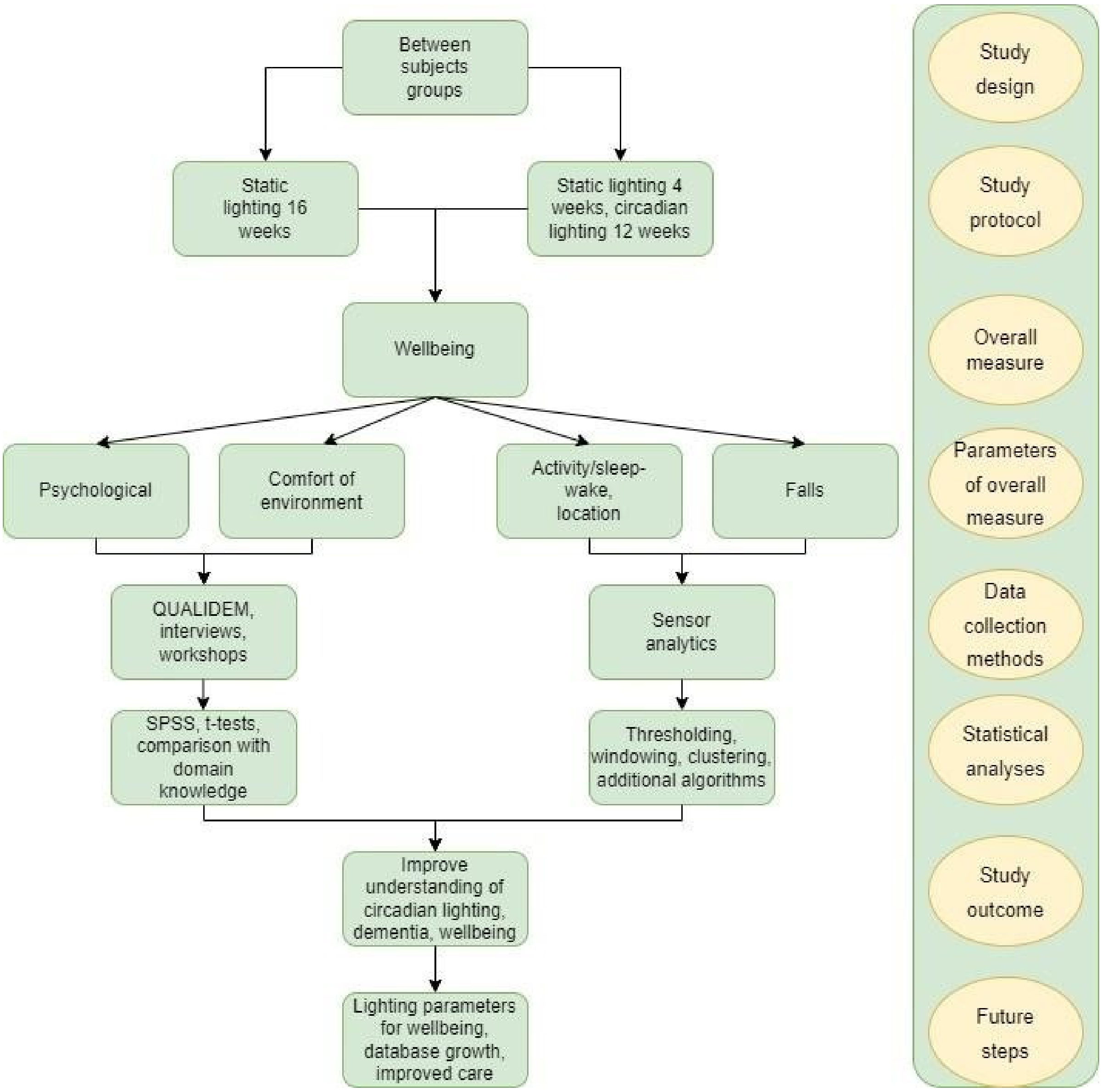

Figure 3: Flow schematic of the study protocol over a 16 week period. It highlights the study measures, collection techniques and expected outcomes.

circadian lighting, impacts to activity, overall consensus of circadian impact, acceptance of technology design and , and willingness to adopt this technology in the future will be presented.

For future work, any suggestions for improvement will be integrated as best as possible into the digital health solution and workshops arranged for re-evaluation purposes.

5 EXPECTED OUTCOMES

Care staff will be presented with an overall high-level dashboard which highlights the locations of the individual residents as labelled by room name. These type of metrics have been reported to be highly useful by care staff (Hall et al. 2017). This dashboard will have a link to another dashboard named ‘Resident overview’, which accumulates the finer-grain detail of the circadian metrics per individual room.

From accessing these health informatics for every individual, care staff can use this data to support their delivery of care. For example, care staff could look at the latest 'wake time' for all residents in order to determine when the breakfast can finish, in order to better plan schedules for the following week.

In terms of contribution to knowledge, the metrics outlined will be critical to understanding the progression of the individual circadian rhythm over time. When combined with the lighting exposure and demographic data also collected in the study, insight into the relationship between circadian rhythms, lighting and wellbeing will hopefully become more apparent.

In addition, the information and can provide insight into whether the circadian lighting is benefitting wellbeing overall in relation to the previous static lighting in place in the care home. As supported by current literature on circadian lighting on dementia cohorts (Sust et al. 2012, van Lieushout-van Dal et al. 2019, Bromundt et al. 2019, Figueiro et al. 2020), it is expected that the parameters of wellbeing impacted by the circadian rhythm will improve.

6 STAGE OF THE RESEARCH

This research has already received the necessary ethical approval, as referenced in section 4.

At present, the novel IoT architecture for the digital health solution has been designed and developed (Turley et al. 2021). Alongside the software, this includes the hardware; luminaires and sensors. The algorithms for deducing circadian-related metrics have also been developed. These algorithms are in the testing phases whereby ground truth metrics are being compared to the sensor processed metrics. The dashboard platform has also been set up and deployed on a local server.

The research is currently underway in the care home and results of the trial are expected to be analysed and published in the coming months.

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