A Review of the Potential of Smart Homes to Support Independent Living

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Between 2015 and 2050, the proportion of the world's population over 60 years of age is expected to nearly double, from 12% to 22%. Whilst hospitals offer care to people with health problems, support at home is generally limited to carers, a costly labour intensive method that impacts on the ability of many elderly patients to live independently. This pushes the demand for housing that caters for elderly people allowing them to remain in their homes but with some level of healthcare support. In the UK, the domestic sector currently accounts for around 30% of total energy consumption and contributes in the region of 27% of total carbon dioxide and greenhouse gas emissions. With an ageing population, offering healthy environments with a cushion against rising energy prices will be essential for people spending most of their time at home and often living on limited budgets. In this context, the drive to reduce energy consumption and associated greenhouse gas emissions from housing has acted as a catalyst in the increasing installation of meters and sensors for monitoring energy use and indoor environmental conditions in buildings. These monitoring technologies can track and record a range of parameters such as temperature, air quality, occupant behaviour etc. Many of these could be optimised to help create environments that assist people such as the elderly to live at home.

This paper aims to review relevant studies and technologies in the areas of smart, energy-efficient and lifetime homes, identifying some of the health needs of elderly people who could live at home if provided with adequate support, the range and type of technologies that could be employed to this objective, and suitable metrics to be used to measure the effectiveness of these technologies. The paper concludes that there is a limited evidence base on the health effects of energy-efficient homes, highlighting the need for more research and post occupancy evaluation using indoor environmental quality monitoring technology and wearable devices to analyse not only the energy performance of 'green' housing but also the possible effects of indoor environmental conditions on the subjective and objective wellbeing of occupants.

Keywords: assisted living, energy-efficient homes, smart homes, environmental monitoring

1. INTRODUCTION

In 2015, 11.6 million people were 65 years old or over in the UK, with 1.5 million people being aged 85 or over (Office for National Statistics, 2015). Over three quarters of a million people over 65 years-old need specially adapted accommodation because of a medical condition or disability, and 145,000 of them are reported to be living in homes that do not meet their needs (Department for Communities and Local Government, 2008). In 2007, around 420,000 frail older people were living in care homes or long-stay hospitals and the Government Actuary projects this number to rise to 1,200,000 by the time the older population peaks in 2071 (Baddley, 2012). Baddley also found that care homes in the UK account for at least 3.4 million tonnes of CO2e each year and £1.07billion in natural resource costs. This suggests that care homes are also not the solution to accommodate the ever growing population in need of care. The elderly and the sufferers of chronic diseases/disabilities, e.g. dementia and impaired mobility, may not be able to live independently in a regular home without healthcare support. In response to this there is an increased interest in how smart home technology could be used to provide the ageing population with smart, healthy and comfortable living environments, which offer the elderly healthcare support to remain at home (Chan et al., 2009). Smart homes use sensors and connected technologies to monitor, assess and control environments, which can improve indoor environmental conditions and reduce energy use.

Rising energy prices has led to a greater number of people experiencing fuel poverty, which affects 12% of households in England (NEA, 2015). Fuel poverty is proven to lead to decreased health, and many of those struggling to afford their energy bills are the elderly. The drive to reduce energy use and the associated carbon emissions has increased the demand for energy efficient homes.

Whilst good examples of smart, low-energy homes and assisted living schemes exist, these concepts have not been brought together fully despite the fact that many of their needs overlap. The aims of this paper are to: a) review existing examples of lifetime, smart and green homes; b) identify some of the health needs of elderly people; c) identify and summarize relevant wearable health monitoring technologies currently on the market; and d) discuss Indoor Environmental Quality (IEQ) metrics, which could be used to measure the effectiveness of these technologies.

2. LIFETIME, SMART AND GREEN HOMES

The ageing population, rising energy prices and climate change has increased the need for smart, low carbon, healthy, lifetime homes, which can adapt to the changing needs of people as they grow older. In the early 1990s, a group of housing experts, including Habinteg Housing Association and the Joseph Rowntree Foundation, developed the Lifetime Homes Standard. The Lifetime Home Standard incorporates 16 Design Criteria aimed to create flexible, accessible and inclusive homes, which support the changing needs of different occupants as they age and/or develop health conditions or disabilities (Lifetime Homes Standards, 2011). There are many examples of lifetime home developments such as the Darwin Court, the Consort Road, the Oxley Woods and the Library Street. In addition, the Barratt Green Home was also designed to respond to the need for lifetime homes to be zero carbon (Lifetime Homes Standards, 2011).

Smart homes are residences that are equipped with technology that facilitate monitoring of residents or promote independence and increase residents' quality of life (Demiris and Hensel, 2008). There are many examples of smart homes, such as PlaceLab (Intille et al., 2005), TigerPlace (Demiris et al., 2008), SPHERE (Woznowski et al., 2015) and the Creative Energy Homes. The Creative Energy Homes project is a seven-house development at the University of Nottingham providing a living, research test-site for different energy efficient technologies in housing such as micro-smart grids, energy storage, demand-side management and occupants' acceptance of innovative technologies. The houses are fitted with smart control technology, energy metering, environmental and occupant monitoring technologies to provide qualitative and quantitative data on environmental conditions, energy performance characteristics, micro-generation output and occupant behaviour (Gillott et al., 2010), (Rodrigues et al., 2016). These monitoring technologies can track and record a range of parameters such as temperature, air quality, occupancy behaviour, etc. The smart technology in particular is used for energy demand side management and to control environmental conditions, equipment and appliances. Many of these could be optimised to help create environments that assist people such as the elderly and the sufferers of chronic diseases/ disabilities to live at home by optimizing environmental conditions such as temperature, humidity, lighting, and air quality. Energy metering and environmental monitoring can help to identify inefficiencies, trends and changes. They can be used to improve systems through automation and regulation, e.g. heating, ventilation and air conditioning or lighting control (Genet and Schubert, 2011), which could be beneficial to the comfort and wellbeing of building's occupants and make homes 'smarter'.

There are several degrees of 'smartness' in homes as this can vary from devices actuated by presence (such as lights) to complex equipment and appliances controls. Smart homes can potentially monitor the behaviour and wellbeing of elderly and disabled people by wireless sensor technologies, and can control the appliances using a decision-making system, e.g. automatically turning off the TV or light for energy reduction, turning off the gas cooker for safety, and locking the door for security. They can include communication technologies to link people with family, friends and healthcare professionals, also allowing transmission of physiological data, e.g. weight, temperature, blood pressure, etc. Siegel and Dorner (2017) undertook a literature review of information technologies for active and assisted living and the impact they had on the quality of life of an ageing society. They concluded that these technologies can successfully contribute to bio-psycho-social dimensions of the elderly's quality of life, as they can empower people to control their health problems, compensate functional disabilities and increase their safety. There are many good examples of lifetime, smart and green homes, however these concepts have not been fully brought together even though many of their needs interconnect.

3. HEALTH NEEDS

In order to design a 'healthy' home, the health needs of the occupant must be understood. Most well-established green building certification systems, such as BREEAM in UK and LEED in US, include categories featuring credits on health and well-being (Altomonte and Schiavon, 2013). These include criteria such as daylighting, sound insulation, VOC's, inclusive design, ventilation and safety (BRE, 2014). In this context, the recently established WELL Standard is the world's first building standard focusing fully on human health and wellness. The WELL Building Standard sets performance requirements in seven categories related to occupant health in the built environment – air, water, nourishment, light, fitness, comfort and mind (International WELL Building Institute, 2016) – and aims to encourage the consideration of health needs in building design. The needs of people change as they grow older, this having an effect on their requirements from home environments. The following sections illustrate the most pressing requirements that a healthy home environment should address, in relation to physical, mental and social well-being.

Falls

As people age there is a reduction in muscle mass and strength and this is widely considered to be one of the major causes of disability in older people (Lauretani et al., 2003). Loss of mobility leads to falls, which are the second leading cause of accidental or unintentional injury deaths worldwide (Melillo et al., 2015). An estimated 424,000 individuals die from falls globally each year, with adults older than 65 suffering the greatest number of fatal falls (WHO, 2016). The BRE Trust published in 2010 the results of a research project that attempted to quantify the cost to the NHS of people living in poor housing in England. They used information from the English Housing Survey on the risk of a home incident occurring and its likely impact on health, measured through the Housing Health and Safety Rating System (HHSRS), combined with information from the NHS on treatment costs. The project concluded that excess cold and falls accounted for the largest number of hazards and, if addressed, would amount to the highest savings to the NHS (Nicol et al., 2010).

Heart problems

One of the most common health concerns for older adults is chronic heart failure, which is another significant causes of mortality, hospitalisation, and total healthcare-related cost (Cook et al., 2014).

Depression

The built environment has both direct and indirect effects on people's mental health (Evans, 2003). One of the most prevalent mental health problems is depression, which affects around 22% of men and 28% of women aged 65 years and over in the UK (Health and Social Care Information Centre, 2007). According to the (King's Fund, 2008), the cost of depression is projected to rise to £2 billion by 2026.

Dementia

It is estimated that there were 850,000 people living with dementia in the UK in 2014. By 2051, this number is projected to exceed 2 million (The Alzheimer's Society, 2014). Dementia affects cognitive ability, hence those with the condition may not be able to appropriately interact with their environments, and adjust their homes to take into account comfort levels nor indoor environmental quality (IEQ) factors. This may have an impact on their health.

Social Exclusion

Statistics show that 3.5 million people aged 65 and over in the UK live alone (Office for National Statistics, 2015a) and, according to studies by Age UK, over 1 million elderly people say they always or often feel lonely (Davidson and Rossall, 2014) in their homes.

4. WEARABLE HEALTH MONITORING TECHNOLOGIES

This review has shown that the ageing population have many different health needs such as dealing with falls, dementia, depression, heart problems and, social exclusion, etc. There are many wearable health monitoring technologies currently on the market, which could be used to address these issues. Some examples of wearable health monitoring equipment are shown Table 1, which offers a brief description of each product and the parameters they record.

Table 1: Examples of wearable health monitoring equipment compiled by the authors

Product	Description	Parameters
Apple Watch (Apple, 2017)	Water-proof fitness tracker, watch, mobile phone, heart rate monitor with built in GPS.	Heart rate, activity, GPS, mobile phone
Fitbit (2017)	Heart rate monitor with built in GPS, sleep tracking and sleep stages, call, text and calendar alerts, steps, various exercises tracker, 7 days battery, clock.	Heart rate, activity, sleep quality
Hexoskin (2017)	Biometric shirts have sensors woven into the fabric to measure heart rate, heart rate recovery , heart rate variability , breathing rate, VO2 max, minute ventilation, activity level, acceleration, calories, cadence, step count.	Heart rate, recovery, variability, breathing rate, VO_2 max
iHealth Rhythm (iHealth, 2017)	Smart connected one lead electrocardiogram, which can deliver 24 to 72 hour monitoring capable of detecting various heart issues. It can detect four types of arrhythmia and the recorder app can track what happens while wearing the device and users can also press a button to record activity when they sense something is wrong.	ECG
Lively Safety Watch (Lively, 2016)	Watch with emergency button. The watch operates like a daily planner and notification tool for the wearer with medication reminders and daily steps tracker. It comes bundled with a Home Hub for data transmission. Activity data is transmitted through a mobile app so that family members and friends can remotely monitor the wearer through the app, email or text messages.	Emergency button, activity
Spire Mindfulness and Activity Tracker (Spire, 2017)	A belt clip to capture breathing patterns reflecting our state of mind. It provides notifications about breathing patterns and has in-app breathing exercises and guided meditation sessions.	Stress levels, activity
Project Zero 2.0 Concept (Omron, 2017)	Wireless wrist blood pressure monitor with clinical accuracy, physical activity and sleep, and syncs with an Omron app to track and share vital data.	Blood Pressure
QardioCore (Qardio, 2017)	Wireless wearable EKG/ECG monitor, measures skin temperature, heart rate, heart rate variability, activity tracking, respiratory rate	EKG/ECG
Ringly rings and bracelets (Ringly, 2017)	Bracelets and rings which track steps, calories burned and connect via Bluetooth to mobile phones.	Activity
Zhor DigitSole shoes (Digitsole, 2017)	They measure steps taken and calories burned, charging wirelessly, and submitting data via Bluetooth to a compatible mobile app.	Activity

The design of watches can now incorporate fitness trackers which can monitor basic heart rate and sleep tracking (e.g. Fitbit), which aim to encourage more active and healthy lifestyles. Some watches (e.g. Apple) also include GPS technology, which can determine and track a person's precise location and could be used for those with dementia to give caregivers reduced anxiety when people get lost (Liu et al., 2017). Mobile phones can also reduce social exclusion by connecting people to friends and can connect people to emergency services. In order to tackle the problem of falls, Lively have designed watches which are connected to a 24/7 team of trained, live operators who aim to reach the user by phone before calling their emergency contacts and if needed, dispatching emergency services. As well as wrist-worn systems, there are also shoes (e.g. Zhor DIgitSole) and rings (e.g. Ringly), which can measure activity. Hexoskin have developed biometric shirts, which can measure heart rate, together with, heart rate recovery, heart rate and variability, breathing rate, VO_2 maximum oxygen use, minute ventilation, activity level, acceleration, calories, cadence, and step count. The Spire Mindfulness and Activity Tracker is the first wearable, which attempts to track stress levels through monitoring breathing and providing mindfulness exercises to track and improve mental health. The use of mindfulness techniques has been shown to reduce the effects of depression (Teasdale and Segal, 2007).

Wearable monitors can track data related to a person's specific health condition such as high blood pressure (e.g. Project Zero). People with heart conditions could use wireless wearable EKG/ ECG monitors (e.g. QuadioCore), which strap around the chest to provide continuous medical grade data to test for heart irregularities. Monitoring technologies can be connected to networks for data collection and profiling. One example of this is the Yecco system (Yecco, 2017), which offers a private social network for medical profiling, connecting patients to medical professionals and provides video consultations. They have medical devices such as blood pressure monitors, pulse oximeters, thermometers and weighing scales to measure vital statistics, which can be shared via its social app to chosen family, friends and clinicians.

Photonic textiles are currently under development. Optical fibres can be integrated into textiles for monitoring a range of physiological parameters such as blood flow, oxygen saturation and heart rate. These textiles can also be used to monitor humidity, temperature, ammonia and CO_2 levels. For people with diabetes socks are being developed that can monitor pressure and blood flow under the foot in order to prevent diabetic foot ulcers. Photonic textiles are also used for sensing wound dressings for healing and infection detection (Morgan, 2016).

As part of a smart home solution, the wearable can provide essential individual health information. The wearable monitor measures individual occupant health on a personal level, whereas smart home monitoring technologies measure not only energy use, but also IEQ, which can have an impact on human health. This will be discussed in the next section.

5. INDOOR ENVIRONMENTAL QUALITY METRICS

The increased use of meters and sensors for monitoring energy use and indoor environmental conditions in buildings has been driven by a number of key factors to: improve energy management and reduce energy consumption; improve energy efficiency; reduce greenhouse gas emissions; comply with regulations and legislations; and, save money (Ahmad et al., 2016). IEQ monitoring technologies can track and record a range of parameters such as temperature, humidity, noise levels, light levels and air quality. Research has shown that IEQ factors may have a number of health effects, as illustrated in Table 2.

Table 2: Indoor Environmental Quality Metrics and Possible Health Impacts References

	Measurement	References	Possible health impacts
Thermal			
Temperature	Temperature Sensor	Mercer (2003) Anderson et al. (2013) Muzet et al. (1983) Lloyd et al. (2008) Marmot Review Team (2011)	Winter morbidity Heat-related morbidity Sleep disturbance Blood pressure Circulatory diseases, respiratory problems and mental ill-health
Relative Humidity	Humidity Sensor	Fisk et al. (2007) Liddell and Guiney (2015)	Respiratory infections and allergies Mental health problems
Light			
Horizontal Illuminance	Daylight monitoring equipment	Boyce (2014)	Performance, productivity
Vertical Illuminance	Wearable	Andersen et al. (2013); Boyce (2014); Stevens et al. (2007); (Strong, 2014)	Effects on sleep, circadian efficacy, increased risk of cardiovascular disease and some types of cancer
Spectral Composition of Light	Daylight monitoring equipment	Lockley et al. (2003); van Hoof et al. (2009); Webb (2006)	Effects on sleep, circadian efficacy.
Noise			
DbA, LAeq,T	Sound level meter	Babisch et al. (2013); Brown et al. (2015); Hume et al. (2012); Ising and Kruppa (2004); Muzet (2007)	Sleep disturbance, cardiovascular effects, mental health problems
Frequencies	Audio measurement device	Baliatsas et al. (2016); Leventhall et al. (2003); van den Berg (2005)	Sleep disturbance, fatigue, headache, impaired concentration, physiological stress, annoyance
Air Quality			
PM2.5	Air Quality Sensors	Jerrett (2005); Pope et al. (2004)	Mortality, morbidity
PM10		Bell et al. (2009)	Mortality
VOCs		Dales et al. (2008); Mendell (2007)	Asthma, Respiratory problems, Sick Building Syndrome (SBS)
CO_2		Strøm-Tejsen et al. (2016) Schwarzberg (1993) Norback et al. (1995)	Sleep disturbance Headaches Respiratory problems
CO		Burr (1997)	CO poisoning
O_3		Kelly (2003), Weschler (2006)	COPD, asthma, morbidity, mortality
Ventilation rate	Calculation	Fisk et al. (2009) Sundell et al. (2011)	SBS Respiratory problems

The 2016 Velux Healthy Homes Barometer surveyed 14,000 Europeans in 14 countries identifying five key characteristics of a healthy home; comfortable indoor temperatures; appropriate levels of humidity; fresh air; good sleeping conditions; and, satisfactory levels of daylight (Velux, 2016). The following paragraphs list the main factors that should be monitored at home with the aim to achieve both energy-saving and healthy living.

5.1. Thermal Environment

The Fanger (1970) PMV model (Predicted Mean Vote) is the most commonly used model for evaluating general or whole-body thermal comfort. The PMV model relates to healthy adults and cannot, without corrections, be applied to older adults and the disabled (Van Hoof, 2008). The perception of thermal comfort in the ageing population has been studied widely, as various authors agree that older people are less likely to feel too hot or too cold in the higher or lower ambient temperatures due to their decreased thermoregulation, impaired peripheral nerves, or delayed vascular regulation (Maeda et al., 2005). Ageing makes people more vulnerable to fluctuations in ambient temperature, as thermal regulation is less efficient and metabolic rates fall (Day, 2015). Furthermore, the body's ability to regulate body temperature may also be affected by a variety of diseases and by medication used for the treatment of depression and sleep disorders, and by beta-blockers used in the treatment of cardiovascular disorders (Mercer, 2003).

Previous work has investigated some of the health implications of the thermal environment such as exacerbation of chronic obstructive pulmonary disease (Almagro et al., 2015), mental health problems (Liddell and Guiney, 2015), blood pressure (Lloyd et al., 2008), respiration problems (Strachan and Sanders, 1989), and effects on sleep (Muzet et al., 1983).The Marmot Review highlights the link between cold housing and circulatory diseases, respiratory problems and mental ill-health, and the exacerbation of common flu and cold and arthritis rheumatisms (Marmot Review Team, 2011). Studies have also shown the health effects of damp homes, which include respiratory (Fisk et al., 2007) and mental health problems (Liddell and Guiney, 2015).

The NHS suggests that homes should be at least at an internal temperature of 18^{o}C in winter for people with reduced mobility, those 65 years old or over, or those with a health condition such as heart or lung disease (NHS, 2016). In UK, on average around 24,000 deaths per year are attributable to excess cold (NICE, 2015). On the other end of the scale, excess heat has been shown by research to cause heat-related mortality (Anderson et al., 2013).

Light

Daylight impacts on human physiology and behaviour as it controls the circadian rhythm of hormone secretions and body temperature, and has implications for sleep/wake states, alertness, mood and behaviour (Webb, 2006). Circadian phase shifts in humans are most sensitive to short-wavelength light, which has been shown to be more effective than longer wavelengths in suppressing nocturnal melatonin and phase delaying the melatonin rhythm (Lockley et al., 2003). Studies have shown that illuminance levels, the spectral composition of light that people are exposed to, the timing and duration of exposure, together with previous lighting history, has an effect on sleep, circadian efficacy, insomnia, metabolic disorders, cardiovascular disease, diabetes and some types of cancer (Andersen et al. (2013); Boyce (2014); Stevens et al. (2007); (Strong, 2014)). However, there is still no consensus on the optimal daily pattern of light and dark exposures for good mental and physical health.

Noise

Levels of environmental noise (DbA, LAeq,T and frequency) can cause sleep disturbance (Muzet, 2007, Hume et al., 2012). Studies have shown that physiological functions may be affected due to prolonged exposure to high noise levels, such as metal health problems, increased blood pressure and cardiovascular effects (Babisch et al., 2013, Baliatsas et al., 2016, Ising and Kruppa, 2004, Brown et al., 2015). There is, however, a lack of studies that demonstrate a definite causal pathway that directly link noise and disturbed sleep with long term health outcomes.

Air Quality

Indoor Air Quality (IAQ) is assessed using measures of different pollutants such as PM 2.5, PM10, VOC's, CO_2, CO, and O_3. A number of studies have explored the possible links between the levels of different pollutants in indoor environments and mortality (Jerrett, 2005), (Pope et al., 2004), Sick Building Syndrome (Fisk et al., 2009) , sleep disturbance (Strøm-Tejsen et al., 2016), and different health issues such as respiratory problems (Sundell et al., 2011).

Nevertheless, Steinemann et al. (2017) argued that there is still insufficient understanding of the links between IAQ pollutant levels and their health effects, and also that different people are affected in different ways to the same pollutant exposure. They concluded that there is a lack of consistent metrics, standards, and consensus on what constitutes favourable IAQ, and that there is an absence of requirements to measure and monitor IAQ (Steinemann et al., 2017). In this context, Bone et al. (2010) questioned whether the drive for home energy efficiency would have a negative impact on the health of occupants especially in relation to reduced air quality due to increased home airtightness. Maidment et al. (2014) undertook a health meta-analysis on the impact of household energy efficiency measures on health, and highlighted a need for future studies in order to investigate the long-term health benefits of energy efficient housing interventions.

6. CONCLUSION

This paper has offered examples of smart, lifetime and green homes, illustrating a need for housing solutions that combine these ideas. The paper identified some of the key health needs of elderly people (e.g. the prevention of falls, reducing social exclusion and tackling rising health problems such as dementia, heart problems and depression) and offers a summary of different wearable and health monitoring technologies, which have been developed to measure different health factors, and parameters of personal comfort and wellbeing.

The authors believe that key metrics linked to thermal environment (e.g. temperature and humidity), light (horizontal and vertical Illuminance and the spectral composition of light), noise (DbA, LAeq,T and frequency) and air quality (PM 2.5, PM10, VOC's, CO_2, CO, and O_3) should be monitored in homes with the aim to achieve energy-saving and healthy living. Research has shown a number of possible links between different IEQ factors and health. However, there is still limited assessment of the effective health effects of short- and long-term exposure in indoor environments of living in energy-efficient homes. This is pushing the need for more research and post occupancy evaluation of not only the energy performance of homes, but also on the health of effects of green living, relating perceived and actual comprehensive measurements of several parameters of indoor environmental quality. Home monitoring needs to be supported by data collection at the personal level (i.e. wearable technologies) in order to link these two levels (the building and the occupant) for a proper assessment of energy efficiency and individual health and well-being.

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