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A field test of a simplified method of estimating circadian stimulus

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Residents of nursing homes often have a very limited access to natural daylight, which is the main environmental cue for circadian entrainment that usually cannot be compensated by standard indoor lighting. For the development of adequate modernization strategies with regard to a more human-centred lighting approach, reliable field measurements of the circadian effectiveness of the prevalent lighting conditions are required. To ease the task for the lighting practitioner, our lab recently developed a simplified method of estimating the biologically meaningful circadian stimulus (CS) metric using standard measurement equipment. In this work, the proposed method is applied for the first time in field measurements to assess the circadian effectiveness of the indoor light conditions including daylight entry of a nursing home in the Frankfurt Rhine-Main area. Reference thresholds for low, moderate and high circadian stimuli derived from the literature were used for subsequent data analysis. Mostly, moderate to rather low CS values were found. It is concluded that the amount of circadian-effective light is insufficient to provoke proper circadian stimulation, which may lead to progressive circadian disruptions manifesting in adverse effects on the residents' health and well-being. Further evidence is provided that the insufficient-lighting-situation in nursing homes is a serious problem in long-term care and needs urgent consideration in health policy.

1. Introduction

Persons with Alzheimer's disease and related dementias (ADRD) often suffer from severe functional disorders of their circadian sleep–wake rhythms, which, for example, manifests in form of excessive daytime sleepiness, nighttime restlessness, agitated behaviour, irritability, erratic mood swings and additionally reduced cognitive functioning.[1–3] When living in the institutionalized environment of a nursing home, their symptoms may further aggravate due to an increased physical inactivity compared to persons with dementia still living in their own households and, as a consequence thereof, an often insufficient exposure to natural daylight conditions.[4–6]

Natural daylight is the main environmental cue for the daily entrainment of the brain's master clock located in the suprachiasmatic nucleus (SCN) to the 24 h light–dark cycle caused by the earth's rotation to regulate and coordinate biological rhythms and metabolism in the human organism. A lack of exposure to a regular, daily light–dark pattern, usually caused by the absence of natural daylight in combination with insufficient artificial light conditions, thus leads to a desynchronization of the SCN, which basically results in a permanent jet lag compromising

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health and well-being in humans.[7] Disturbed circadian rhythms, sleep disorders and related dysfunctions are the consequences.

For the elderly, being exposed to insufficient lighting conditions is the rule rather than the exception.[2,4,5,8–10] In a review article summarizing the literature on sleep disturbances in nursing home settings, Neikrug and Ancoli-Israel[11] reported that 4% of institutionalized ADRD patients hardly ever experienced light levels of more than 500 lx. Bright light exposure above 1000 lx was in fact observed in 53% of the subjects, but only for a median of 10.5 minutes per day resulting in a reported median daytime light exposure of just 54 lx. In institutionalized settings, this lack of sufficient exposure to bright light is considered as one of the main causes of circadian disruption.[12]

Youngstedt *et al.*,[13] who investigated the relationship between the time spent at high levels of illumination and indicated sleep disturbances in a group of community-dwelling older adults with symptoms of depression, reported decreased illumination levels to be associated with increased night-time wakefulness and longer sleep-onset latency. Similarly, Sakurai and Sasaki,[14] who studied sleep–wake patterns in a group of community-dwelling elderly, found that almost half of the subjects that showed poor rhythms also experienced insufficient levels of light exposure.

In a nursing home study intended to compare sleep, circadian rest-activity behaviour and light exposure between residents with severe dementia and those showing only mild, moderate or no symptoms of dementia, Ancoli-Israel *et al.*[2] found that the former suffered from more blunted activity rhythms, showed an increased daytime sleep and spent significantly less time in bright light conditions than the latter. In addition, those individuals who had more light exposure during the day showed a less fragmented, more consolidated sleep at night. Based on these results in combination with previous data,[15,16] they have concluded that extreme sleep fragmentation, frequently observed in nursing home residents, may partly be due to low levels of daytime light-exposure.

In this context, light therapy to promote circadian entrainment has proven to be a promising non-pharmacological treatment method to consolidate sleep-activity patterns, attenuate cognitive deterioration and reduce depression and agitated behaviour in persons with ADRD living in long-term care facilities.[17–22] The effectiveness of such interventions, on the other hand, can be understood as an indicator of the poorness and inadequacy of existing lighting installations to appropriately stimulate the residents' circadian system during daytime.[23] Indeed, the greatest positive effects on sleep, mood and behaviour in persons with ADRD were observed in tailored-lighting intervention studies, in which all-day light conditions were optimized for a maximum stimulation of the circadian system[24–27] by using the circadian stimulus (CS) metric.[28]

Being based on fundamental reflections on human circadian phototransduction (i.e. how the retina converts light information into neural signals for the circadian system[28]), CS is considered as a biologically meaningful measure to evaluate the circadian effectiveness of a light source. Research in various fields of application, including lighting design for nursing homes and long-term care facilities, has shown that an exposure of at least 1 h to a CS of 0.3 or greater at eye level preferably in the morning hours may effectively stimulate the circadian system, eventually leading to better sleep as well as improved mood and behaviour.[24–27,29–31]

In the light of the ongoing COVID-19 pandemic, entailing strict lockdowns of nursing homes to protect their vulnerable residents from infections, and with regard to the discussed general lack of sufficiently bright light conditions in institutionalized settings, the urgent need for action to overcome the state of 'biological darkness' many of our beloved ones are living in is more pressuring than ever. This situation, of course, has not been caused by the Corona virus, but the latter certainly aggravates it as lockdown-induced restrictions on getting outside further limit the residents' chance to compensate their bright light deficiency with natural daylight. Adequate modernization strategies for a better and more human-centred indoor lighting in nursing homes are required and demand for reliable field measurements to assess and evaluate the current situation.

To ease this task for the lighting practitioner, Truong *et al.*[32] recently developed a simplified method to estimate the circadian effectiveness of the indoor light conditions in terms of CS using standard measurement equipment. The present study is the first to apply their proposed method in field measurements to report on the amount of circadian-effective light (including daylight entry) that is received indoors by the residents of a senior care facility in the Frankfurt Rhine-Main area. Based on the assessment of CS as a biologically meaningful quantity, this work adds further evidence to the findings of two recently published studies of Konis[23] and Kolberg *et al.*,[33] who both confirmed the general inadequacy of lighting conditions in nursing homes in terms of equivalent melanopic lux[34] and melanopic equivalent daylight illuminance,[35] respectively. Even without the pandemic, the insufficient-lighting-situation in nursing homes is a serious problem in long-term care that should urgently be addressed by national health policy.

2. Method

The following sections are intended to provide an overview on the measurement and data collection procedures adopted for this work. In particular, a brief discussion on the theoretical background of the CS quantity and its measurement using standard instrumentation will be given. In addition, the applied measurement protocol and data analysis procedure will be presented.

2.1 Estimation of the Circadian Stimulus

The hormone melatonin has proven to be an excellent biomarker to assess the spectral sensitivity of the human circadian system. In two independent studies conducted by Brainard *et al.*[36] and Thapan *et al.*,[37] nocturnal melatonin suppression in humans was shown to peak at 460 nm with an approximately 110 nm wide absorption band at half-maximum sensitivity. From these empirical data, it was clear that no single photoreceptor of the human retina, including the intrinsically photosensitive retinal ganglion cells (ipRGCs),[38,39] which constitute the main conduit of light signals to the SCN,[40–43] is capable of describing the observations made on circadian phototransduction. Instead, as stated by Rea and Figueiro,[28] all retinal photoreceptors must be taken into account as ipRGCs, even though being intrinsically photosensitive, also receive indirect light information from the rod and cone photoreceptors of the outer retina.[44] Thus, by explicitly considering the neuroanatomical, neurophysiological and operational characteristics of the human retina and brain, Rea *et al.*[28] developed the most complete model of the spectral sensitivity of the human circadian system based on the nocturnal melatonin suppression data. To characterize the circadian-effectiveness of an arbitrary light source, they further defined the CS metric, providing the functional relationship between the light source's model-weighted irradiance and the theoretically provoked melatonin suppression in percent.

Other popular metrics for assessing the non-visual effects of light, such as the α-opic quantities recommended by the CIE[35,45,46] or the equivalent melanopic lux[47] adopted for the WELL standard,[34] are basically tied to single receptor sensitivity functions. While this might be beneficial for certain aspects in the context of non-visual research, evaluating the contributions of each photoreceptor separately appears to be inconsistent with scientific evidence indicating that all three kinds of photoreceptors (i.e. rods, cones and ipRGCs) considerably contribute to human circadian phototransduction.[48,49] As a consequence, these single photopigment-based quantities have been concluded to be incapable of adequately describing compound effects of lighting in relation to circadian responses.[50]

The CS metric, on the contrary, features this consistency as it complies with the neuroanatomy and neurophysiology of the circadian system and explicitly considers the contributions of all photoreceptors.[28,51–55] Although it has not been sanctioned by any national or international lighting standard yet, the CS metric and its physiological relevance have been validated in many field studies.[24–27,29–31,56,57] In particular, it has been applied successfully for designing tailored lighting interventions to promote circadian entrainment and improve sleep and behaviour in persons with ADRD living in the institutionalized environment of a nursing home.[24,26,27] This previous field research provides evidence for the suitability and biologically meaningfulness of the CS metric to be used in the present work for assessing the circadian effectiveness of indoor light conditions with regard to the needs of the elderly.

Due to its complexity, the determination of CS in field measurements imposes a challenging task on the lighting practitioner as it usually requires a spectroradiometer or some other dedicated device,[58,59] both of which must be considered as being non-standard equipment. In two recent articles published by our lab, Truong *et al.*[32,60] therefore developed a family of computational approximation methods that can be used to calculate CS values from well-known photometric and colorimetric quantities that are easily available using standard instrumentation. The first method models CS as a function of photopic illuminance E_v in lux and the colorimetric 2° chromaticity coordinate z, both measured vertically at eye level, while the second method makes use of the correlated colour temperature (CCT) instead of the z coordinate. Although CCT is a widely used and standardized feature in lighting design and measurement, which was the main reason for developing the second approximation method, CS model predictions based on this quantity become significantly inaccurate for light sources ranging from 3220 K to 3710 K. Thus, the CCT-based approximation method should not be applied in this range.[60] Instead, the first method should be used which allows for predicting sufficiently accurate CS values for white light sources of arbitrary CCTs in an illuminance range of 10 lx to 10 000 lx. Compared to Rea *et al.*'s original model, a maximal prediction error of $|\Delta \mathrm{CS}|_{\max} = 0.058$ has been reported.[32]

As many of the subsequent measurements of the nursing home's indoor light conditions fall into the prohibited CCT range, the second method was disregarded, and only the first one was used to determine CS from standardized quantities. The corresponding model expression reads

$$\mathrm{CS}(z,E_v) = \begin{cases} 0.7 - \dfrac{0.7}{1 + 0.016781 \cdot \left(z \cdot E_v^{0.509265}\right)^{2.268904}} & \text{if } z > 0.195 \\ 0.7 - \dfrac{0.7}{1 + 0.011376 \cdot \left(z \cdot E_v\right)^{1.109998}} & \text{if } z \leq 0.195 \end{cases} \quad (1)$$

where the discontinuity at $z = 0.195$ represents an essential feature of the circadian phototransduction known as spectral opponency.[50,61,62] Depending on the blue versus yellow (b − y) opponent receptor signal, given by the difference between the S-cone response and the sum of the L- and M-cone responses (i.e. $V(\lambda)$), contributions from this b − y mechanism add to the response of the ipRGCs if the spectral power distribution (SPD) of the light source causes it to signal 'blue',[28] that is, for $b - y > 0$. However, no such contribution is added if the SPD causes the b − y mechanism to signal zero or 'yellow', that is, for $b - y \leq 0$. In this latter case, the spectral sensitivity of the circadian system is solely defined by the sensitivity of the ipRGCs. It should be noted that the previously discussed alternative models for assessing the non-visual characteristics of light fail to model this important feature of human circadian phototransduction.

For a better visualization of the opponency effect, Figure 1 illustrates the resulting behaviour for a Planckian radiator as a function of its CCT using equation (1) to estimate the corresponding CS values at three different vertical illuminance levels of 250 lx, 400 lx and 600 lx, respectively. As can be seen, the discontinuity at $z = 0.195$, which corresponds to a CCT of 3395 K, yields to a sudden drop of the circadian effectiveness of the Planckian radiator. As shown by Rea and Figueiro,[28] this is due to the fact that the spectral opponency translates to a subadditive component in the spectral sensitivity function where the accordingly weighted light spectrum subtracts from the overall response of the circadian system. At this swap point, it is even possible that higher illuminance values for slightly larger CCTs may result in a reduced CS compared to lower illuminance levels for slightly smaller CCTs. However, it should also be noted that CCT is not an accurate characterization of whether spectral opponency shows an effect or not. The drop in CS at 3395 K only holds for the Planckian radiator. For other light sources, specifically for those whose chromaticity coordinates are not lying on the Planckian locus, the swap points may occur at significantly different CCTs. Nonetheless, it is very important for the lighting practitioner to be aware of this pitfall when attempting to optimize light conditions for an enhanced circadian effectiveness. In this context, equation (1) provides an easy-to-use CS approximation method based on well-known quantities that can facilitate the circadian lighting design process accordingly.

Concerning the present work, a standard measurement protocol using a conventional photometer was eventually applied to conduct fast and accurate field measurements of the circadian effectiveness of the indoor light conditions in the nursing home environment based on the

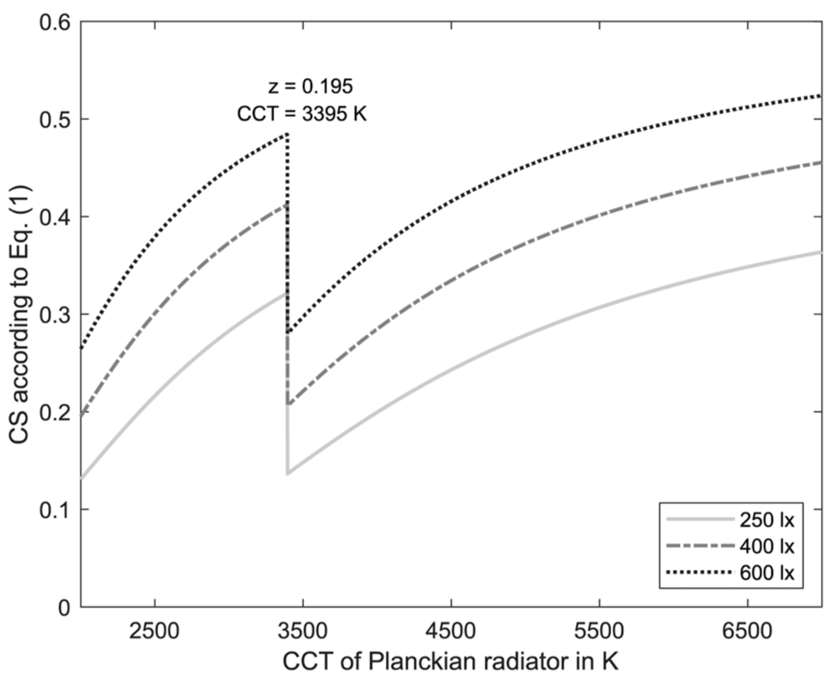

Figure 1. Circadian stimulus as a function of correlated colour temperature for the Planckian radiator calculated by using equation (1) at different vertical illuminance levels. The discontinuity at $z = 0.195$ representing the spectral opponency of human circadian phototransduction corresponds to a correlated colour temperature value of 3395 K

discussed approximation method. No additional spectral measurements have been performed. The reason for this was mainly twofold: (i) Due to rigorous lockdown regulations, the permit to stay in the nursing home to perform the data acquisition was extremely time-limited. It was therefore decided to capture only those quantities that were required for the application of equation (1) using a simple photometer approach that offered fast integration times without any additional time-consuming preparation steps. (ii) Apart from the lighting community, this work should also address healthcare policy stakeholders as well as the health and nursing management of long-term care facilities. Using inexpensive measurement equipment in combination with an easy-to-implement method of data acquisition may therefore provide a valuable tool for assessing and improving the actual lighting situations in nursing homes that can be applied easily in the field also by non-lighting practitioners.

2.2 Data Collection and Analysis

Data collection was performed during the COVID-19 December 2020 lockdown in Germany for a single nursing home in the Frankfurt Rhine-Main area. It was built in 2014 and comprises four structurally identical senior living communities on two floors (1st and 2nd floor). Each community consists of 10 private rooms for 10 residents and one large shared space that serves as the kitchen area and dining hall. Two of these communities – one on the 1st, the other on the 2nd floor – were selected as adequate examples to obtain a valid estimate of the nursing home's indoor light conditions. Measurements were performed on a sunny day (8 Dec. 2020) around noon (i.e. between 11 a.m. and 1 p.m.) to assess the circadian effectiveness experienced by the nursing home's residents under the assumption that natural daylight entry through windows maximally (relative to the time of the year) supplemented the artificial indoor lighting.

Figure 2 documents the visual conditions at the different measurement locations of the nursing home's 1st floor community. All test rooms including the common living area, the residents' rooms and the ensuite bathrooms were lit by the same type of fluorescent ceiling lamps (Lightnet GmbH, BX1ASER-122–40). Each of these non-dimmable, surface-mounted luminaires had a diameter of 40 cm and used microprismatic optics diffusers to achieve a homogeneously diffuse direct–indirect illumination, see Figure 2(a). For the direct component, they were equipped with an Osram FC 22 W/830-Warm White TR-5 fluorescent tube with a CCT of 3000 K, whereas an Osram FC 40 W/830-Warm White fluorescent tube of the same form factor and CCT but with a higher wattage was used for the indirect component. In the bathroom, an additional fluorescent-tube-based lamp was installed above the mirror, see Figure 2(c). An Osram HO 24 W/830 was used as the corresponding light source. The residents' bedside was equipped with an examination lamp, see Figure 2(b), that comprised a single E27 halogen light bulb. Besides these standard lighting installations that were defined by the nursing home's architecture and management, each resident was encouraged to bring their own floor and bedside lamps to their rooms, which resulted in a certain variety of each room's artificial light conditions, reflected in the corresponding CS measurement data.

With the exception of the bathrooms, which were painted in an orange colour, see Figure 2(c), most of the nursing home's walls and all ceilings were painted in a standard matte white. Accents of colour were only used in the common living area on the structure pillars and for some of the furniture, see Figure 2(a). The floors in the hallways and the common living area were made of medium-gray matte linoleum, while a brownish linoleum floor with wood optics was chosen for the residents' rooms. Dark-gray tiles covered the bathroom floors. The window areas in the different test rooms were relatively large and extended in all cases from the floor to the ceiling. The exact amount of daylight entry was not measured explicitly. It can be stated, though, that the nursing home's architecture complies

Figure 2. Image representations of the different test rooms of the nursing home selected for performing field measurements of the circadian effectiveness of their lighting conditions including daylight entry. (a) Common living area. (b) Resident's room. (c) Ensuite bathroom. ©Caritasverband Darmstadt e.V. (available in colour in online version)

with the ASR A3.4 guideline for workplace design,[63] which demands a daylight factor of at least 2% for the indoor environment.

Figure 3 shows the simplified floor plan and illustrates the different measurement locations and directions of measurement used for data acquisition. Note that the same measurement layout was applied on both floors. Some of the rooms were not accessible due to an acute COVID-19 infection of their residents. Nonetheless, with all the rooms being mostly identical, in particular with regard to their fixed lighting installations, the current data set is assumed to be a representative cross-section of the circadian effectiveness that can be expected to be encountered indoors by the residents of this specific nursing home.

With the permit to stay in the nursing home for non-medical purposes being very limited in time, the individual measurement locations and directions for the residents' rooms were chosen carefully with the intention of getting an average estimate (centre of the room) of the maximal (measurement direction pointing towards the windows) and minimal (measurement direction pointing towards the bed) values for the circadian effectiveness with as few measurements as possible. In addition, the residents' typical light exposure when staying in bed or using the bathroom should be assessed. Corresponding measurements were added accordingly. Following a similar argumentation, the minimum and maximum estimates for the common living area were complemented by measurements in the directions of view of the residents when having their meals.

For each measurement location and direction of measurement, photopic illuminance E_{v} and the chromaticity coordinate z were measured vertically at eye level using an HCT-99D handheld photometer (Gigahertz-Optik GmbH, Türkenfeld, Germany). The eye level for the measurements performed in the common living area and at the central locations of the residents' rooms was defined in relation to an average-sized elderly person with a height of 165 cm (approx. mean value of people at the age of eighty-two[64]) sitting in a wheel chair. For the bathroom measurements, the same dummy person was assumed, but this time in an upright position facing the mirror. The bedside measurements, on the other hand, should imitate the residents' view when lying in bed on their backs in a slightly erected position, for example, for watching TV or reading a book.

Curtains were opened and all lights were switched on. All measurements were performed

Figure 3. Illustration of the nursing home's floor plan and measurement layout. Measurement locations and directions of measurement are marked by solid dots and arrows, respectively. Existing lighting installations in the residents' rooms and the shared spaces are explicitly indicated by corresponding symbols explained in the legend. ©Caritasverband Darmstadt e.V. (available in colour in online version)

twice, and the data were subsequently averaged. Data analysis was then performed by using equation (1) to convert from photometric and colorimetric quantities to corresponding CS values. In order to evaluate the different light conditions in terms of their circadian effectiveness, the following reference thresholds were defined based on the literature[24–31,56]: For CS $\geq$ 0.3, which represents a large CS, positive effects on sleep quality, mood and behaviour are expected; for moderate stimuli with $0.15 < CS < 0.3$, neither positive nor severe negative effects are assumed; for CS $\leq$ 0.15, insufficient circadian stimulation must be concluded, which may eventually lead to progressive circadian disruptions and severe negative effects on well-being and behaviour. Results were categorized accordingly with a summary being given in the following section.

3. Results and Discussion

Table 1 summarizes the cross-sectional measurement results and CS calculations obtained for the measurement layout shown in Figure 3. In all cases, measurements pointing towards the windows (labeled with an 'a') show slightly larger z values and CCTs than obtained for the remaining measurements in the same room, which represents the daylight influence. Relatively small z values and CCTs, on the other hand, are observed for the measurements performed in the ensuite

Table 1. Cross-sectional measurement results and CS calculations obtained for the measurement layout shown in Figure 3 for the 1st and 2nd floor of the nursing home. Light grey (green in online version) and dark grey (red in online version) shaded table entries indicate high (CS ≥ 0.3) and low (CS ≤ 0.15) circadian stimuli, respectively, whereas non-shaded (non-coloured) CS entries represent moderate values (0.15 < CS < 0.3)

	1st floor				2nd floor			
	E_v in lux	CCT in K	*z* value	CS value	E_v in lux	CCT in K	*z* value	CS value
Room 1 a	248.6	4973	0.291	0.261	347.0	5345	0.306	0.348
Room 1 b	180.4	3784	0.216	0.121	133.9	3743	0.212	0.087
Room 1 c	245.1	3795	0.218	0.163	195.8	3784	0.215	0.130
Room 2 a	202.5	4131	0.246	0.170	284.0	5415	0.311	0.314
Room 2 b	116.7	3630	0.200	0.067	242.1	3833	0.222	0.167
Room 2 c	143.2	3735	0.216	0.097	215.1	3916	0.228	0.157
Room 2 d	201.1	2535	0.093	0.159	227.6	2713	0.118	0.213
Room 3 a	260.5	4551	0.268	0.241	318.5	5796	0.327	0.356
Room 3 b	269.7	3582	0.199	0.151	152.5	3916	0.227	0.113
Room 3 c	210.2	3619	0.202	0.123	209.6	4006	0.235	0.162
Room 4 a	269.6	4161	0.240	0.209	343.2	4836	0.281	0.311
Room 4 b	171.8	3597	0.200	0.100	148.6	3562	0.199	0.085
Room 4 c	179.4	3632	0.203	0.107	200.5	3679	0.205	0.122
Room 5 a	502.0	3838	0.227	0.303	525.7	4431	0.261	0.368
Room 5 b	355.7	3633	0.203	0.200	390.1	3702	0.205	0.219
Room 5 c	302.3	2883	0.144	0.299	411.1	3220	0.171	0.393
Room 5 d	341.7	3612	0.197	0.184	474.6	3795	0.214	0.270
Average	**247.1**	**3747**	**0.209**	**0.174**	**283.5**	**4100**	**0.231**	**0.224**

bathrooms on the first and second floor (labeled by 'room 2 d'), which, as can been seen from Figure 2(c), is caused by the impact of the light reflected from the orange-painted walls. Overall, the results clearly emphasize the low amount of circadian-effective light that is typically received indoors by the nursing home residents. In fact, even on a sunny day with all indoor light sources being additionally switched on, our measurements revealed that the resulting light conditions rarely exceed the threshold of 0.3 in CS to adequately stimulate the residents' circadian system during daytime.

As can be seen, a large CS is only achieved in 20% of the cases and is primarily limited to measurement locations on the 2nd floor close to windows with the measurement device pointing towards them. That is, a sufficient amount of circadian-effective light is only perceived by the 2nd floor's nursing home residents when standing or sitting near the windows with their gaze being oriented straight to the outside to benefit from the additional amount of natural daylight falling into the room. In most of the other cases, and in particular for the residents of the 1st floor, only moderate to rather low stimuli are observed.

The sample means ± standard deviations of CS values are 0.174 ± 0.071 for the 1st floor and 0.224 ± 0.106 for the 2nd floor, respectively. As these values were collected in such a way (curtains open; all lights turned on) that they represent a cross-sectional estimate for the maximum in circadian effectiveness (relative to the time of the year) of the light conditions experienced by the nursing home residents, an even lower effectiveness can be assumed under deviating preconditions, such as, for example, on a cloudy day or when the indoor light sources are switched on only partly. Thus, from the measurements reported here and the findings of Konis[23] and Kolberg *et al.*,[33] it seems clear that the light conditions typically found in nursing homes and senior care facilities rarely meet the requirements for good and healthy circadian lighting. Instead, the rather low amount of circadian effectiveness observed in all these studies is likely to result in a progressive disruption of the residents' circadian rhythms – a situation which is further exacerbated by the strict COVID-19 lockdown conditions as they massively limit the nursing home residents' access to natural daylight for compensation.

Of course, the present study provides only a pretty rough estimate of the true situation in terms of CS as it reports on cross-sectional measurements conducted in a single nursing home only that cannot necessarily be considered to be representative for all German long-term care facilities. However, as this specific nursing home was recently built and, thus, adheres to the latest architectural directives, standards and guidelines regarding the construction and design of living spaces for the elderly, there is no need to cast doubt on the significance of the present results. Indeed, it is expected that the insufficient-lighting-situation sketched as part of this work in terms of the physiologically relevant CS measure is even worse for older buildings, where the implementation of the latest or updated standards in architecture can be a very challenging and, sometimes, even an impossible task. It is therefore believed that, when taking into account all different kinds of nursing homes, the true extent of the problem is even bigger than indicated by the current numbers of Table 1. Nonetheless, further field measurements are still required and should be performed as part of future work.

For the development of adequate modernization strategies to introduce significantly enhanced and human-centred lighting concepts into long-term care, it will also be important to include the aspect of the duration of light exposure. Circadian effectiveness is not only a matter of intensity and spectral composition but also determined by the time spent under a certain illumination.[65] In the present case, it can, for example, be expected that the nursing home residents spend most of their day in the common living areas, where, compared to the lighting conditions in their private rooms, higher CS values were obtained on both floors. However, from the latest field studies of Figueiro *et al.*,[26,27] it can be concluded that a long-term, all-day light exposure with CS ≥ 0.3 is favorable to observe positive outcomes in persons with ADRD regarding the improvement of sleep quality as well as the reduction of depressive symptoms and agitated behaviour. Thus, it should be ensured that the weighted-average CS as obtained from the residents' temporal daytime light exposure profiles always exceeds this critical value. With regard to the present data, this might be the case for nursing home residents who spend most of their day in the 2nd floor's common living area, but only if the preconditions discussed above do not significantly change. On a cloudy day, for example, the circadian effectiveness will be reduced considerably so that, even when temporally weighted, the average CS cannot be expected to exceed the presumably required threshold value.

4. Conclusion

Good lighting is one of the most important, but least considered, design elements to create supportive environments for the elderly. Particularly in institutionalized settings, it is essential to maximize independence, quality of life, health, well-being and safety of their residents.[66] Normal age-related changes to vision as well as potential changes induced by progressing eye diseases must be addressed likewise in order to adequately compensate for sensory loss and increasing frailty.[67–69]

However, as discussed in the introduction of this paper, the lighting needs of older people are not limited to vision aspects only, but also include the biological effects of light on the human organism, such as the regulation of sleep or the stabilization of endocrine and metabolic circadian rhythms. Appropriate exposure to natural daylight has been shown to mediate entrainment and improve sleep quality in older adults leading to increased physical and social daytime activity.[70,71]

Unfortunately, in many institutionalized settings, the lack of appropriate lighting parameters and design in the built environment in conjunction with the current COVID-19 restrictions prevent most residents of nursing homes or senior care facilities to compensate their need for circadian-effective light. In this context, the present work is the first study that reports on field measurements in a long-term care setting adopting the recently developed CS approximation method of Truong *et al.*[32] to assess the circadian effectiveness of the indoor light conditions using a simple photometer approach. Corresponding measurements were limited to a single nursing home in the Frankfurt Rhine-Main area and revealed the inadequacy of the existing lighting installations to properly stimulate the residents' circadian system. In fact, mostly, moderate to rather low values of the biologically meaningful CS metric were found although the building itself adheres to the latest construction and design standards.

The present results comply with those reported by Konis[23] and Kolberg *et al.*,[33] who both confirmed that the light conditions typically found in nursing homes and senior care facilities rarely meet the requirements for good and healthy circadian lighting. Instead, the rather low amount of circadian effectiveness observed in all these studies is likely to result in a progressive disruption of the residents' circadian rhythms that may lead to severe negative effects on well-being and behaviour, especially when access to natural daylight for compensation is further restricted, like, for example, experienced during the COVID-19-provoked lockdown in Germany.

But even without the burden of a pandemic, many institutionalized people, ahead of all patients with ADRD living in long-term care, generally suffer from this insufficient-lighting-situation as they usually have only very limited access to natural daylight. Thus, the present data, supplementing previous findings, further emphasize the need for an improved lighting in institutionalized settings that does not only provide an optimal visual support but should also meet the non-visual requirements of the elderly. To determine the optimal lighting design parameters required to create such healthy and supportive long-term care environments, further evidence-based research is necessary and should be provided as part of ongoing work.

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