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# Exploring the influence of indoor environment and spatial layout on changed behaviours of people with dementia in a nursing home

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ABSTRACT

People with dementia sometimes show changed behaviours such as agitation, hallucination, and wandering during the moderate and severe dementia stages. In addition to individual health factors, contextual factors, such as indoor environment conditions, spatial layout, and human activities, may trigger or influence these behaviours, but there is a lack of solid evidence. We used mixed methods to collect data, including the fly-on-the-wall method to observe the residents' daily lives and deploying environmental sensors to monitor the indoor environments of two central living rooms and ten bedrooms in a nursing home in the Netherlands. A data collection campaign from August to September 2022 focused on the indoor environmental parameters, ventilation control of monitored rooms, the observation of ten participants' locations, activities, clothing levels, and changed behaviours. The data were analysed using Fisher's exact tests and heatmap analysis. The results show that even though the nursing home was well maintained according to existing indoor environmental quality standards, the room conditions of temperature, TVOC, and HCHO levels and contextual factors (main activity and numbers of people in the space) were significantly correlated with locations of changed behaviours. By analysing observation data with spatial layout, participants had larger activity ranges on the days that exhibited changed behaviours than those without. Most of these behaviours were observed at the edge of common spaces, where caregivers need to pay more attention.

## 1. Introduction

Dementia is characterised by 'a decline in cognitive faculties and the occurrence of behavioural abnormalities which interfere with an individual's activities of daily living' [1]. Following the dementia progression, people in advanced stages may have severe implications on their daily lives, such as extra demands regarding their indoor environment, as they are generally very sensitive to changes in indoor conditions [2]. However, due to the hallmarks of dementia (limited cognitive, sensory and verbal abilities), they are often unable to adjust according to discomfort situations and require substantial attention and assistance from caregivers [3,4]. In the Netherlands, an estimated 280,000 people have been diagnosed with dementia, of which 70,675 live in care facilities [5]. If designed or managed incorrectly, care facilities might be overheated in the summer, too dry in winter, air pollutants higher than outdoors, and light intensity lower than required by the standards [6–9]. Thus, controlling indoor environmental conditions is nonnegligible in dementia care for maintaining and improving the living quality of this target group.

The adult population spends 80%–90% of their day indoors. This percentage is likely even higher among nursing home residents, who have less independence [10]. Indoor environmental factors (e.g. surroundings that are too hot, cold, or loud) could contribute to behavioural and psychological symptoms of dementia (BPSD) [11]. BPSD include agitation, aberrant motor behaviour, anxiety, elation, irritability, depression, apathy, disinhibition, delusions, hallucinations, and sleep or appetite changes [12]. Existing studies have shown that more than 90% of people with dementia develop at least one BPSD, and more than half will exhibit two or more changed behaviours [13]. The frequent behavioural disturbances and related disorders reported are irritability (64%), tiredness (62%), depression (57%), rapid mood change (57%), anxiety (57%), threat of violence (54%), lack of initiative (44%), and inappropriate social behaviour (26%) [14]. An appropriate indoor environment could positively impact health, ameliorate dementia symptoms, and reduce behavioural changes [15,16]. The specific determinants of the changed behaviours remain unclear. Based on the triadic reciprocal causation model (person, behaviour, and environment) of Bandura's theory [17], besides personal factors of people with

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dementia, predisposing factors of changed behaviours may include physical and social environment characteristics [18]. Many medical and environmental science studies have explored the patterns of single behaviour in care facilities. For instance, agitation was originally defined as any inappropriate verbal, vocal or motor activity which, according to an outside observer, does not result directly from the needs or the confusion of the agitated person [13]. Screaming in people with dementia is often designated as 'agitation', which is related to the experience of vulnerability, suffering, and loss of meaning [19]. Wandering refers to 'seemingly aimless or disoriented ambulation throughout a facility, often with observable patterns such as lapping, pacing, or random ambulation' [20]. Hallucination is 'experiencing visual sensory perception without an external stimulus, seeing something others cannot' [21]. A growing number of studies concentrate on relationships between indoor environmental factors and the behaviours of people with dementia, using mixed methods and technologies for data collection (Table 1). However, there is still a lack of knowledge linking the indoor environment to contextual factors (e.g. building layout and management) and behavioural changes.

Existing studies on contextual factors of care facilities and the influences on residents' behaviours are usually from design perspectives. The spatial layout of public and individual rooms in care facilities has been validated as playing a crucial role in influencing residents' navigation ability and BPSD [33]. Early research revealed residents in group-living units with I-shaped corridors experienced a higher degree of dyspraxia, restlessness, lack of vitality, and loss of identity than residents in L-, H- or square-shaped units [33,34]. Nursing homes with long hallways can decrease residents' awareness, orientation, safety, and security [33,35]. The open kitchen/dining room design creates positive sensory stimulation and a supportive built environment, which may encourage residents to gather and influence their daily activities [36]. Transitional spaces between the bedroom and social area maintain the privacy of older adults' social behaviour [37]. The small-scale and homelike-designed special care units have positive effects on the behavioural and psychological symptoms of people with dementia [38]. These studies mainly focused on the impacts of building design and the wandering behaviour of people with dementia, such as spatial accessibility and frequency of wandering, standing, and socialising [39,40]. People with dementia could exhibit changed behaviours randomly in care facilities, but knowledge of where and how they are influenced by indoor environments is still missing [41]. Furthermore, only a few studies examined whether environmental interventions have benefits or make no difference in the prevalence of BPSD. There remains a dearth of high-quality evidence to conclusively guide the selection of any

**Table 1**
Recent studies on indoor environments and behaviours of residents living in care facilities.

| Author(s) | Year | Focus | Data collection method (tool) | Data analysis method | Findings |
|---|---|---|---|---|---|
| Liu et al. [22] | 2023 | Air-conditioning usage behaviour | Manufacturer monitoring database, Hobo data loggers | Clustering analysis | The inactive usage group with short-term and discrete air-conditioner operation would prefer a fast-cooling setting. The all-day usage group showed that the dynamic cooling demand may exist in older adults' long-term daily air-conditioner usage. |
| yoon Yi et al. [23] | 2022 | Applicability of existing thermal comfort models | Kestrel 3000, thermo-scan device (Model LF 40), micro-bolometer detector (model A-600 series), questionnaire survey | Logistic regression, independent-samples *t*-test, one-way ANOVA | Three approaches (PMV, Adaptive Comfort, and IRT) have limitations in accounting for the distribution of thermal sensations collected from people with dementia. |
| Zheng et al. [24] | 2022 | Dynamic thermal comfort demands | Questionnaire survey, temperature and humidity recorder (HOBO UX100-003), globe temperature recorder (HQZY-1), wind speed recorder (TESTO425) | Linear regression | Older adults in Xi'an were very active in adapting to the indoor thermal environment through behavioural adjustment and had higher acceptance and lower psychological expectations. |
| Yang et al. [25] | 2021 | Interior daylight environments | Questionnaire survey, TES-1337 digital illuminometer | RadianceIES module | Older adults have different expectations for sunlight illuminance of different functional spaces. |
| Zhan et al. [26] | 2021 | IEQ acceptance levels | Questionnaire survey, wireless sensor network | Multivariate logistic regression | Air temperature had the greatest impact on the overall IEQ acceptance, while visual environment and illuminance level had the least influence. |
| Bankole et al. [27] | 2020 | Early signs of agitation and environmental triggers | Sensors, questionnaire and interview | Assessment of distributions, variance or dispersion, and exploration of communality | A relationship has been validated between the presence of dementia-related agitation and environmental factors. |
| Leung et al. [28] | 2020 | IBE- Behaviour model | Dementia care mapping, questionnaire survey | Pearson correlation analysis, Multiple regression analysis, Structural equation modelling | Factors of the space management component have no impact on the behavioural symptoms of people with dementia; lighting, lifts and water supply influence demented residents' negative emotion, positive emotion, sleeping disturbance and limited mobility; loneliness is affected by the supporting facilities factor of furniture. |
| Jin et al. [29] | 2020 | Thermal and humidity comfort and skin condition | Questionnaire survey, Courage-Khazaka MPA-5 Central Multi-probe Unit with the Tewameter TM 300, Corneometer CM 825 | T-test and ANOVA | The Stratum Corneum Hydration showed a significant correlation with the indoor absolute humidity. |
| Thomas et al. [30] | 2020 | Acoustic performance and comfort | Sensor nodes, semi-structured interview, focus group | Thematic analysis | Acoustic interventions have direct positive outcomes and both positive and negative outcomes from perceived indirect effects. |
| Yu et al. [31] | 2020 | Thermal comfort | Wireless sensor networks | APMV model | Significant seasonal variations show in nursing home thermal environments, thermal comfort, thermal sensation and adaptive behaviours of older adults. |
| Tartarini et al. [32] | 2018 | Thermal perceptions, preferences and adaptive behaviours | Questionnaire survey, IEQ Cart | Linear regression (F-tests) | Residents were more tolerant of temperature variations and preferred higher temperatures than non-residents. |

Note: PMV-predicted mean vote; APMV-adaptive predicted mean vote; IRT-long wave infrared thermography; IEQ-indoor environmental quality; IBE-indoor building environment.

particular built environment intervention [42]. Thus, this study includes:

1) Collect the nursing home residents' information (e.g. dementia stage, illness, and symptoms).
2) Monitor the indoor environmental parameters and record contextual factors (e.g. daily routine of residents, building layout, and facility operation) in the nursing home that may influence changed behaviour occurrence;
3) Record the type, time, location, and surroundings information when the changed behaviour appears;
4) Analyse the data and explore the relevance of these factors on observed changed behaviours.

## 2. Research methods

### 2.1. Case study

The case study includes a small-scale care facility in the Netherlands that provides thirty-two single rooms for older people with dementia. The building has a concrete structure and double glazing to achieve the standardised insulation level of old-age care facilities. Each floor consists of sixteen bedrooms, two activity rooms, a central living room (with a kitchen), and a nurse station. A spacious green courtyard is on the ground floor, and two semi-opened terraces are on the first floor. The central living rooms are semi-opened spaces located at the junction of the L-shaped floor plan and connect to the courtyard or terraces (Fig. 1). Each central living room has a small kitchen, four dining tables, two sofas, some easy chairs, and a television. The elevator and staircase are near the entrance, but the staircase is normally closed for safety reasons. Bedrooms are orientated south or southeast. Each bedroom includes a private bathroom and is furnished with a single bed, cabinet, table, sofa, and television. Most furniture is against the walls to ensure the space for residents using wheelchairs and walkers. Residents can furnish their rooms with personal belongings. The ventilation is centrally controlled, and airflow in common spaces is higher than in bedrooms. The floor heating system supplies hot water during the heating season or cold water to cool down the indoor temperature in summer. The setting temperature for indoor spaces is 23 °C (4 a.m.–6 p.m.) and 22 °C (6 p.m.–4 a.m.) throughout the year.

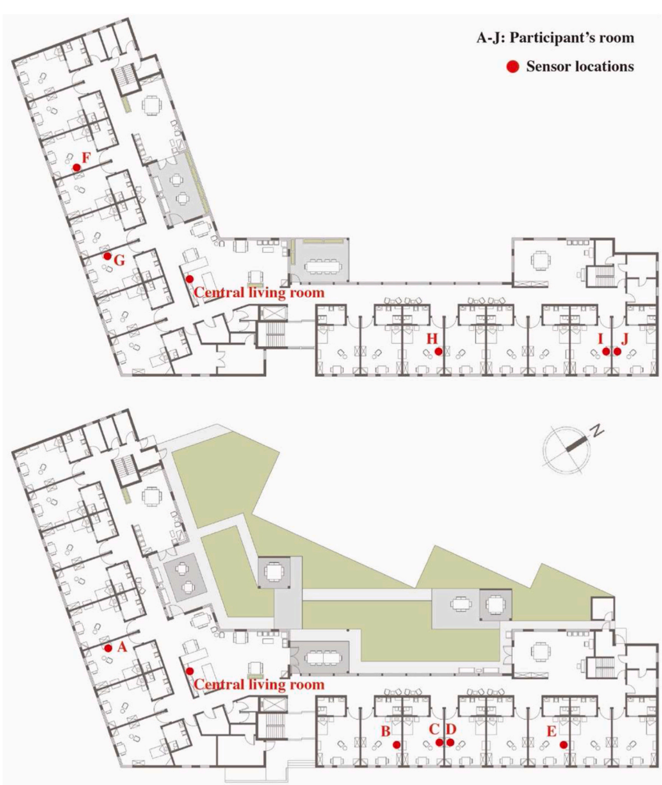


**Fig. 1.** Sensor locations in the case study.

### 2.2. Research participants

Ten participants voluntarily participated in this research through an ethically approved recruitment process. Five participants lived on the ground floor, and the other five lived on the first floor. Their dementia stages have been assessed according to the Clinical Dementia Rating (CDR) shown in Table 2 [43]. All residents kept regular routines in the nursing home, which were not influenced by the study. Researchers collected observation data at a distance from the residents without interfering with their daily activities. Due to residents' ages and dementia stages, they had various degrees of hearing, reading and writing difficulty. All the residents in the nursing home and their guardians were informed of the research background, methods and objectives. The consent forms were signed and returned by participants or their families.

### 2.3. Research procedure

Indoor environmental data was continuously monitored by sensors from August to October 2022, and the observation data collection was carried out for fourteen days within the monitoring campaign. The design of this study and the use of sensors referenced the methods of the studies in Table 1. Twelve sensors were deployed in ten participants' bedrooms and two central living rooms (red dots in Fig. 1). Sensors in bedrooms were installed 0.8–1 m high (the breathing height of sedentary or bedridden people) in their activity zone. The installation height in the central living rooms was 2 m (on the cabinets), and sensor locations were near the kitchen to measure air quality variations during cooking times. Table 3 shows the specifications of sensors, including air temperature, relative humidity, $CO_2$, the total volatile organic compound (TVOC), formaldehyde (HCHO), and particulate matter ($PM_{2.5}$ and $PM_{10}$). The TVOC unit has been converted from ppb to $\mu g/m^3$ based on an average molar mass of TVOC molecules [44]. All devices were connected to the local Wi-Fi network and sent readings every 5 min to the cloud storage.

The study used the fly-on-the-wall observation method to record the actual behaviour of people with dementia [45,46]. In August and September, researchers selected fourteen days (based on the arrangement of the nursing home and weather conditions) to record the ventilation control of monitored rooms as well as each participant's location, activity, clothing level, and changed behaviour. The observation data was converted into numerical data (e.g. clothing level: 1-short sleeve, 2-pyjamas, 3-shirt, 4-sweater, 5-jacket; activity: 1-sleeping, 2-sitting/-napping, 3-reading/watching, 4-chatting/eating, 5-walking,

**Table 2**
Participants' information from nursing records.

| Participant | Gender | Age | Dementia stage (CDR) | Illness or symptoms |
|---|---|---|---|---|
| A | Female | 87 | 2-moderate | Sleep problems |
| B | Male | 65 | 2-moderate | |
| C | Female | 75 | 2-moderate | Frequency of urination |
| D | Female | 81 | 2-moderate | Wandering |
| E | Female | 89 | 2-moderate | |
| F | Female | 98 | 2-moderate | Arthralgia |
| G | Female | 89 | 2-moderate | |
| H | Male | 85 | 3-severe | Frequency of urination, sleep problems |
| I | Female | 78 | 2-moderate | |
| J | Male | 90 | 3-severe | Wandering, sleep problems |

Note: CDR = 0 (Health), CDR = 0.5 (Questionable impairment), CDR = 1 (Mild impairment), CDR = 2 (Moderate impairment), CDR = 3 (Severe impairment).

**Table 3**
Sensor specifications (device: Edimax AI-2003W).

| Parameter | Range | Sensitivity |
|---|---|---|
| $PM_{2.5}$ | 0–500 μg/m$^3$ | >100 μg/m$^3$, ±20 %<br><100 μg/m$^3$, ±15 μg/m$^3$ |
| $PM_{10}$ | 0–500 μg/m$^3$ | |
| Temperature | 0–80 °C | ±1 °C |
| $CO_2$ | 0–10000 ppm | ±30 ppm |
| TVOC | 0–1000 ppb | ±15% |
| Humidity | 0–100% | ±5% |
| HCHO | 0–1 mg/m$^3$ | ±10% |

6-exercising, 7-out of the building). Based on the schedule of participants (they usually were dressed and ready to come out of their bedrooms before 10 a.m. and went back to their bedrooms to rest after supper around 6 p.m.), the observation started from 10:00 till 18:00. The researcher went through the common spaces in the nursing home to check all participants in the different floors and stopped for a few minutes for data logging. The participants were not being continuously observed, and their information was logged every 30 min by filling out the form and using floorplans, pictures (people not included), sketches, and notes as supplementary information. Considering the fly-on-the-wall observation method could influence the residents' activities and behaviours, researchers frequently visited the nursing home before the study started to reduce the strangeness. Ten participants' names and bedroom numbers were coded using letters from A to J. After data collection, both sensor data and observation data were input into SPSS software for analysis.

### 2.4. Data analysis

In this study, we collected three categories of data: 1) participants' background information (age, gender, and dementia stage); 2) indoor environmental data (air temperature, relative humidity, $CO_2$, TVOC, HCHO, $PM_{2.5}$, and $PM_{10}$; and 3) observation data (building facility management, participants' locations, clothing levels, daily routines, changed behaviours, number of residents in the rooms, and residents' main activities). We used SPSS Version 26 for data description and Fisher's exact tests to explore the influences of indoor environmental and contextual data on participants' changed behaviours ($p < 0.05$ as significant). In addition, heatmap charts were made to show the participants' locations at some specific moments according to the data analysis results. These charts associated with sensor data are used to describe the environmental conditions when changed behaviours were observed.

## 3. Results

Table 4 lists the date, time slot, location, the number of residents and their main activity in the space when a participant exhibited any changed behaviour and the indoor environmental conditions at the exact moment. The changed behaviours observed in the courtyard were excluded from the data analysis. Most of the observed changed behaviours in the indoor environment were wandering, which half of the participants had. Besides, participants H and J showed more than one behaviour. The wandering behaviour was mostly exhibited but was not limited to common spaces (corridors or central living rooms). Sometimes, the participants were found pacing in their bedrooms. Participants' hallucinatory symptoms can be recognised as participants (A, F, and H) were soliloquising to the air or objects (e.g. dolls). Participant J showed agitated behaviour once on 27th August, lasting for a few minutes. During these observations, there were no extreme indoor conditions in the nursing home, such as being too cold or hot, too humid or dry, or poor air quality.

Fisher's exact tests were conducted for data analysis. Table 5 shows the relationship between behaviour types and contextual factors. For the test, all variables were categorised: behaviour types (three categories: wandering, hallucination, and agitation), indoor locations (two categories: common spaces and bedrooms), time slots (three categories: morning 10:00 to 12:00, dining time 12:00 to 13:00 and 17:00 to 18:00, and afternoon 13:00 to 17:00), ventilation controls (three categories: natural, mechanical, and both), and clothing levels (four categories: short-sleeve shirt, long-sleeve shirt, sweater, and jacket). The result shows the behaviour types are only statistically correlated with clothing levels. Amongst twenty-eight recorded changed behaviours, twenty-four of them were observed in the common spaces (sixteen in central living rooms and eight in corridors), significantly higher than in bedrooms (Table 6). Since the location was not found to be related to the behaviour types, and given that wandering was significantly more often seen than all other behaviours, the changed behaviours were considered as a whole in the subsequent analysis. Table 7 shows the relationship between the location of changed behaviour observed (two categories: common spaces and bedrooms) and indoor environmental factors (three categories: higher, approximate, and lower). Due to the lack of knowledge about the range in which people with dementia can perceive the changes of environmental indicators, we define parameter differences, comparing the data of the room changed behaviour observed and the data of other spaces. For this, we consider a difference of less than one average standard deviation (SD) of twelve monitored rooms (fourteen observation days) as approximate (temperature = 0.69, relative humidity = 10.37, $CO_2$ = 55.08, TVOC = 1.62, $PM_{2.5}$ = 2.81, and HCHO = 0.02) as similar. A difference larger than a standard deviation (±SD) was coded as 'higher' and 'lower' respectively. Additionally, we also investigated with Fisher's exact test, the relationship with the main activity carried out (four categories: sitting, reading/watching TV, eating/chatting, and walking) and the number of residents present (eight categories: one to eight) in the spaces where changed behaviours were observed (Table 7). The result shows that room temperature, TVOC, HCHO levels, the number of residents, and their activities are statistically correlated with the locations.

The indoor environmental parameters captured in the spaces when changed behaviours observed were steady (temperature mean value M = 23.25 °C, SD = 0.65; relative humidity M = 62.85%, SD = 10.18; $CO_2$ M = 563.75 ppm, SD = 84.67; TVOC M = 5.95 μg/m$^3$, SD = 3.90; $PM_{2.5}$ M = 3.96 μg/m$^3$, SD = 2.01; HCHO M = 0.04 mg/m$^3$, SD = 0.02). However, as shown in Figs. 2 and 3, changed behaviours present a clear pattern for factors statistically related (e.g. temperature), while such distinction cannot be (visually) made for factors not statistically related (e.g. relative humidity). Indoor temperatures (fourteen observation days) of Rooms A to E and the central living room on the ground floor are at the upper part of Fig. 2, Rooms F to J and the central living room on the first floor are at the bottom part. Exterior conditions are shown at the top of the figures for each day. The different colours of solid and dotted lines indicate the temperatures in the rooms, and the colour dots accompanying the letters of participants indicate the type of their changed behaviours. On scorching weather days, the average temperature on the first floor was 1 °C higher than on the ground floor. The data deviation of rooms on the first floor was larger than on the ground floor. Most changed behaviours were exhibited in the warmest central living rooms or the coolest Rooms F and H, between 22 and 25 °C, which were maintained in the ranges as ASHRAE 55 suggested [47]. The temperature in the central living room rose more significantly during cooking and dining times, while the other rooms had tiny fluctuations.

The indoor relative humidity in the nursing home was stable during the daytime (Fig. 3). The ranges during the monitoring campaign were from 35 to 85%. Each room variated about 10% during one day. Unlike indoor temperature variations, relative humidity was usually highest in the morning, lowest in the middle of the day, and gradually picked up in the evening. The average humidity level on the first floor (bottom part) was 5% lower than on the ground floor (top part). Based on the simultaneous observation and monitoring, participants' occupancy in bedrooms had tiny influences on the data fluctuation. In Fig. 3, the changed

**Table 4**
The environmental and contextual data of changed behaviours.

| Participant | Date | Time slot | Behaviour | Location | Temperature (°C) | Humidity (%) | $CO_2$ (ppm) | TVOC (μg/m$^3$) | $PM_{2.5}$ (μg/m$^3$) | HCHO (mg/m$^3$) | People counting | Main activity |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | Aug 25 | 11:30–12:00 | Hallucination | Courtyard | 29.00 | 42.00 | – | – | – | – | 2 | 1 |
| C | Sep 17 | 11:30–12:00 | Wandering | Common space | 23.33 | 51.92 | 558.00 | 5.88 | 4.00 | 0.04 | 7 | 1 |
| D | Aug 18 | 13:00–13:30 | Wandering | Common space | 22.98 | 76.28 | 672.00 | 8.33 | 2.00 | 0.05 | 6 | 1 |
| E | Aug 16 | 11:30–12:00 | Wandering | Common space | 22.55 | 76.29 | 591.00 | 12.74 | 4.00 | 0.08 | 8 | 1 |
| | Aug 16 | 15:30–16:00 | Wandering | Common space | 23.52 | 72.68 | 660.00 | 13.23 | 5.00 | 0.05 | 5 | 3 |
| | Aug 18 | 11:30–12:00 | Wandering | Common space | 22.63 | 76.90 | 653.00 | 4.41 | 2.00 | 0.03 | 7 | 1 |
| | Aug 18 | 15:30–16:00 | Wandering | Common space | 23.14 | 74.78 | 753.00 | 8.82 | 2.00 | 0.04 | 8 | 1 |
| | Aug 23 | 13:00–13:30 | Wandering | Common space | 22.84 | 69.49 | 646.00 | 8.33 | 5.00 | 0.05 | 3 | 1 |
| F | Aug 16 | 11:30–12:00 | Hallucination | Bedroom | 23.23 | 69.67 | 447.00 | 0.98 | 3.00 | 0.02 | 1 | 1 |
| | Sep 15 | 17:30–18:00 | Hallucination | Bedroom | 22.20 | 53.22 | 476.00 | 1.96 | 2.00 | 0.02 | 1 | 2 |
| H | Aug 18 | 11:30–12:00 | Wandering | Common space | 22.31 | 74.87 | 630.00 | 7.84 | 2.00 | 0.06 | 8 | 3 |
| | Aug 18 | 17:00–17:30 | Wandering | Common space | 23.91 | 73.21 | 476.00 | 3.92 | 1.00 | 0.03 | 4 | 3 |
| | Aug 23 | 15:00–15:30 | Wandering | Bedroom | 23.63 | 60.93 | 563.00 | 2.45 | 5.00 | 0.03 | 1 | 4 |
| | Aug 23 | 15:30–16:00 | Wandering | Courtyard | 29.00 | 44.00 | – | – | – | – | 8 | 3 |
| | Aug 23 | 16:00–16:30 | Hallucination | Common space | 24.16 | 62.73 | 465.00 | 2.45 | 7.00 | 0.02 | 7 | 3 |
| | Aug 27 | 11:30–12:00 | Wandering | Common space | 22.60 | 61.77 | 499.00 | 0.98 | 3.00 | 0.02 | 4 | 1 |
| | Aug 27 | 15:00–15:30 | Wandering | Common space | 23.11 | 61.46 | 585.00 | 4.90 | 2.00 | 0.03 | 6 | 3 |
| | Sept 1 | 11:30–12:00 | Wandering | Common space | 24.30 | 50.18 | 466.00 | 2.94 | 3.00 | 0.03 | 7 | 1 |
| | Sept 3 | 13:30–14:00 | Wandering | Common space | 24.79 | 46.44 | 495.00 | 5.88 | 7.00 | 0.04 | 3 | 1 |
| | Sept 5 | 14:00–14:30 | Wandering | Bedroom | 22.88 | 55.22 | 538.00 | 4.90 | 4.00 | 0.03 | 1 | 4 |
| | Sept 10 | 11:30–12:00 | Wandering | Common space | 22.47 | 73.62 | 532.00 | 4.90 | 7.00 | 0.04 | 7 | 1 |
| | Sept 10 | 14:00–14:30 | Wandering | Common space | 22.80 | 71.83 | 469.00 | 3.92 | 7.00 | 0.04 | 1 | 4 |
| | Sept 22 | 10:30–11:00 | Wandering | Common space | 22.88 | 49.36 | 656.00 | 7.84 | 5.00 | 0.05 | 5 | 1 |
| | Sept 22 | 13:00–13:30 | Wandering | Common space | 23.90 | 50.18 | 671.00 | 11.76 | 5.00 | 0.06 | 3 | 1 |
| J | Aug 23 | 16:00–16:30 | Wandering | Common space | 24.16 | 62.73 | 465.00 | 2.45 | 7.00 | 0.02 | 6 | 3 |
| | Aug 27 | 12:30–13:00 | Agitation | Common space | 22.88 | 62.71 | 505.00 | 16.66 | 2.00 | 0.11 | 2 | 2 |
| | Aug 27 | 14:00–14:30 | Wandering | Common space | 22.98 | 62.90 | 509.00 | 3.43 | 4.00 | 0.03 | 3 | 1 |
| | Aug 27 | 14:30–15:00 | Wandering | Common space | 23.70 | 61.24 | 531.00 | 3.43 | 3.00 | 0.03 | 6 | 1 |
| | Sept 22 | 14:00–14:30 | Wandering | Common space | 23.65 | 49.49 | 653.00 | 5.88 | 7.00 | 0.04 | 2 | 1 |
| | Sept 22 | 14:30–15:00 | Wandering | Common space | 23.49 | 47.69 | 621.00 | 5.39 | 4.00 | 0.04 | 2 | 1 |

**Note**: Main activities 1-siting, 2-reading/watching, 3-eating/chatting, 4-walking.

**Table 5**
Fisher's exact test of changed behaviour types and contextual factors.

| Factors | Exact Sig. (2-sided) (with changed behaviour types) |
|---|---|
| Indoor locations | 0.086 |
| Time slots | 0.057 |
| Ventilation controls | 1.000 |
| Clothing levels | 0.010* |

**Note:** (*) Significant at $p < 0.05$.

**Table 6**
The locations of the changed behaviours observed (indoor).

| Changed behaviour | Location | | Total (count) |
|---|---|---|---|
| | Bedroom | Common space | |
| Wandering | 2 | 22 | 24 |
| Hallucination | 2 | 1 | 3 |
| Agitation | 0 | 1 | 1 |
| Total (count) | 4 | 24 | 28 |

**Table 7**
Fisher's exact test of changed behaviour locations and indoor environmental or contextual factors.

| Factors | Exact Sig. (2-sided) (with changed behaviour locations) |
|---|---|
| Temperature | 0.001* |
| Humidity | 0.270 |
| $CO_2$ | 0.057 |
| TVOC | 0.022* |
| $PM_{2.5}$ | 0.146 |
| HCHO | 0.033* |
| Number of residents in the space | 0.004* |
| Main activity of residents | 0.029* |

**Note:** (*) Significant at $p < 0.05$.

behaviour occurrence does not show a clear pattern with the relative humidity trend (not always in the warmest or coolest room), which is consistent with Fisher's exact test results. However, it can be seen from the figure that most of the changed behaviours appeared in the interval of 60–75% humidity.

The observation data of participants and environmental data of rooms they stayed in were logged and integrated into floor plans to find the relationships. Figs. 4 and 5 compare the participants' daytime activities, movement ranges, the locations of changed behaviours, as well as indoor and outdoor environmental parameters. The purpose is to illustrate the difference between the day with changed behaviours exhibited and the day without. However, since it was not observed a large number of changed behaviours on the same day and two floors, we conducted separate comparisons between the ground floor (three records) on the 18th of August, the first floor (five records) on the 27th of August, and both floors with no records on the 13th of September. These three days were under essentially the same outdoor and indoor

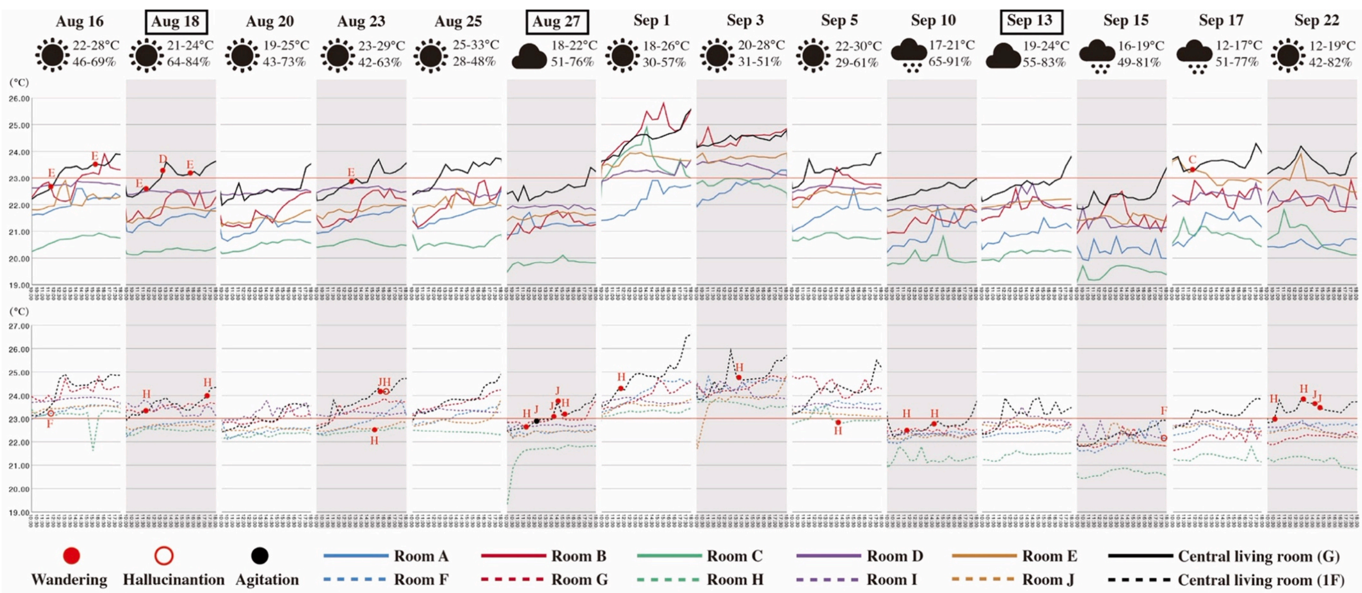


**Fig. 2.** Indoor air temperature, outdoor weather, and participants' changed behaviours on the observation days.

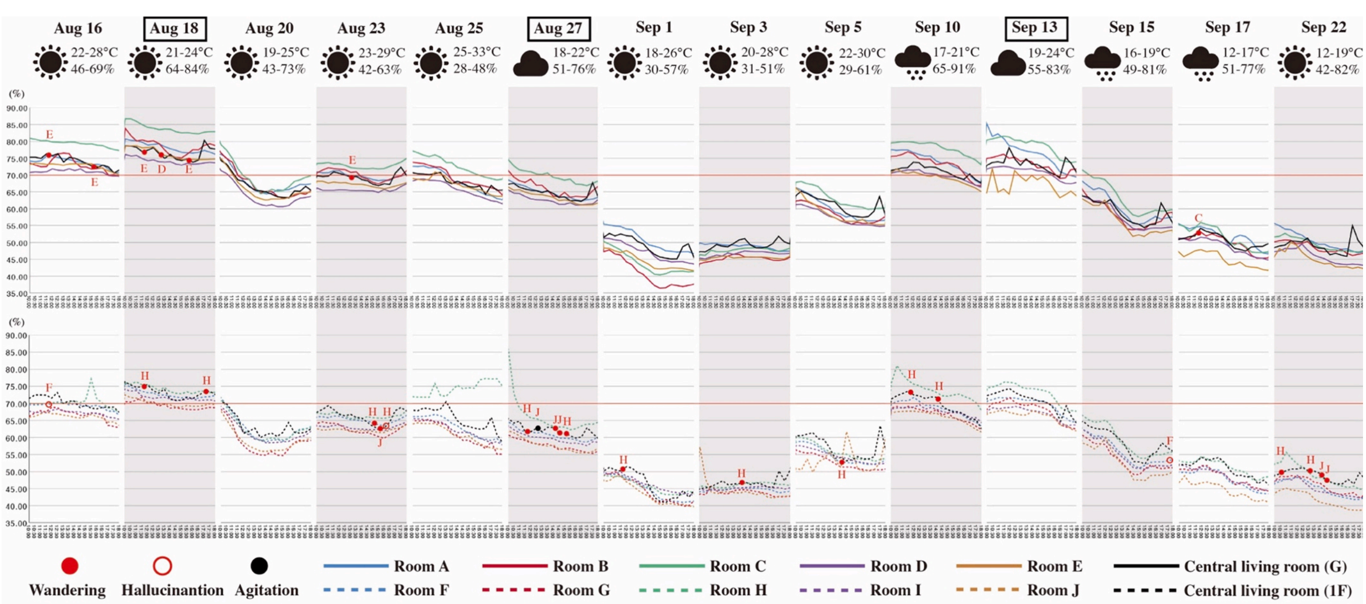


**Fig. 3.** Indoor relative humidity, outdoor weather, and participants' changed behaviours on the observation days.

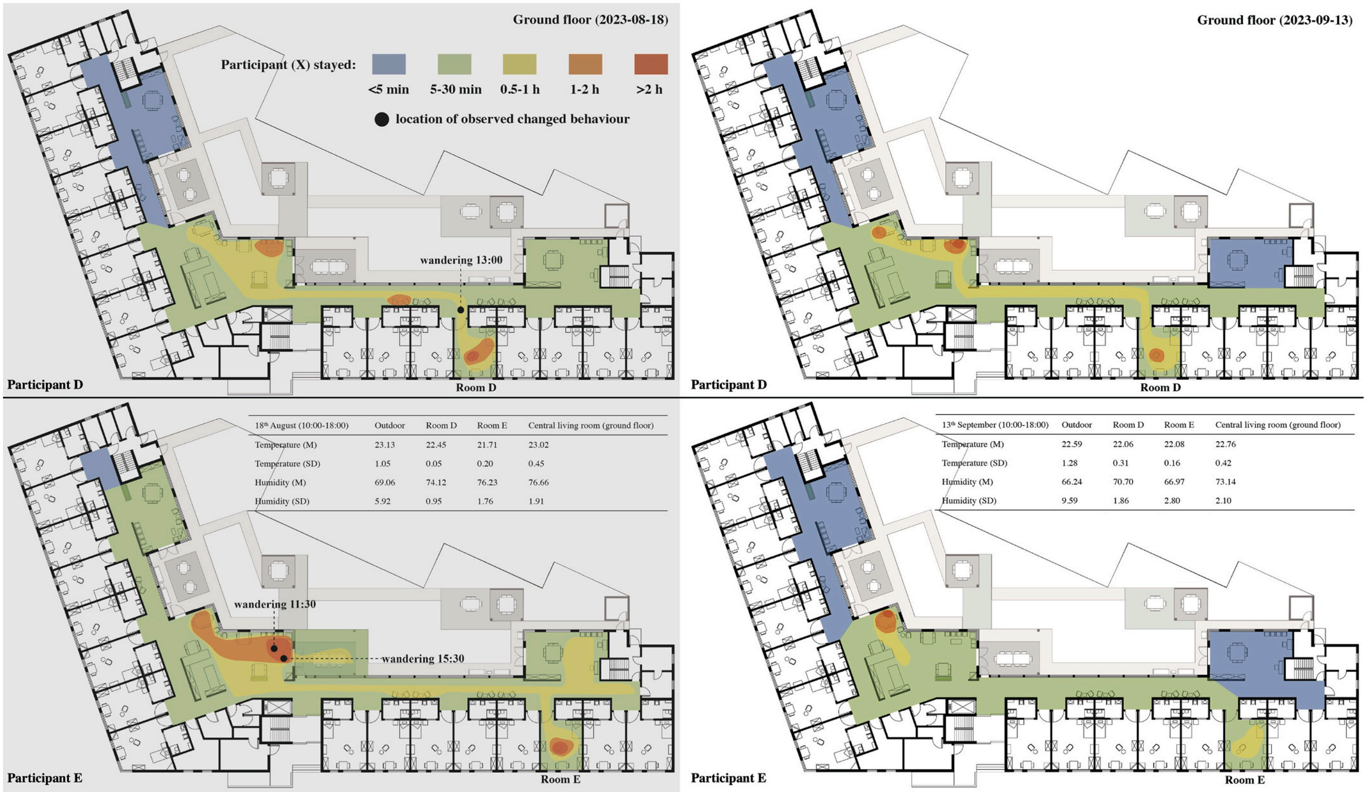


**Fig. 4.** The heatmap chart of two observation days with (left: 18th August) and without (right: 13th September) changed behaviours on the ground floor.

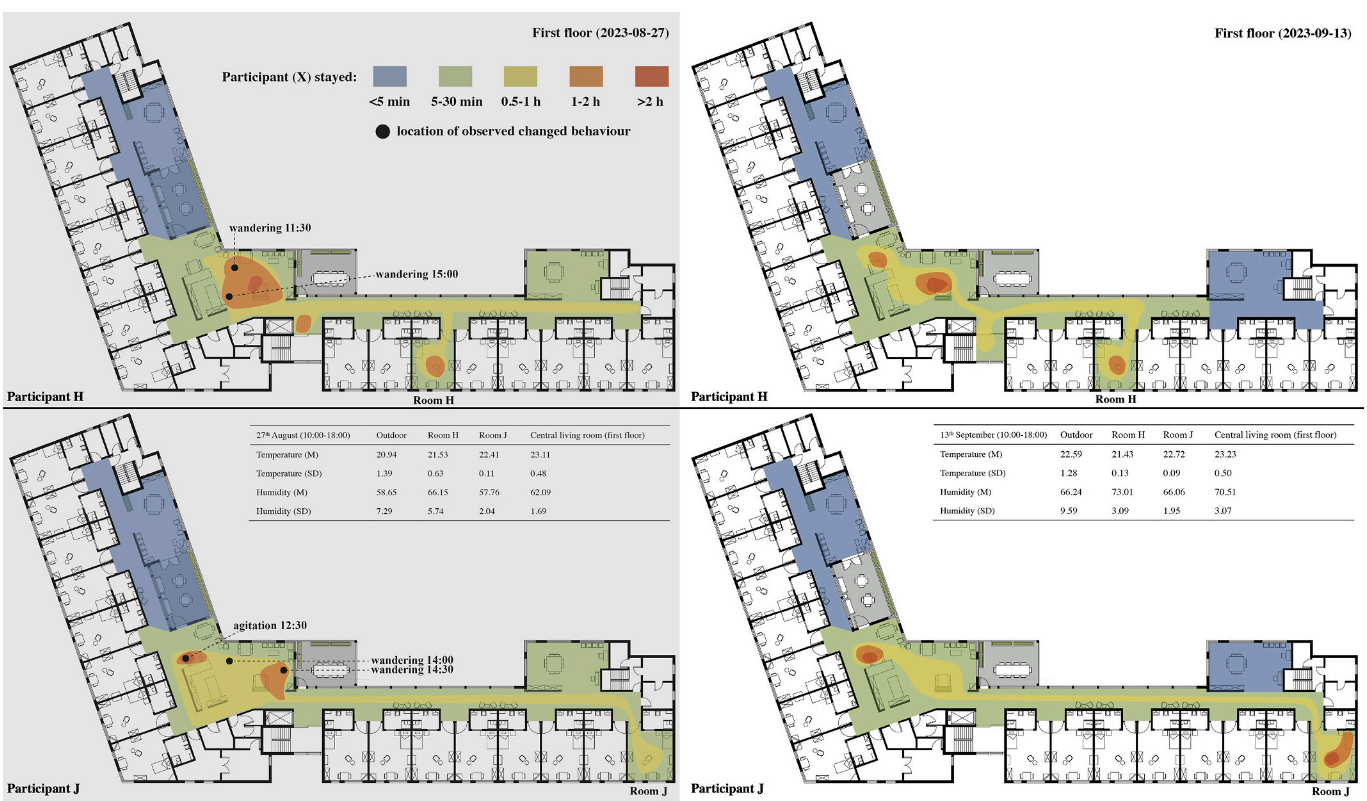


**Fig. 5.** The heatmap chart of two observation days with (left: 27th August) and without (right: 13th September) changed behaviours on the first floor.

conditions, which minimised the influences of environmental factors. In these heatmap charts, the blue areas indicate participants seldom arrived, and the green areas were the places they shortly stayed. In the yellow and orange areas, participants stayed longer than 0.5 h and 1 h. For instance, the upper part of Fig. 5 shows that Participant H usually talked with others in front of the staircase, so the areas were yellow or orange rather than blue. The red areas mean participants stayed longer than 2 h. The black dots show the time and type of specific participant who exhibited changed behaviour. These charts show that participants (D, E, H, and J) had larger activity ranges on the days with changed behaviours (left) than on the days without (right). The hotspots of the daytime activities were concentrated in central living rooms and bedrooms. Moreover, based on the observation data of other residents' states, we found that they were relatively spread out when participants exhibited changed behaviours. They were sitting or napping on the chairs and had little interaction with each other, so the changed behaviour was seldom intervened.

The routes and extent of wandering were random. Sometimes, the participants paced repeatedly between the doorways of their bedrooms and central living rooms, or they walked to the end of a corridor and then turned back. Although each bedroom door pasted the portrait photo and name tag, participants could still lose their way back. Hallucinatory symptoms usually happened to the participants staying alone. One record in the corridor was participant H soliloquising and gesturing in front of his bedroom. During the observation, agitation was only observed once in the central living room as Participant J yelled at care professionals without signs and pushed away the tableware during lunch. In conjunction with the participant's personal information, the locations of changed behaviours are related to the individual's mobility and degree of dementia. For instance, participant F had mobility limitations, and her changed behaviours were observed in her bedroom. Participants H and J were in the severe dementia stage and exhibited more changed behaviours than others.

Further analysis of the nursing home layout using the DepthmapX software reveals that the changed behaviours exhibited less in the areas of higher visibility and pedestrian flow (red, orange, and yellow colours in Fig. 6). Changed behaviours were mostly in areas which could be overlooked (green and blue colours in Fig. 6). There were six records (20%) of changed behaviours recorded in bedrooms or outdoor spaces, five (16.7%) were in the centre areas of the building, and nineteen (63.3%) observed in the edge of common spaces, such as at the corners of central living rooms.

## 4. Discussion

In this study, we investigated the effect of indoor environmental and contextual factors on the behaviours of people with dementia. We focused on the conditions of changed behaviour exhibited and analysed the indoor environmental and contextual factors logged during the period of fly-on-the-wall observation. Thus, we collected different data types to explore these relationships and considered outdoor weather data and participants' clothing levels, activities in common spaces, and


**Fig. 6.** The locations of observed changed behaviours combined with Visibility Graph Analysis.

building facility operations. Thirty changed behaviours, wandering, hallucination, and agitation, listed in Table 4, were from seven participants. Some contextual factors (e.g. clothing levels) remained unchanged during the daytime in this study. However, clothing adjustment is a good way to adapt to environmental changes, which may be beyond the abilities of people with dementia [24]. Thus, these factors could trigger participants' changed behaviours or encourage them to move to other areas.

The floor plans of the studied nursing home are L-shaped. The staircase, elevator, and central living rooms are located at the junction of two corridors, and each corridor is a linear system with one or multiple corners [39]. Corridors play a crucial role in linking the indoor spaces. The availability of different rooms for different purposes, activities, and arrangements impacts residents' preferences to stay and their living qualities [48]. Thus, the L-shaped layout makes the space centripetal, and residents prefer to stay near the central living rooms rather than the activity rooms in corners (Fig. 6). The basic typology of wandering patterns is proposed as lapping, pacing, random, and direct individual ambulation episodes, and random has been validated as the most common [49]. However, people with dementia often exhibit more than one pattern. In this study, these patterns have been shown clearly in the linear floor plan. Participants' routes were random (pacing in a small area or walking directly to the end of corridors), and the time of wandering start and end was also unpredictable. Sometimes, residents could wander onto the other floors through the elevator because the elevator is easy to access (the staircase was closed). The location of elevators in nursing homes needs to be carefully considered. Another imperfection of the building layout is centralised with the long, straight, materially identical, similar furnishing arrangement corridor. This centralisation of personal and common space instils residents an alienation from spaces they do not often access and gives them a sense of disorientation to their surroundings [50]. Residents were found wandering in the corridors but rarely went to the corner activity rooms.

The building quality of the studied nursing home was high, the facilities were new and operating well, and all bedrooms were similar in layout and orientation. Indoor environmental quality and care-related factors, such as thermal properties of the building, ventilation, cooling and heating systems and care service schedule, were consistent in the studied nursing home [51]. Sensor data shows the temperatures in bedrooms basically fluctuated between 18 and 24 °C as the WHO suggests for sedentary people [52], and each room usually had less than 1 °C standard deviations during one day. Relative humidity data varied between 35% and 85%, and the fluctuations were around 10% within one day of all monitored rooms. Besides, the air quality was well maintained in the nursing home. Based on existing research, the healthy threshold of $CO_2$ concentration has been set at 800 ppm, and the harmless limit is 1000 ppm [53]. The TVOC limit proposed by the European Commission is 300 μg/m$^3$, and the comfort range is under 200 μg/m$^3$ [54]. WHO air quality guidelines suggest the short-term (24 h) $PM_{2.5}$ and $PM_{10}$ levels are 15 μg/m$^3$ and 45 μg/m$^3$, whilst the annual $PM_{2.5}$ and $PM_{10}$ levels are 5 μg/m$^3$ and 15 μg/m$^3$ [55]. The guideline value for HCHO of the Netherlands is 0.12 mg/m$^3$ [56]. The average mean values of $CO_2$ were around 500 ppm, TVOC mean values were less than 5 μg/m$^3$, $PM_{2.5}$ mean values were 4 μg/m$^3$, and HCHO levels were below 0.04 mg/m$^3$ in the nursing home. Although data analysis results show that the indoor environments were not under extreme indoor conditions, the relationships between room conditions (air temperature, TVOC, and HCHO levels) and the locations of the changed behaviours were significant in this case study. According to the observation records, Fig. 7 shows the percentage of the room conditions (changed behaviours observed) that were similar, higher or lower compared with other spaces on the same floor. In these rooms, temperature had a larger percentage warmer than the average (67.9% in red colour); relative humidity had a larger percentage approximately the average (89.3% in grey colour); and air quality parameters had slightly larger percentages higher, which partly confirms that the thermal environment has a significant impact on

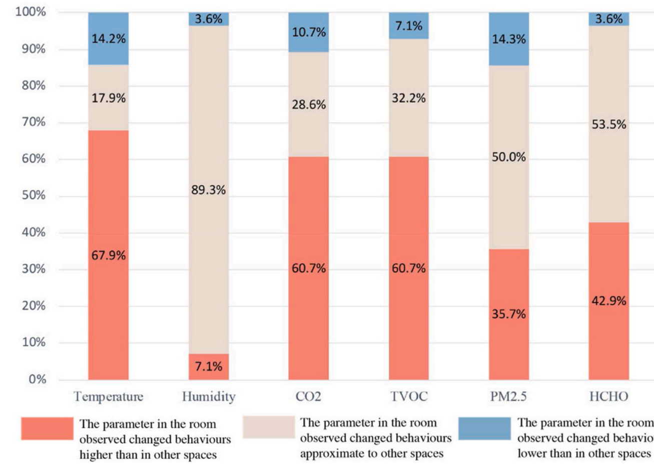


**Fig. 7.** The percentage of indoor environmental conditions when changed behaviours were observed.

nursing home residents [26]. In this study, the proportions of $CO_2$ and TVOC, as well as $PM_{2.5}$ and HCHO, are consistent, but only TVOC and HCHO are statistically significant. The reason could be the interconnection between indoor environmental indicators (e.g. HCHO negatively correlated with indoor temperature in summer) or specific activity causes indicators to increase (e.g. cooking) [57]. People with dementia's tolerance ranges of these air quality indicators still need to be explored.

This study specifically focuses on the relationship between two factors (changed behaviours and indoor environment) of the triadic reciprocal causation model [17]. The findings reveal that indoor environmental factors (temperature, TVOC, HCHO, and activities of other residents) influenced participants' changed behaviours, and the behaviour patterns showed differently in the indoor spaces. Personal factors, such as dementia stage and illness, also influence the occurrences, ranges, and locations of changed behaviours to some extent. However, limitations exist in this study, including the scale of the nursing home, data collection period, and number of participants, which need to be extended and addressed in future research. We observed other changed behaviours from the rest of the residents (e.g. screaming and depression). As they were not participants in the study, their information was not included. Limited sampling sites and participants meant that the relationships between indoor environmental indicators, activities, locations, and behaviours could hardly be assessed quantitatively and did not allow for more general conclusions to be drawn. Considering the heterogeneity of older adults and nursing home conditions, collecting data from more residents living in different nursing homes may bring new challenges for data analysis. People with dementia may have different sensations of indoor environmental changes, and there is no exact perception range of the parameter changes for this group [23,32]. Thus, we categorised and analysed the indoor environmental data according to both observation records and standard deviations of the sensor data for Fisher's exact tests. Furthermore, we had no permission to observe participants at night to check if they had sleep disturbance and restlessness. Some behaviours with no obvious characteristics (e.g. apathy) were excluded from data collection and discussion. Protecting privacy when using the fly-on-the-wall observation method is essential. Participants habitually returned to their bedrooms for napping after lunch and locked the door. In this case, we needed care professionals' help to check the participants' conditions since they were familiar with and brought minimum interference. Moreover, existing research found a high incidence of wandering behaviour around dinner time [58,59], but the changed behaviours more frequently appeared in this study before lunch (nine records of 11:30 to 12:00). Food and medication could also be stimulations, which trigger the changed behaviour but were considered out of the scope of this study. Last, we only collected data during the summer, given that in newly built buildings, it is more difficult to maintain comfortable parameters in the summer (e.g. overheating) than in the winter. We observed very similar indoor parameters in this nursing home in other seasons.

## 5. Conclusion

This study was conducted in a small-scaled nursing home in the Netherlands to collect indoor environmental data, contextual data, and details of participants' changed behaviours. Its objective was to explore the relevance of environmental and contextual factors with the occurrences and locations of changed behaviours. Although the excellent building thermal properties and facility operation, the indoor air temperature, humidity, and air quality parameters deviations were small, the room conditions of temperature, TVOC, and HCHO levels could be factors influencing where the changed behaviours were exhibited. We also found that the changed behaviour was significantly related to the clothing levels, the number of people present in the space, and their main activities when it happened. Besides the individuals' health conditions, the floor plan and spatial layout impact residents' activity ranges to some extent. If conditions allow, future research is suggested to focus on behavioural changes amongst people with dementia who live in a variable indoor environment, such as older non-renovated buildings, to explore the appropriate indoor environmental conditions that could help to reduce changed behaviours and improve their living quality. Because the changed behaviours of people with dementia are not eliminated by being with others or living in well-maintained indoor environments, the recommendation for nursing home design is to increase the visibility of the indoor spaces and avoid setting common areas at corners. Caregivers are suggested to pay more attention to the edge of common spaces if older adults stay there for a long time. Changed behaviours are likely to be exhibited in these overlooked spaces, which need to be distinguished to prevent serious consequences.

## CRediT authorship contribution statement

**Chuan Ma:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Olivia Guerra-Santin:** Writing – review & editing, Supervision, Software, Methodology. **Masi Mohammadi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

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