Received: 5 March 2020 | Revised: 14 July 2020 | Accepted: 28 July 2020 | Published online: 22 August 2020

DOI: 10.1002/trc2.12079

Alzheimer's & Dementia
Translational Research & Clinical Interventions

RESEARCH ARTICLE

Sensing a problem: Proof of concept for characterizing and predicting agitation

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Funding information
National Institute on Aging, Grant/Award Numbers: P30 AG008017, P30 AG066518, P30 AG024978, U2CAG0543701

Abstract

Introduction: Agitation, experienced by patients with dementia, is difficult to manage and stressful for caregivers. Currently, agitation is primarily assessed by caregivers or clinicians based on self-report or very brief periods of observation. This limits availability of comprehensive or sensitive enough reporting to detect early signs of agitation or identify its precipitants. The purpose of this article is to provide proof of concept for characterizing and predicting agitation using a system that continuously monitors patients' activities and living environment within memory care facilities.

Methods: Continuous and unobtrusive monitoring of a participant is achieved using behavioral sensors, which include passive infrared motion sensors, door contact sensors, a wearable actigraphy device, and a bed pressure mat sensor installed in the living quarters of the participant. Environmental sensors are also used to continuously assess temperature, light, sound, and humidity. Episodes of agitation are reported by nursing staff. Data collected for 138 days were divided by 8-hour nursing shifts. Features from agitated shifts were compared to those from non-agitated shifts using *t*-tests.

Results: A total of 37 episodes of agitation were reported for a male participant, aged 64 with Alzheimer's disease, living in a memory care unit. Participant activity metrics (eg, transitions within the living room, sleep scores from the bedmat, and total activity counts from the actigraph) significantly correlated with occurrences of agitation at night ($P < 0.05$). Environmental variables (eg, humidity) also correlated with the occurrences of agitation at night ($P < 0.05$). Higher activity levels were also observed in the evenings before agitated nights.

Discussion: A platform of sensors used for unobtrusive and continuous monitoring of participants with dementia and their living space seems feasible and shows promise for characterization of episodes of agitation and identification of behavioral and environmental precipitants of agitation.

KEYWORDS
actigraphy, agitation, bed pressure mat, environmental sensing, later-stage dementia, motion sensor, multimodal sensing

1 | BACKGROUND

Agitation is the most frequently experienced neuropsychiatric symptom of moderate to severe dementia, according to reports from formal and informal caregivers.[1,2] Dementia-related agitation is associated with a number of adverse outcomes for the person with dementia including faster progression to severe dementia, nursing home placement, increased use of pharmacological interventions, and death.[3,4] Typically, agitation is reported by family members and caregivers, adding to the care-related strain that is already higher in the context of more severe neuropsychiatric symptoms.[4,5]

To effectively prevent or manage dementia-related agitation, objective and standardized data are essential for understanding evolving behaviors and the impact of underlying environmental conditions.[6,7] Relying upon reports from emotionally stressed formal and informal caregivers presents practical challenges and may yield a less sensitive measure of agitation than is required for proactive early management. Often pharmaceutical interventions are introduced to manage agitation, but poorly informed application of these treatments can result in undesirable side effects.[8,9] Thus, another important reason to gain more frequent and sensitive measurement of agitation is to better gauge the effectiveness of pharmaceutical interventions and whether the impact of medications on behavior is "worth" the risks of prescribing them. Finally, studies suggest that the environment within formal care settings can affect the frequency of episodes of agitation and may be amenable to change.[10-14] Objectively detecting the environmental precipitants of agitation thus increases the potential for predicting agitation and more effectively implementing non-pharmacological environmental interventions.

Behaviors of persons with dementia have been observed and objectively assessed using wearables, computer vision, and multimodal sensing in research studies.[15] The most commonly used technology in this area of research has been wearable actigraphy devices, which have advanced the characterization of agitation in people with dementia through the detection of differences in activity levels.[15-18] However, wearable actigraphy devices may not always be the ideal solution for researchers or participants, as they have limited capability of monitoring the environment around the participant, require frequent downloading of data, and may cause local contact skin irritation or other additional agitation leading to removal of the device. Incorporating other sensors—such as ambient motion sensors, bed pressure mats, and environmental sensors—has potential advantages especially because they are unobtrusive, but thus far a multimodal sensing platform has not been tested for the detection and prediction of dementia-related agitation within formal care settings.

In our study, MODERATE (Monitoring Dementia-Related Agitation Using Technology Evaluation), we seek to develop objective behavioral markers of agitation and to identify environmental and behavioral precipitants of agitation using multimodal sensing among participants with later-stage dementia living within memory care and related residential care facilities. The purpose of this article is to provide proof of concept for characterizing and predicting agitation using a system which continuously monitors a patient's activities and environment within memory care facilities. We exemplify the concept in this article in a case study of one participant.

2 | METHODS

2.1 | Target population

The MODERATE study was approved by the Institutional Review Board at Oregon Health & Science University (OHSU; Study #18464) and is currently ongoing and open to enrollment. Eligible participants are those who reside in memory care facilities and who have received a diagnosis of dementia by a clinical care provider and/or are on a dementia medication. To meet the criteria of agitation, a score above 50 on the Cohen-Mansfield Agitation Inventory[19,20] is needed. Because the target population of MODERATE has moderate to severe dementia and is decisionally impaired, every effort is made to obtain informed consent from participants, but it is also required that a legally authorized representative provides informed consent in addition to, or in lieu of, the participant, depending on whether the participant is able to engage in the informed consent process. Legally authorized representatives for participants in the MODERATE study also sign a HIPAA (Health Insurance Portability and Accountability Act) form upon enrollment, to authorize the disclosure of the participant's records to the study team during the period of enrollment. Participants are recruited from residential care facilities in the metropolitan Portland area. Before conducting this study, participating care facilities signed a memorandum of understanding and the research team met with administrative and care staff to ensure that the deployment of the system did not interfere with the day-to-day care and activities of both the patient with dementia (PwD), and the staff. In this article, we report findings from a male participant aged 64 years with a diagnosis of Alzheimer's disease (AD) who enrolled in this study in 2019.

2.2 | Procedures

2.2.1 | Clinical assessments and records

At baseline, the participant's legally authorized representative completes the Cohen-Mansfield Agitation Inventory to gain a subjective measurement of behaviors indicative of agitation occurring in the

2 weeks before enrollment. Episodes of agitation during the study period are identified through documentation in the medical record, primarily from the medication administration record and the nursing progress notes. As part of their normal scope of practice, licensed nursing staff administer prescribed medication, both on a scheduled basis and as needed (ie, pro re nata [PRN]), for the treatment of agitation. The time of administration and the indication for use of any PRN medication is documented in the medication administration record. Additionally, the licensed nursing staff document in the progress notes notable behavior such as agitation and aggression. Typical progress notes are two to three sentences long and describe behaviors such as refusal of care, inappropriate language, and sleeplessness. These medical records are accessed in person by the researchers every 1 to 2 weeks and transferred on-site to the study database using a secure electronic survey (Qualtrics).

RESEARCH IN CONTEXT

1. **Systematic Review**: The authors reviewed the literature using traditional sources. In past research, actigraphy showed promise for monitoring and quantifying agitated behaviors in people with dementia. Limited studies have examined the effectiveness of other behavioral monitoring technology and the feasibility of proactive management of agitation. While the association between agitation and environmental factors has received some attention, more evidence is needed and additional environmental factors remain to be studied.
2. **Interpretation**: In addition to actigraphy devices, environmental sensors, passive infrared activity sensors, and bed pressure mats can also provide metrics that can unobtrusively characterize agitation in an individual. Higher activity levels were measured before agitation occurred at night. Low humidity was also found to be associated with agitation.
3. **Future Directions**: Increase the experience and evidence base with more diverse participants in studies to identify factors associated with and predictive of agitation both specific to each participant and generalizable across participants.

2.2.2 | Digital assessment system

Platform

The digital assessment platform used in the MODERATE study was developed at the Oregon Center for Aging & Technology (ORCATECH) at OHSU.[21-23] It is an end-to-end suite of technologies that has been established for the unobtrusive and continuous monitoring of older adults at their homes over extended periods of time. The platform was developed by a team of clinical and engineering researchers, statisticians, and software developers for more than a decade. Sensor data about everyday participant activity are transmitted to a Raspberry Pi hub computer in the home.[24] Data from the hub computer are uploaded to the ORCATECH servers via a secure internet connection. Specifically for the MODERATE study, the sensors used can be categorized into behavioral and environmental sensors. The data capture schema is presented in Figure 1.

Behavioral activity sensors

The behavioral sensors used in this study include (1) ambient sensors manufactured by NYCE Sensors (Vancouver, BC); (2) bed pressure mats manufactured by Emfit (Finland); and (3) wearable actigraphy devices, Actiwatch Spectrums, manufactured by Philips Respironics (Murrysville, PA).

The ambient sensors include wall-mounted motion sensors, door contact sensors, and curtain sensors that form a sensor line above the entryway. The wall-mounted motion sensors detect motion within the room, the contact sensors detect door opening or closing events, and the sensor line formed by curtain sensors can be used to measure walking speed.[25,26] In addition, we installed three wall-mounted motion sensors with restricted-view (created using custom 3D printed covers that conceal part of the motion sensor lens) within the living room in the participants' living quarters: one above the bed; one above the futon, couch, or chair frequently occupied by the resident; and one above the entry door. Each restricted-view wall-mounted motion sensor only detects motion within the subsection in the living room where it is placed.

The Emfit bed pressure mat is installed underneath the participant's mattress. The pressure mat is able to detect the presence of the participant and uses validated algorithms to measure the duration of time awake in bed; total duration of sleep; and durations of rapid eye movement (REM) sleep, light sleep, and deep sleep of the participant based upon their physiological signals (ie, heart rate variability and respiratory rate).[27,28]

The wearable actigraphy device, Actiwatch Spectrum, is worn on the non-dominant wrist of the participant for measuring their overall activity level. The Actiwatch Spectrum is equipped with an accelerometer from which the activity count per 15-second epoch is calculated. The Actiwatch Spectrum also comes with an off-wrist detector with which one can conclude how often the participant wears the device. The activity count data are stored locally on the Actiwatch. The participant's Actiwatch is swapped out every 4 weeks for the data to be downloaded and for the device to be charged.

Environmental sensors

The environmental sensors used are the Thunderboard Sense 2–SLTB004A from Silicon Labs (Austin, TX), which measure ambient light, sound level, humidity, atmospheric pressure, temperature, carbon dioxide, total volatile organic compound, and ultraviolet index. The environmental sensors record these measurements continuously and transmit the data via Bluetooth to the Raspberry Pi hub computer.

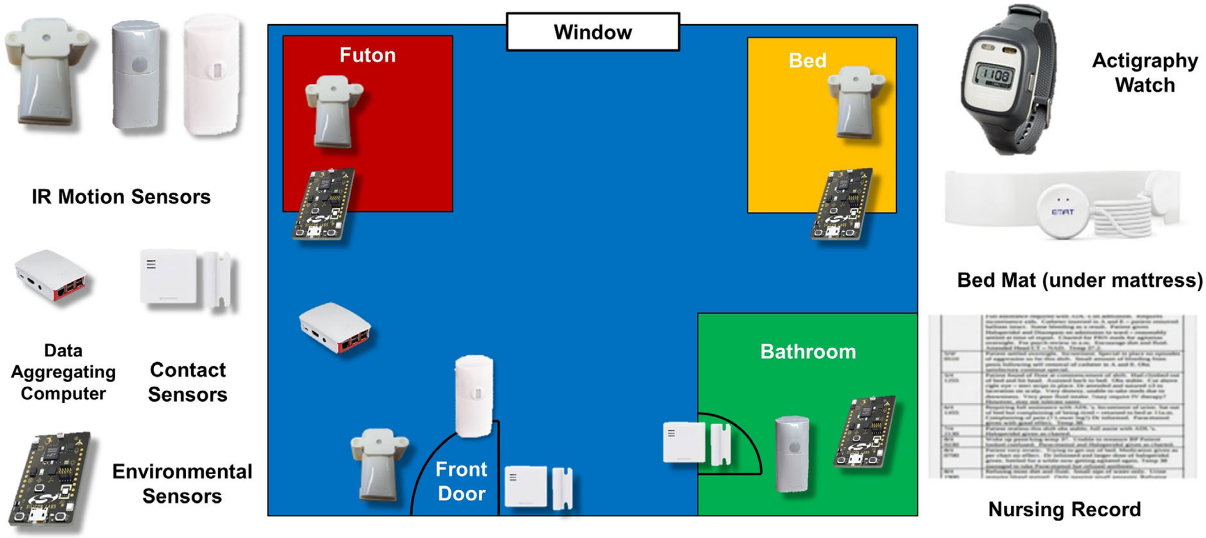

FIGURE 1 Living space with data capture sources: passive infrared motion sensors, contact door sensors, environmental sensors, bed pressure mat, actigraphy watch, and nursing record

As these environmental sensors have never been validated in this setting, before the installation of these sensors in the living quarters of the participant, we ran scripted tests which were designed to change the light level and sound level of the environment and examined if those changes were reflected in the measurements. In addition, to examine their consistency, two environmental sensors were installed side-by-side in the same room subsection and the correlation between the data streams from the two sensors was calculated. Results of these validations can be found in the supporting information Appendix.

2.3 | Data analysis for characterization and prediction of agitation

Behavioral and environmental data collected were divided by the nursing shifts (6 am–2 pm day shift, 2 pm–10 pm evening shift, and 10 pm–6 am night shift) and then the features (described below) were extracted. These features were grouped into shifts with agitation and shifts without agitation. The shifts with agitation were compared to the shifts without agitation at the same time on different days (eg, agitated night shifts vs non-agitated night shifts). This was done for two reasons. First, narrowing the analysis window by nursing shift allows a focus to be placed on specific periods of agitation. Second, behavioral patterns follow a daily cycle (eg, being awake during daytime and asleep during nighttime). To detect anomalies in people's behavior, one needs to compare their behaviors within similar time periods across days.

Features were extracted from the behavioral sensors based on domain knowledge. For example, it was anticipated that agitation is associated with pacing, excessive motor activity, and/or poor sleep at night. Accordingly, pacing was assessed using the data from the restricted-view motion sensors, recording the number of transitions between subsections in the living room. Motor activity was assessed by total activity counts from the Actiwatch Spectrum. For disturbed sleep, we examined the sleep score estimated from the Emfit bedmat, which is a measure of the quality of sleep and a function of variables such as total sleep time, the amount of REM and deep sleep, and the number of awakenings.[29] The Emfit sleep score falls in the range of 0 to 100. Higher sleep scores indicate better sleep quality. For each environmental variable, we extracted the maximum, minimum, median, mean, and standard deviation for each nursing shift from available data. Features from agitated shifts and non-agitated shifts were compared to each other using *t*-tests. Significant variables are identified when their *P*-values are less than 0.05. This method of analysis is valid for an n-of-one experiment.

For identification of behavioral and environmental precipitants for agitation, we compared features between the 8-hour nursing shifts preceding the 8-hour nursing shifts during which agitation occurred and the 8-hour nursing shifts preceding the 8-hour nursing shifts during which agitation did not occur.

3 | RESULTS

3.1 | Validation of the environmental sensor Thunderboard

The Thunderboard sound and light measurements met our expectation during the scripted test, and the correlations between the two Thunderboards in each subsection of the room were high (see the supporting information Appendix).

3.2 | Participant characteristics and episodes of agitation

The participant was initially being administered scheduled doses of twice daily risperidone and nightly melatonin for treatment of

TABLE 1 Characterization: List of activity metrics for agitated and non-agitated shifts

Feature	Nursing shift	Mean (SD)	Mean (SD)	*t*	*P*-value
Actiwatch total activity counts	Day	Agitated (n = 11)	Non-agitated (n = 84)		
		58762 (16451)	70514 (17120)	−2.15	0.0342
	Evening	Agitated (n = 5)	Non-agitated (n = 90)		
		65405 (18012)	67897 (13104)	−0.406	0.686
	Night	Agitated (n = 14)	Non-agitated (n = 80)		
		39427 (14717)	18897 (13957)	5.04	2.34E-06
Number of space transitions within living	Day	Agitated (n = 11)	Non-agitated (n = 104)		
		33.2 (27.5)	75.0 (63.9)	−2.15	0.034
	Evening	Agitated (n = 6)	Non-agitated (n = 109)		
		69 (62.7)	109 (67.3)	−1.41	0.161
	Night	Agitated (n = 15)	Non-agitated (n = 100)		
		61.5 (51.0)	28.1 (39.4)	2.95	3.90E-03
Living quarter Dwell times (minutes)	Day	Agitated (n = 11)	Non-agitated (n = 104)		
		137 (88)	178 (110)	−1.19	0.235
	Evening	Agitated (n = 6)	Non-agitated (n = 109)		
		245 (170)	273 (118)	−0.549	0.584
	Night	Agitated (n = 15)	Non-agitated (n = 100)		
		184 (109)	204 (97)	−0.747	0.457
Bathroom dwell times	Day	Agitated (n = 11)	Non-agitated (n = 125)		
		8 (6)	13 (14)	−1.17	0.245
	Evening	Agitated (n = 6)	Non-agitated (n = 130)		
		16 (12)	24(12)	−1.50	0.136
	Night	Agitated (n = 19)	Non-agitated (n = 117)		
		16 (17)	6 (8)	4.08	7.59E-05
Emfit sleep score	Night	Agitated (n = 9)	Non-agitated (n = 82)		
		63.9 (23.0)	87.8 (17.0)	−3.856	0.000218

Notes: The number of agitated and non-agitated shifts is different for each feature because of the technologies being installed on different dates or because of missing data.

agitation and sleeplessness, and the dosage increased to three times per day after 4 months. Additionally, the participant had a prescription for PRN risperidone for the treatment of agitation or insomnia. Using clinical data collected from the electronic health record over a 138-day period, 37 episodes of agitation, all treated with PRN medication, were identified. Nineteen episodes occurred within the night shift, twelve within the day shift, and six within the evening shift. The progress notes indicated that these episodes included behaviors such as exit-seeking, physical aggression, pacing, and slamming doors.

3.3 | Data from sensors

3.3.1 | Presence activity motion sensors

Motion sensor data were collected without technical difficulty for 138 days. Restricted-view ambient sensors were added in the living quarters on day 32 after enrollment.

3.3.2 | Sleep activity

Data were successfully collected from the participant for 91 out of 137 nights. Nights with missing data were likely due to the participant either not sleeping on their bed or WiFi issues.

3.3.3 | Motion activity

The participant started wearing the Actiwatch Spectrum on day 52 after enrollment. The downloaded data from the Actiwatch indicated that it was off-wrist intermittently for 2.01% of the time.

3.3.4 | Environmental data

Thunderboard data were collected for 48.0% of the time (data were considered lost when the time gap between consecutive data points

TABLE 2 Characterization: List of significant environmental variables for distinguishing agitated and non-agitated shifts

Nursing shift	Space	Feature	Agitated (n = 5) Mean (SD)	Non-agitated (n = 72) Mean (SD)	*t*	*P*-value
Day	Above futon	Max. sound (dB)	67.8 (6.54)	72.3 (4.71)	−2.05	0.0439
	Bathroom	Median sound (dB)	51.2 (0.832)	50.2 (1.04)	2.10	0.0391
	Above bed	Max sound (dB)	66.3 (6.37)	72. (4.25)	−2.83	0.00593
Nursing shift	**Space**	**Feature**	**Agitated (n = 10) Mean (SD)**	**Non-agitated (n = 62) Mean (SD)**	***t***	***P*-value**
Night	Above futon	Min. sound (dB)	44.6 (3.01)	46. 8 (2.50)	−2.54	0.01343
		Max. humidity (%)	37.1 (8.03)	42.5 (4.76)	−3.03	0.0034
		Min. humidity (%)	32.9 (6.83)	39.1 (5.55)	−3.21	0.00203
		Mean humidity (%)	35.3 (7.63)	40.6 (5.10)	−2.86	0.00564
		Median humidity (%)	35.5 (7.91)	40.5 (5.19)	−2.60	0.01145
	Bathroom	SD of sound (dB)	1.56 (0.605)	1.24 (0.383)	2.28	0.02584
		Max. humidity (%)	33.7 (5.15)	36.9 (3.72)	−2.42	0.01806
		Min. humidity (%)	30.8 (5.12)	34.8 (3.87)	−2.89	0.00509
		Mean humidity (%)	32.1 (5.08)	35.8 (3.71)	−2.80	0.00659
		Median humidity (%)	32.0 (5.14)	35.8 (3.70)	−2.84	0.00588
	Above bed	Min. sound (dB)	44.8 (2.54)	46.5 (2.16)	−2.29	0.02474
		Max. humidity (%)	35.5 (7.16)	40.1 (4.52)	−2.75	0.00768
		Min. humidity (%)	31.9 (6.11)	37.0 (4.95)	−2.89	0.0051
		Mean humidity (%)	34.0 (6.51)	38.4 (4.60)	−2.62	0.01069
		Median humidity (%)	34.2 (6.64)	38.4 (4.59)	−2.52	0.01417

was larger than 10 minutes). During the periods of data collection, the Thunderboards were a Beta component of the ORCATECH platform and were still under development. As issues were discovered with the Thunderboards (ie, data loss), software patches were deployed to the system.

3.4 | Characterization of agitation

During the 138 days of observation, the PwD was reported to have 36 total shifts with agitation (1 day shift had two episodes of PRN-treated agitation). Table 1 shows the list of activity metrics for both agitated and non-agitated shifts. There were higher activity counts from the Actiwatch Spectrum, more transitions within the living room, longer dwell times in the bathroom, and lower sleep scores from Emfit on agitated nights. Also, there were significantly correlative variables with agitation in the day, including variables that went against a priori expectation (eg, lower activity counts and less space transitions on agitated days). However, there were no significant distinguishing variables for agitation occurring in the evening shifts.

Environmental conditions significantly associated with agitation are presented in Table 2. No significant variables can be found for the evening shifts. There were three variables significantly associated with agitation in day shifts which are all related to sound, while there were 15 significant environmental variables associated with agitation at nights. Out of these 15 agitation-associated variables, 12 of them were related to humidity. The humidity was significantly lower during agitated shifts.

3.5 | Prediction of agitation

Table 3 lists the activity metrics in shifts before agitated and non-agitated shifts. There were two significant variables distinguishing evenings before agitated nights and evenings before non-agitated nights: total activity counts and the number of space transitions within the living room. There were more activity counts recorded and fewer space transitions within the living room in the evenings before agitated nights. This aligns with the recorded dwell times in the living space during the same period of time with the participant spending less time within their living quarters (43 minutes less time) in the evenings before agitated nights.

In distinguishing evenings before agitated and non-agitated nights, humidity in all three room spaces played an important role (Table 4). There was lower humidity in the evenings before agitated nights. Also, there was less ambient sound in the living room in the evenings preceding agitated nights. This is also consistent with the shorter dwell times in the living quarters as noted above. There was also a lower

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TABLE 3 Comparison of activity metrics for shifts before agitated and non-agitated shifts

Feature	Mean (SD)	Mean (SD)	*t*	*P*-value
Actiwatch total activity counts	Nights before agitated days (n = 10)	Nights before non-agitated days (n = 83)		
	27109 (13366)	21237 (16096)	1.11	0.271
	Days before agitated evenings (n = 5)	Days before non-agitated evenings (n = 90)		
	63060 (11668)	69492 (17622)	−0.804	0.423
	Evenings before agitated nights (n = 14)	Evenings before non-agitated nights (n = 81)		
	75853 (19081)	66368 (11621)	2.54	0.0129
Number of space transitions within living room	Nights before agitated days (n = 11)	Nights before non-agitated days (n = 103)		
	30.6 (28.3)	32.9 (43.8)	−0.171	0.865
	Days before agitated evenings (n = 6)	Days before non-agitated evenings (n = 109)		
	49 (76.4)	72 (61.8)	−0.860	0.392
	Evenings before agitated nights (n = 15)	Evenings before non-agitated nights (n = 100)		
	67.8 (53.0)	112.8 (67.6)	−2.46	0.0152
Living quarter dwell times (minutes)	Nights before agitated days (n = 11)	Nights before non-agitated days (n = 103)		
	209 (63)	202 (102)	0.219	0.827
	Days before agitated evenings (n = 6)	Days before non-agitated evenings (n = 109)		
	214 (101)	172 (109)	0.911	0.364
	Evenings before agitated nights (n = 15)	Evenings before non-agitated nights (n = 100)		
	234 (116)	277 (120)	−1.30	0.197
Bathroom dwell times (minutes)	Nights before agitated days (n = 11)	Nights before non-agitated days (n = 124)		
	7 (7)	8 (11)	−0.271	0.787
	Days before agitated evenings (n = 6)	Days before non-agitated evenings (n = 130)		
	9 (6)	13 (14)	−0.734	0.464
	Evenings before agitated nights (n = 19)	Evenings before non-agitated nights (n = 117)		
	19 (14)	24 (12)	−1.82	0.0716
Emfit sleep score	Nights before agitated days or evenings(n = 5)	Nights before non-agitated days or evenings (n = 131)		
	84.2 (15.4)	85.5 (19.4)	−0.21	0.834

Notes: The number of pre-agitated and pre-non-agitated shifts is different for each feature because of the technologies being installed on different dates or because of missing data.

ambient light level in the bathroom in the evenings before agitated nights, which suggests that there was less bathroom use. This is consistent with shorter dwell times in the bathroom in the same evenings as shown in Table 3. The effect size in distinguishing nights before agitated and non-agitated days was the largest for ambient light in the living room ($P < 1e\text{-}6$).

4 | DISCUSSION

In this article, we have presented a proof of concept, exemplified by an intensive case study, which indicates that using a passive sensor system to continuously characterize dementia-related agitation and identify potential environmental precipitants within residential care facilities

TABLE 4 Comparison of significant environmental variables for distinguishing shifts before agitated and non-agitated shifts

Space	Feature	Evenings before agitated nights (n = 10)Mean (SD)	Evenings before non-agitated nights (n = 65)Mean (SD)	*t*	*P*-value
Above futon	Min. sound (dB)	45.9 (2.39)	47.5 (2.14)	−2.17	0.0332
	Mean sound (dB)	52.7 (1.22)	54.0 (1.55)	−2.49	0.0150
	Median sound (dB)	52.3 (1.43)	53.6 (1.53)	−2.42	0.0179
	Mean humidity (%)	35. 6 (6.93)	40.1 (5.16)	−2.46	0.0162
	Median humidity (%)	35.4 (7.06)	39.8 (5.25)	−2.33	0.0227
Bathroom	Min ambient light (lux)	58.6 (95.7)	137 (93.7)	−2.45	0.0167
	Mean ambient light (lux)	149 (81.2)	194 (55.4)	−2.27	0.0259
	SD of ambient light (lux)	45.2 (49.4)	17.6 (26.5)	2.69	0.00885
	Median ambient light (lux)	146 (104)	197 (58.1)	−2.31	0.0239
	Mean humidity (%)	33.9 (4.72)	36.5 (3.46)	−2.14	0.0354
	Median humidity (%)	33.2 (4.91)	35. 8 (3.54)	−2.02	0.0467
Above bed	Mean sound (dB)	52.2 (1.19)	53.2 (1.37)	−2.15	0.0350
	Median sound (dB)	51.7 (1.46)	52.7 (1.42)	−2.11	0.0386
	Max. humidity (%)	38.7 (5.62)	43.2 (4.91)	−2.62	0.0106
	Mean humidity (%)	34.2 (5.90)	38.0 (4.39)	−2.49	0.0152
	Median humidity (%)	34.1 (5.87)	37.8 (4.44)	−2.35	0.0213
Space	**Feature**	**Nights before agitated days (n = 5)Mean (SD)**	**Nights before non-agitated days (n = 67)Mean (SD)**	***t***	***P*-value**
Above futon	SD of ambient light (lux)	11.5 (16.4)	0.672 (0.960)	5.82	1.66E-07
	SD of humidity (%)	1.62 (0.918)	0.856 (0.781)	2.08	0.0414
Bathroom	Max ambient light (lux)	162 (91.0)	217 (45.4)	-2.43	0.0177
Above bed	SD of ambient light (lux)	10.4 (14.8)	0.515 (0.875)	5.86	1.38E-07

is valid and feasible. The preliminary results suggest that unobtrusive and continuous monitoring of behaviors of dementia patients and their environment show promise for improved characterization of episodes of agitation and identification of behavioral and environmental precipitants for agitation. The system was well tolerated as it is largely passive except for the requirement that the PwD wear an actigraph on their wrist.

The case study demonstrated concurrent validity of using the sensor system to detect periods of agitation. Features such as the number of space transitions within the living room, Emfit sleep score, and the total activity counts from the Actiwatch Spectrum per shift correlated well with the occurrences of agitation at night for the participant. The relationship of daytime reports of agitation relative to activity counts was not apparent. This particular participant is normally highly active and likes to walk around. Therefore, a ceiling effect may exist in this case study. For future work, new behavioral features will be explored to effectively characterize agitation during daytime.

The data presented herein indicate that episodes of agitation may not be isolated events. Higher activity counts were detected in the evenings preceding agitated nights. This in combination with the shorter dwell times within the living quarters may suggest that the participant might have felt restless and wandered around the facility outside his own living quarter in the evenings before he was agitated at nights.

As it can be seen, the ambient motion sensors not only provide information about the participant's behaviors within the living quarters but also inform whether the participant is outside their own living quarter. For future work, such information can be used to examine the relationship between the occurrences of agitation and the activities that happen around the memory care unit. This may enable more accurate prediction of agitation.

While the more frequently studied environmental precipitants of agitation include ambient light level[14] and sound level[12], our finding of humidity being associated with occurrences of agitation at nights is novel and the first time this has been reported to our knowledge. Lower humidity in combination with shorter dwell times in the bathroom in the evenings preceding agitated nights may indicate that a lack of showers in the evenings could lead to agitation at night. This hypothesis may need to incorporate potential confounding factors such as visits from family members as his wife would give the participant showers when she visited.

Besides periods of agitation, our platform may prove to be useful in gaining further insights about related behaviors such as periods of anxiety or low mood and activity. More detailed records of PwD behaviors will help verify such speculations.

An important feature of our platform is that it does not record audio or capture photographs or video so that the privacy of participants is preserved. In addition, the platform does not add to the burdens of the nursing staff. During the study, we received no complaints from the nursing staff regarding the platform interfering with their work. A study found that asking PwD to wear a wrist-worn activity monitors for prolonged periods appeared to be both feasible and acceptable.[30] We reason that our study would also be feasible and acceptable to PwD collectively as the additional sensors in our study are all ambient and do not interfere with the participants' activities.

4.1 | Limitations

These findings represent preliminary findings from a single subject, and as such, require meticulous replication before generalization can be considered. It is at this point only suggestive as to whether the ability to detect early indicators of agitation may translate across patients. Although this proof of concept is based on a case study, the intensive measurement approach is a valid method for n-of-one studies yielding reliable results that pertain to the individual. Since enrolling a large number of PwD for conducting studies of behavioral disturbances in AD and related dementias is challenging, the n-of one approach is an important methodologic design to research in this area.

4.2 | Implications

Digital behavioral markers can enable continuous monitoring of PwD for episodes of agitation and facilitate the assessment of the effectiveness of different treatments. At this stage, this platform is used for monitoring the participants' behaviors and their living environments to derive behavioral markers and environmental precipitants of agitation. However, successfully identifying factors or events associated with agitation will enable proactive management of agitation. Findings from this study point to a clinical trial in which participants enrolled in a memory care and related settings may be more effectively studied with important environmental and precipitating variables objectively captured and controlled.

To conclude, behavioral and environmental sensing is shown to be feasible for characterizing and predicting agitation in this study. Objective meaningful indicators could be derived from the behavioral and environmental sensors to characterize agitation and to find its precipitants. A continued effort will be applied to the identification of factors that contribute to agitation, both specific for each individual participant and generalizable across all participants.

ACKNOWLEDGMENTS

Thank you to the staff at Pacific Gardens Alzheimer's Special Care Center, Portland, OR. Supported by National Institute on Aging (NIA) grants: P30 AG008017; P30 AG066518; P30 AG024978; U2CAG0543701.

CONFLICTS OF INTEREST

None of the authors have conflicts of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

How to cite this article: Au-Yeung W-TM, Miller L, Beattie Z, et al. Sensing a problem: Proof of concept for characterizing and predicting agitation. *Alzheimer's Dement*. 2020;6:e12079. https://doi.org/10.1002/trc2.12079