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Quantifying movement variability with fractals: From fall prediction to pharmaceutical evaluations and automated social distancing

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Abstract

Background: Movement speed is by definition the distance between two points divided by the time spent traversing it. Movement path tortuosity (Fractal D) describes the actual path traversed; it increases as more random turns are added. Although time is not used in its calculation because it is a spatial measure, the quantification of path tortuosity has yielded a novel means to describe path characteristics that correlate with temporal measures.
Objective: After summarizing the initial published application of Fractal D to human movement paths, its applications to numerous areas are reviewed.
Method: Fractal D quantifies the degree a path deviates from a straight line, yielding an index that ranges from 1.0 (perfect straightness) to 2.0 (chaotic). Fractal D has been successfully used when subjects' real time location systems data are the source.
Results: Research is summarized relating elevated path tortuosity to cognitive deficits in young and elderly adults, the prediction of future falls, movement paths during searches of virtual spaces, evaluation of drug effects, and automatic monitoring of multiple persons moving in common spaces and social distancing.
Conclusion: After its application from describing free movements of wild animals, the adaptation of Fractal D to human movement path variability has spread to several areas of study.

Keywords: Fractal D, movement path tortuosity, cognitive decline, fall prediction, brain disease, aging

INTRODUCTION

What is Fractal Dimension?

Fractal Dimension (Fractal D) derived from the geometry of lines measures the length of an irregular path in a two-dimensional space, e.g., the length of the coast of Britain in Mandelbrot's (1967) classic paper. Animal ecologists adapted it to describe the unrestricted movements of animals in their natural habitats (Nams, V.O., 2006). Nams' procedures are available online at https://www.dal.ca/faculty/agriculture/plant-food-env/faculty-staff/our-faculty/vilis-nams.html. Nams' use of Fractal D to characterize the paths of animals formed the starting point leading to the creation of a significant methodological improvement that allowed Fractal D to be calculated automatically during individual episodes of movement using a Real Time Fractal Path Analysis algorithm developed by Craighead (2011). It is beyond the scope of the current paper to describe the mathematics involved in the calculation of Fractal D, but the interested reader may wish to consult Craighead (2011) for details on the protocol. A second description of the foundations of Fractal D is in Kearns, Fozard and Nams (2016).

Increased navigational variability (tortuosity) in self-guided movement results in increases in Fractal D. from 1.0 (straight line) to 2.0 (chaotic) for each path generated. In its simplest sense, a trail having only a starting point and an ending point are connected by a straight line which requires just one dimension, Length, (thus a Fractal D value of 1) to describe it. As the subject's line of travel becomes more tortuous, it requires progressively more of a second dimension, Width, to describe it until Fractal D reaches a maximum value of 2, that being a plane comprising both length and width which describes a completely random travel pattern. Hence Fractal D values fall between 1.0 (perfectly straight) and 2.0 (chaotic).

How is Fractal D measured?

As illustrated in *Figure 1*, the measurement of Fractal D is based on changes of location in two dimensions; its computation can be based upon any source capable of reporting location, using X and Y coordinates. When used to assess movements its value is influenced by the number of successive locations sampled during an episode of movement. The spatial scale of the stride cor-

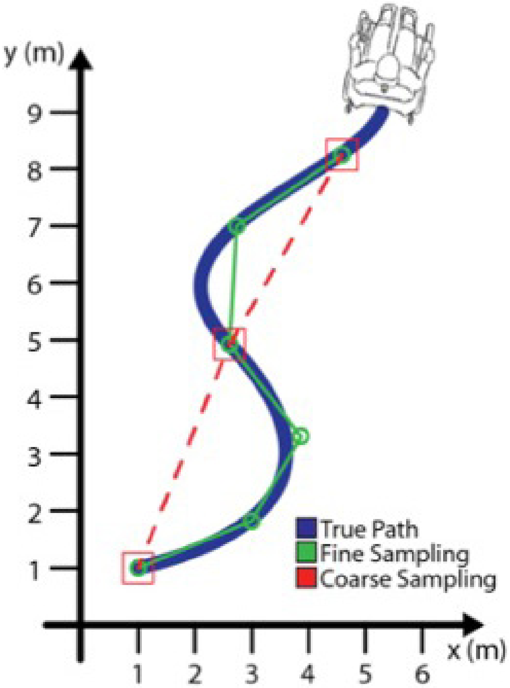

Figure 1. The measurement of Fractal D. Actual path (solid line) displays deviations from straight line distance (dotted line). Coarse (Squares) and fine (circles) represent successive samplings of distance on actual path. Figure courtesy of Innovative Design Laboratories, Minneapolis, Minnesota.

responds to the size of the organism: elephants have larger strides than field mice. Measurements required for Fractal D in movement paths can be obtained in various ways. Sujeet, Kaur & Sandhir (2016) computed Fractal D by measuring successive locations on a measurement grid placed over the photographically recorded path of rodents swimming the Morris Water Maze. More commonly in real-time location systems, triangulation methods are used that employ time-delay-of-arrival and/or angle-of-arrival solutions to determine changes in location of a signal transmitted from a moving subject to sensors surrounding the perimeter of a monitored space.

Method

Initial application of Fractal D to human movement

Fractal D was first used to describe wandering behavior in persons with cognitive deficits or clinically diagnosed dementia, usually as measured by Folstein's Mini Mental Status Exam (MMSE). (Kearns & Fozard, 2007).

To evaluate the role of Fractal D in describing the relationship between movement path tortuosity and cognitive impairment, residents in an assisted living facility (ALF) had Fractal D measured for 30 days as they moved freely about the lobby of the ALF. The input source for Fractal D calculations was data from 4 Ultra-wideband sensors located in the lobby that gathered location data from subjects' wrist-worn transponders. The central premise was that highly tortuous paths would be associated with cognitive impairment, not unlike that of an intoxicated person who finds it difficult or impossible to walk in a straight line.

As predicted, there was a significant negative correlation (r= -.46) between MMSE scores and Fractal D (Kearns and colleagues, 2010, 2011). While there was a negative correlation between Fractal D and residents' travel speed, Fractal D was the strongest predictor in multiple regression analyses predicting MMSE values. Slower walking characterized more tortuous paths. These results have since been replicated using a more extensive array of sensors (Bowen, personal communication). Subsequent investigations have indicated that a larger number of sensors do not materially improve the estimation of Fractal D obtained with the mere four-sensor system used by Kearns and colleagues.

Figure 2 displays the movement paths generated by two elderly ALF residents during the same time period. The resident with the higher MMSE score generated the path in the upper panel.

Results

Refinements to the original clinical classifications of wandering

Algase (2007) summarized her own and earlier research (Algase, Beattie, & Therrien, 2001) on wandering as measured by direct human observation. Movements were classified as purposeful (direct) or wandering, the latter further subdivided into pacing, lapping or random categories. Because of the difficulty in reliably identifying random movements, that component was estimated as the residual, after the identification of direct, lapping and pacing had been accomplished.

Multi-level correlational procedures revealed relationships between cognitive impairment and the lapping, pacing, and random components not directly measured by Fractal D. Using a data set from Kearns et al (2012) Kumar and colleagues (2016) successfully recreated Algase's classifications showing that the random component of wandering was the most prominent. Kumar's research provides independent support for the earlier classification system and demonstrates that movement data collected using sensors can be analyzed using the older descriptive system.

Fractal D and traumatic brain injury

The U.S. Department of Veterans Affairs established and operates the polytrauma transitional rehabilitation program (PTRP) for Veterans with

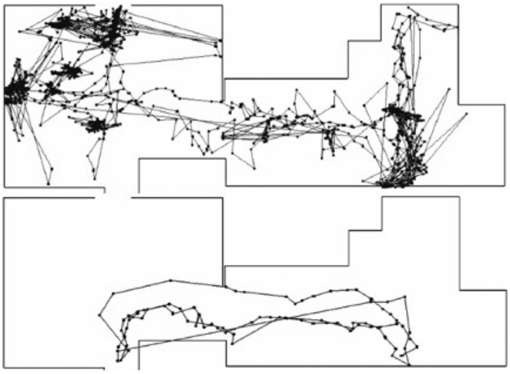

Figure 2. Movement paths generated by two elderly ALF residents at the same time and monitored lobby area. Paths in the upper panel were generated by a resident with a lower MMSE score than that of resident in lower panel. Figure reproduced from Kearns, Fozard and Nams (2016).

traumatic brain injury at the James Haley Veterans Hospital in Tampa, Florida. The program at the time of this research, was housed in a single level of a multistory structure, with limited access to 5 apartments, space for activities of daily living, a gymnasium, offices and treatment areas (Jasiewicz & colleagues, 2011).

An Ultra-Wideband automatic movement tracking system, described earlier having 188 sensors, was installed throughout the facility to gather movement data. It gathered the precise location data on any person wearing a tracking transponder. The tracking system was integrated with a behavioral monitoring system employing a large number of wall-mounted video panels that displayed personalized messages, behavioral prompts, and instructions to the wearer whenever they passed near one of the screens.

During their stay, typically one year, Fractal D was measured continuously from movements of patients throughout the PTRP facility. As shown in *Figure 3*, Fractal D was discovered to be positively related to the severity of the TBI as measured by the Mayo Portland Adaptability Index, and declines in Fractal D predicted improved functioning in the clinical measure over the treatment period (Kearns & colleagues (2016).

The technology was adapted to allow Fractal D to be derived from outdoor human ambulation using GPS tracking devices. The validation study compared outdoor path tortuosity of community-dwelling veterans with a history of TBI versus a control group. Results showed that even after ten years, path tortuosity of free outdoor ambulation was positively correlated with the severity of TBI gathered from concurrent clinical measures (Kearns and colleagues, 2014). In another study with PTRP patients described above, Fractal D measured with the indoor sensor-based system and the GPS outdoor system were significantly and positively correlated (Kearns & colleagues, 2016).

These studies illustrate the value of Fractal D as a robust measure of functional status irrespective of the source of the positional data and spatial scaling factors. The accuracy of the Ubisense real-time indoor location sensor system is about 15 cm; the accuracy of the GPS is about 2.5 m.

Short-term increases in Fractal D as predictors of future falls

Age-associated changes in ambulation predictive of future falls (Mirka & colleagues, 2020) include lower walking speed measured on a pressure-sensitive gait mat, poorer balance while standing on firm or soft gait mats or time to arise from a chair and walk a prescribed distance, reverse direction and return to a seated position in the chair (Hausdorff, 2005). Poor performance on these tasks has some fall predictive value but Kearns, et al. (2012) found many older persons could not or refused to complete the required tasks rendering their use as predictors for these individuals questionable.

For those who cannot or will not perform the test, the default assumption is that they are at the highest risk for a fall. The test therefore simply provides no information. The useful predictive interval for these tests (if performed) is about 3 months, meaning they must be repeated often to maintain their prognostic value. As a punctate measure, they cannot reflect subsequent changes in health due to an infection, medication or systemic changes. Thus, the amount of time between the predictor variable and the predicted fall must ideally be kept as brief as possible to ensure maximum sensitivity.

To evaluate the relationship between movement path tortuosity and future falls, 53 ALF residents volunteered to have their normal daily ambulation measured within the lobby area of the ALF for a year. The Fractal D indoor tracking data were gathered as described earlier. Prior to the beginning of the observation period, participants were administered three formal assessments of balance, gait, and walking speed in a prescribed path. Their medication records during the observation period and the prior year were reviewed with an emphasis on antipsychotics, anti-depressives, strong pain medications, and antibiotics. Falls, recorded on standard incident reports, were evaluated to determine if they met the study's criterion for a movement-related fall (i.e. one not involving passively slipping from one's chair due to falling asleep). Many of the incident reports merely described the location and time the fall was discovered by staff, but omitted causal factors.

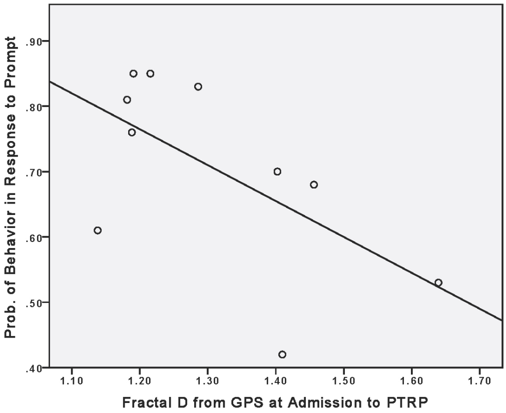

Figure 3. Negative correlation between likelihood of complying with customized prompts (vertical axis) as a function of Fractal D (horizontal axis) for 10 patients in a dedicated treatment unit for Traumatic Brain Impairment at the Tampa Florida Veterans Hospital. Relatively greater compliance is associated with greater treatment success. Figure reproduced from Kearns and colleagues, 2016.

Among 23 fallers, Fractal D values rose above baseline values between one and two weeks before the fall. Predictive value of medication use, performance on the formal gait and balance tests, and MMSE added very little or no predictive value beyond that of Fractal D. As in earlier research history of one or more falls in the year preceding the fall was the strongest predictor overall of a future fall. *Figure 4* shows the relationship between Fractal D and the probability of a fall with and without the addition of the fall history data for the prior year.

Fall prediction does not identify specific best practices preventive measures for the short interval between elevated Fractal D and the fall event.

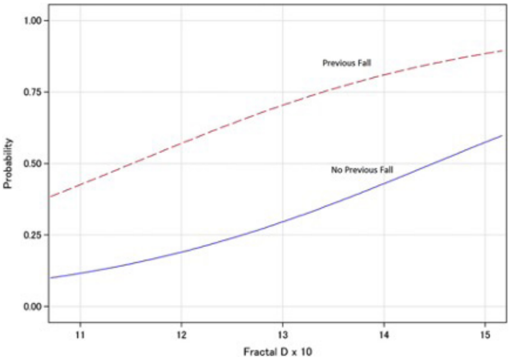

Figure 4. Relationship between Fractal D level seven to ten days prior to a fall (horizontal axis) and probability of a fall (vertical axis). Lower function is for Fractal D as the sole predictor; upper function is for Fractal D plus a history of one or more falls in prior year. Figure reproduced from Kearns and colleagues (2012).

An independent investigation, using the same type of monitoring system used in the research, is exploring possible intervention measures. The significance of these results is the potential for timely prediction of a fall in an unselected elderly population without the use of the traditional formal evaluation procedures. The data for the prediction comes from their unrestricted self-guided voluntary ambulation.

Using a machine vision-based system, Mehdizadeh & colleagues (2019) measured casual path movement variability over two weeks in residents of a dedicated dementia treatment facility. Using the number of falls as the outcome measure, they found that the number of falls (1-10 per participant) was positively correlated with higher step width and stride time variability as well as poorer performance on standard gait and balance assessments. Although Fractal D was not computed, the results suggest that the movements captured by the Kinect system could provide another method for describing movement path variability. Important differences between the Mehdizadeh study and earlier research include: the participants all had clinical diagnoses of dementia; the observation period was just two weeks, and many participants were excluded from the analyses because they had too few recorded movement episodes.

Path tortuosity in traversing a water maze by rats with drug-induced dementia or epilepsy

The Morris Water Maze is routinely employed to evaluate the impact of an experimental drug on the navigational ability of rodents. Test subjects are required to learn the location of a clear glass table hidden below the water's surface at the goal. Once learned, the rodent's time to traverse the distance from start to goal platforms is recorded. Deviations from the mean swimming time to the goal are assumed to be the result of the drug being tested. However, the time required by normal rats to locate and swim to the water maze goal increases with age, which necessitates the use of only littermates of the same age. Swimming times were greater in rats experiencing chemically induced dementia by scopolamine or epilepsy (Pentylenetetrazol). Fractal D was measured by counting the grids traversed in the optically recorded paths of the animals as they swam to the goal table. Path tortuosity was superior to swimming time as a measure and was insensitive to the effects of age because the measure was based upon spatial components. Across measures, latency was longer, and path distance and Fractal D were higher than saline-injected controls under both experimental conditions of scopolamine and pentylenetetrazol (Sujeet, Kaur & Sandhir, 2016).

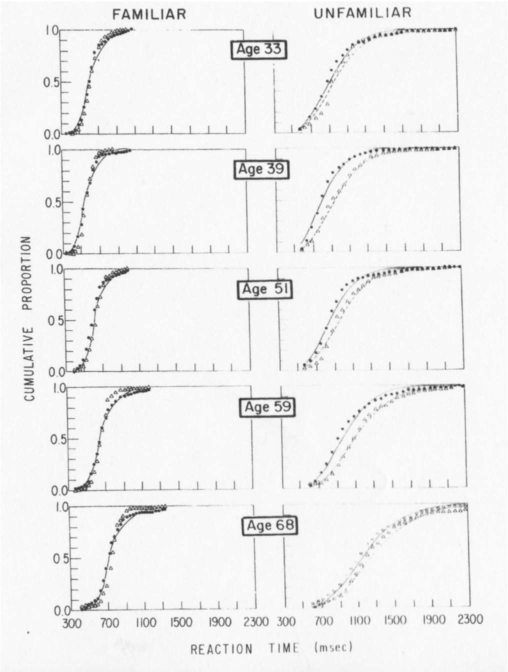

Figure 5. Frequency distributions of response latencies of correct decisions that a test letter was in a previously memorized set of six letters, abcdef (familiar set) or ptgkri (unfamiliar set). Each distribution displays successive latencies in 50 msec. intervals of all participants in the age groups with mean ages shown on the horizontal axis. The solid lines represent the values generated by the incomplete gamma function fitted to the distribution. Figure reproduced from Fozard (1984).

Path tortuosity while examining foods in a virtual buffet

Yaremych, Kistler, Trividi, & Persky (2019) studied paths generated made by parents of young children as they made food choices in a virtual food buffet, a tool used to study food selection behaviors of parents when choosing lunch items for their children. The choices made are then related to outcome questionnaires designed to elicit reasons for the choices made, such as concerns for the child's health, children's preferences, etc. The purpose of their research was to examine path tortuosity as a measure to describe movements involved in making choices themselves, rather than just relying upon the outcomes and questionnaire data. Their general hypothesis, supported by research results, was that greater path tortuosity would be associated with higher levels of cognitive effort made in choosing the child's lunch. In this situation, elevated cognitive effort reflects emotional factors such as guilt while selecting lunch items from the many categories of food in the buffet. Correlational analyses showed that elevated Fractal D (erratic paths while choosing food) was positively correlated with number of unique items and total calories of the lunch plate, and with feelings of guilt about the lunch items chosen. The significance of this study is that Fractal D can be used to characterize complex decision-making processes independently of post-administered questionnaires.

Response latency variability in choice reaction tasks may reflect the same cognitive processes measured by Fractal D

In older age, longer times are required to initiate and/or execute movements in choice reaction times in which choices are indicated by pressing one or another telegraph-type response keys. A common feature of these tasks is that the movement distances of the response keys are, by design, very short and calculation of measures such as Fractal D are not feasible. The reaction time choices are made over multiple trials so the frequency distributions of their times, in addition to average speed, can be used to describe variability. Just as movement speed decreases and its variability increases with age, both measures should change in the same way in choice reaction time.

Dykiert & colleagues (2012) performed a critical review and analysis of studies that published frequency distributions as well as means; the results supported the hypothesis; age differences could not be accounted for by the positive correlation between mean and variance (coefficient of variation) in skewed frequency distributions.

The simultaneous age differences in average speed are illustrated visually in *Figure 5* by Fozard (1981, Figure 3.10, p. 84) using data from Thomas, Waugh, & Fozard (1978). Male participants in the mean age groups shown on the horizontal axis of *Figure 5* pressed one key for 'yes' when a test letter presented was in a previously memorized set of six letters and the other key when it was not. One memorized list of letters was, in order, abcdef, (familiar), in the other, ptgkri, (unfamiliar). The frequency distributions are the mean values of all participants within the named age group. Each data point shown represents successive 50 msec. intervals. The continuous functions represent values expected from the incomplete gamma functions applied to the distributions.

Mean speed and variability increased with age, more so in the unfamiliar condition. The increases were most evident in the longer times in the distributions. The overlap with age in the fastest responses shown in the lower half of the frequency distributions indicates that older persons generate response times as short as younger participants, however, they generate fewer of them. One comment by a listener during a presentation including *Figure 5* at a meeting of the Psychonomic Society in 1974 commented that in most reaction time studies with young adults the long response times displayed would be excluded from the analysis because they represented outliers unrelated to the research question being addressed.

Applications based movement path variability and location in congregate settings

The applications of movement path variability described above all involved formal research studies. Most applications of the underlying Ubisense RTLS do not involve research applications, but rather control of the sequence of manufacturing processes or the remote location of human and machine assets in complex environments such as hospitals and factories. The Ubisense RTLS can simultaneously monitor movements and locations of multiple persons sharing the same monitored space as illustrated in the study of veterans being treated for TBI. Similar applications not described in formal studies include the behavior of multiple persons viewing particular merchandise displays or art items in a museum gallery. It can be used to measure the distances between people sharing the same physical space. A relatively new application described by Ubisense (Market guide for social distancing Technology – Ubisense 2020) automatically monitors the distances among multiple persons in a monitored space and sends automated warning messages to persons whose separations violate social distancing guidelines. The social distancing guidelines have proven to be one of the most difficult to control and monitor (CNN, May 5, 2020). A Florida-based company that licensed the University of South Florida patented Human and Physical Asset Movement Pattern Analyzer has produced a similar commercial application of this technology. Because of its newness, the extent and usefulness of this application have not yet been formally reported.

Discussion

Computation of Fractal D requires no temporal information such as rate or time spent walking. It can be computed using ANY source capable of generating X and Y coordinates from a location grid. A path left in stone by a dinosaur over 1 million years ago, one generated by a college sophomore in a college laboratory, or the length of the coast of Britain can be analyzed in the same way. This provides an additional tool for analyzing movement by temporal measures, especially those that may require gathering walking speed or the total distance traversed during extended periods, e.g., body-worn technology capable of operating for perhaps several days in order to gather sufficient samples. In our research relating cognitive difficulties to movement paths, Fractal D was especially useful because the movements were generated freely by those monitored. Fractal D was calculated only when the person moved. Spatial variability in an open field measured by Fractal D, provides insights to cognitive performance using relatively small surveillance windows, even as small as an assisted living facility lobby, a virtual space, or a maze - see Ngankan, et al (2020) for a review. Age-associated behavioral slowing has been a central core of gerontological research since its inception. Response speed and Fractal D provide complementary ways of analyzing such behavior: speed defines the total time to complete a movement, however achieved, while Fractal D provides a measure of how that movement activity is accomplished (tortuosity).

The measurement of movement path tortuosity of humans was first developed to study the behavior of persons with cognitive impairments or dementia. It was adapted from ethological research characterizing free movements of wild animals in native habitats. It is applicable to the study of movement with or without aids such as canes, walkers, or wheelchairs (Kearns & colleagues, 2019). Its analytical qualities when coupled with precision real-time location sensor systems are superior to direct human observation, e.g., police officers determining if a driver is inebriated or determining patterns of wandering behaviors for reasons outlined earlier. The procedures employed in our prior investigations allow the free movements of more than one hundred different persons to be monitored in the same area for extended periods of months or years.

Fractal D is higher in older age, in cognitive deficits, and in elderly persons with mild cognitive decline or dementia, and in adults with traumatic brain injury. In traumatic brain injury cases, Fractal D is positively related to the severity of the injury and declines over time with rehabilitation. It can be measured from indoor or outdoor ambulation monitoring devices.

The use of short-term changes in Fractal D to predict future falls was derived from the extensive body of controlled studies relating movement patterns to falls. The basic hypothesis was that path tortuosity would capture some of those features even though they were not specifically identified in Fractal D. This idea is consistent with the interpretation of the results of Mehdizadeh and colleagues (2019).

Some different procedures for calculating Fractal D were illustrated in the research on lunch selection in a virtual buffet, and maze swimming by rats cited above. Kolokowski and colleagues (2020) describe a procedure for increasing the range sensitivity of Ultra-wideband real-time location systems that can augment the areas surveyed by this technology.

There have recently been significant developments in the use of GPS-based technology to describe outdoor movement trajectories indicative of wandering behavior, (Kearns and colleagues, 2015; Kin and colleagues, 2015). Martinez-Balliste, Al-Molegi, and Batiste (2018) published a comprehensive and elegant discussion of ways to identify wandering in large published ambulatory movement trajectories for both indoor and outdoor movements. The same basic elements used in Fractal D—the locations and rate of sampling of successive X and Y positions—are described in several ways: the ratio of sharp to small turns, evaluation of the complexity of the visual displays of the paths, etc. The application of these approaches was illustrated using several large published movement trajectory data sets. A similar but less comprehensive review of various analyses of movement path trajectories is given by Abdulrahman & colleagues (2016).

It is anticipated that the development of methods to describe movement paths can be applied economically to individual 'smart home' technologies. Oftentimes movements in these technologies are described using passive sensors activated when a person passes nearby (motion detectors). The applications sense exits and/or entrances to individual rooms in the house, or a person passing by a series of sensors within a monitored space. A good example of the use of these systems is provided by Kolokowski & colleagues (2020), who devised a smart house application to measure nighttime wandering by an elderly woman living alone. The application included the automatic spoken message urging the resident to return to bed when the door to the house was opened late at night.

Moffat (2009) described the importance of movement variability as a tool to understand the role of environmental cues that guide orientation behaviors. Many possible applications are using Fractal D to study the time spent and locations utilized by persons related to the use of appliances, furniture, location of objects of art, other persons, etc. in common spaces, e.g., lobbies in congregate living spaces, art museums, offices, etc. Retailers would obtain useful information about optimal display locations for items in the store. This type of application was illustrated in the study of meal selection cited. Because Fractal D can be obtained on the same individual's movements in both indoor and outdoor settings, the variety of potential applications increases. For example, Fractal D may be measured in self-guided wheelchair movements. This suggests that passive Fractal D monitoring devices could evaluate how safely a powered wheelchair may be guided by an elderly user, who may have cognitive deficits. Kearns & colleagues (2019) reported results of a focus group study indicating that such a device would be acceptable to powered wheelchair users and their caregivers. Such a device would also be a useful aid in the ongoing development of automatic movement controls.

Conclusion

This review has described many examples of the use and usefulness of location-aware technology in the description of movement path variability. Examples ranged from studies relating Fractal D to cognitive deficits in elderly and young persons, fall prediction, to a selection of meals in a virtual buffet, and automatic monitoring of multiple persons in a common space. The common feature of these applications is the use of ordinary self-guided ambulation as the basis for the analyses. This provides a useful addition to the existing formal procedures used to study movement.

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