Multilevel linear and temporal analyses on the effects of weather indices on movements and behaviors

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Abstract

Weather indices significantly affecting movements, affective, and behavioral states remain largely unknown among children with profound or severe intellectual and multiple disabilities (PIMD/IDs). Main, seasonal interaction and 24-hour time-offsets effects of outdoor weather indices on the movements and behaviors of children with PIMD/IDs were explored using hierarchical and general linear models. Caregiver-interpreted facial, body, and limb movements and behaviors of 20 8-to 16-year-old children with PIMD/IDs and simultaneous online-API-and-sensor-collected app-based weather, proximity and time data were collected in 105 single-dyad video-recorded (30-hour) natural-child-caregiver-dyadic interactions over 5 months. Fluctuations in outdoor atmospheric pressure, humidity, cloudiness, wind speed, season, daylength, time (12 to 1 pm), and conditions were predictive of variations in movements and behaviors, which in turn, also responded to increased indoor UV, humidity, and cloudiness levels during winter, and increasing atmospheric pressure and decreasing humidity during fall. While outdoor temperature, atmospheric pressure, humidity, and cloudiness immediately affected variations in movement and behavior outcomes, time-offset wind-related indices had significant delayed effects at several time lags. Evidently, variations in movements and behaviors of children with PIMD/IDs are affected by seasonal variations and current or delayed fluctuating levels of outdoor weather indices which has significant implications for communication and educational interventions.

Introduction

Consistent patterns of differences in weather variable indices associated with physical activity and movement-related behaviors have been documented in literatures across ages and settings[1–3]. Several investigations have also identified seasonal and geographical weather variations associated with or predictive of childhood behavioral and affective states[4–7]. This field of study has also broadened yet finding inconsistent current or delayed effects of fluctuations on weather indices between adults and children with psychiatric, neurological, or behavioral conditions[8–15].

Varying levels of physical activities among children were found associated with age and gender, and several geographic and weather indices. A repeated measures study found variations in the relationships between temporally auto-correlated local weather conditions and daily accelerometer-measured physical activities (counts per minute or cpm)[2]. Multilevel regressions revealed that lower levels of mean cpm were associated with increased precipitation (113.2/cm) and wind speed (-10.3/10kph), higher visibility (10.3/10km) (measure of how far humans can see), and longer hours of daylight (daylength) (7.6/h). Interestingly, the interactions between temperature, precipitation, age, and location showed greater associations indicating younger children and participants from Northern European countries and Australia were more active as compared to those from the US and Western Europe[2]. A relatively more recent study among 6–12-year-old children also investigated accelerometer-monitored physical activities and sedentary behaviors from a 7-year longitudinal health-oriented project which were cross-sectionally analyzed and matched with weather conditions and seasons[3]. Although no distinct patterns were found in the association between season and behavior outcomes, longer daylengths (1-hour increase) were associated with lesser sedentary behavior (by 2 mins.), and age- and sex-adjusted warmer temperature (every 5°C) and dryer weather increased moderate-to-vigorous physical activity (MVPA) by 72 mins. in males and 67 mins. among females[3].

Levels and domains of behavioral and affective states of children related with variations in weather indices have also been gaining attention for decades across settings and seasons. Increasing humidity and temperature were positively correlated with irritability and externalizing problems, and alertness, respectively, while solar radiation had positive association with level of positive feeling of enthusiasm and emotional strength, which in turn had negative correlation with problematic behaviors among children[4,5]. More recently, in analyzing the impact of winter weather conditions on the day-care collected behavior and affective states of 61 3-to-36-month-old children using multilevel linear models, Ciucci, Calussi, and Menesini[6] found that humidity and solar radiation were main predictors of children's affective and behavior outcomes. Specifically, the levels of frustration, sadness and aggression increased (by 0.02, 0.02, and 0.01, respectively) as outdoor humidity increased, and decreased as solar radiation increased (by 0.23, 0.40, and 0.29, respectively). In a follow-up study among 2- year-old children across different seasons, they concluded that relative outdoor humidity was also found to be a good predictor of children's behavior and affective states in any season[7]. Multilevel hierarchical regression models revealed outdoor humidity (-0.63) which is positively influenced by outdoor temperature, decreases activity level and increases attentional focusing during summer (0.39). Conversely, outdoor humidity has positive effect on levels of frustration (0.19) and aggression (0.15) during winter.

There also exists a considerable body of literature on the significant current or delayed effects of fluctuations or variations in weather indices among adults with psychiatric, neurological, or behavioral conditions. For instance, in a time-series analysis study, associations between lagged daily weather variables and symptomatology in a patient suffering from recurrent anxiety disorder were examined. Results revealed that energy levels were lower when the wind blew from the southeast[8]. In another study, increased incidents of aggressive behaviors based on coercive measure records among psychiatric patients were also investigated[10]. The frequency of coercive interventions following aggressive behavior incidence was associated with drop in barometric pressure and humidity, and higher air temperature and foehn wind. Further, a review of literature on the effects of ultraviolet (UV) light on mood, depressive disorders and well-being found studies demonstrating increased positive affect and decreased negative affect and depression scores after UV light stimuli exposure intervention among patients with fibromyalgia syndrome, dermatological conditions, multiple sclerosis, and seasonal affective disorder (SAD)[9]. The current and delayed effects of the duration of sunshine and global radiation among other factors linked to periods of low natural light (horizontal visibility, cloud cover, and mist) and temperature, humidity, and pressure, were significantly linked to SAD symptoms according to a longitudinal 6-year symptom evaluation among 291 individuals with SAD[11]. Another more current large-scale hospital-based time-series longitudinal multi-site analysis study also assessed the short-term delayed association between climatic factors and daily hospital admissions for schizophrenia from 1996 to 2015[16]. Linear and lag non-linear models revealed regional variations on the immediate negative and positive effects of daily mean temperature, air pressure, and relative humidity respectively, on schizophrenia admissions. Significant geographic within-region variations and pooled delayed effects of temperature (0–4 lag days), relative humidity (0–7 days), and rainfall (0–21 days) on hospital admissions for schizophrenia were also observed. Several other hospital-based studies also examined and found nearly similar results on the clinical significance of fluctuations in weather indices such as atmospheric pressure on patients with migraine, epileptic seizures, and affective disorders. Okuma, Okuma, and Kitagawa[12] found that slight fluctuations or decreasing atmospheric pressure by 6–10 hPa from a standard level of 1013 hPa stimulated frequent migraine attacks in adult patients with migraine[12]. Similar hPa trend index (every 10.7 hPa) was found to be associated with an increased risk (of 14% and 48%) for epileptic seizures among adult patients with unprovoked epileptic seizures and high relative air humidity (> 80%) in a bidirectional case-crossover study conducted by Rakers et al.[13]. However, in contrast, high ambient temperatures (> 20°C) decreased the risk for the seizures by 46% more in males than females. Likewise, among other weather parameters such as sunshine hours, diurnal variations in temperature and rainfall, a significant delayed effects of relative humidity to the daily numbers of psychiatric admissions for affective disorders has also been reported by Salib and Sharp[14].

Investigating the associations between weather conditions and human affective or behavioral states and physical activity have potential implications to parenting, teaching and support interventions that ranged from classroom management, program promotion initiatives to improving ecological and physical environment as well as for childhood social relationships development[2,3,6,7]. This field of study also constitutes an important role in reducing the severity and predicting or preventing the occurrence of psychiatric and neurologic symptomatology and related risks among adults[10,12,13,16]. Despite the considerable number of extant literatures, studies involving children with neurologic, motor, or physical disabilities and functioning impairments are surprisingly inadequate. Thus, VanBurskirk and Simpson[15] considered this underexplored area to be a justified and significant subject for investigation. They explored whether barometric pressure, humidity, outdoor temperature, and moon illumination affect classroom-collected behavioral data of three children with autistic disorders with significant behavior problems (screaming, falling to the floor, head-butting, biting, kicking, hitting, and elopement). Interestingly, there is little to no empirical evidence that the behaviors of the children were affected by weather conditions or moon phase inferring these variables are not robust behavioral influences[15]. Although results appear inconsistent with prior studies among typically developing children and psychiatric studies among adults, the authors argued that the findings were likely to be influenced by methodological limitations of this preliminary study which clearly do not rule out weather variables affecting the aberrant behavior of the children with severe disabilities. The inherent heterogenous autism-related disabilities, the small sample size of children who were attending school with heated indoor environment (thus, less interaction with ambient outdoor temperature) who were followed for a brief period during winter, and the extreme snowing halting classes prior to the study may have confounded weather indices variations affecting the behavior outcomes[15]. These limitations point out that this problem remain an area of significant interest for hypothesis testing to provide rationale for including weather as focal point to interpret the behaviors of children with neurological, behavior or motor impairments for support and intervention.

Children with profound intellectual and multiple disabilities or PIMD, as the name implies, have severe or profound intellectual disabilities (IDs) (IQ < 25) which are often combined with chronic health, sensory or functional impairment comorbidities (e.g., epilepsy, visual impairments, deformations, incontinence, and reflux). These impede understanding spoken or verbal language and symbolic interaction with objects limiting communication[17–22]. Due to profound or severe neuromotor dysfunctions, their communication is often on a presymbolic (nonsymbolic) or protosymbolic level with no shared meaning and manifested through atypical, minute, and refined movements and behaviors[19–21,23–25]. These limited their communication group as their caregivers are the most capable of discerning and interpreting the mostly unique and idiosyncratic movements and behaviors[20,23,25,26].

Supporting communication among individuals with PIMD/IDs is crucial and constitutes a great significance for several prior inquiries on describing assessment approaches and psychometric properties, peer- or sibling-directed interactions, and dyadic dialogical meaning making[19,20, 22–24,26]. Nevertheless, since the use of standardized assessment tools which are unlikely sensitive to the complex and atypical development trajectories of children with PIMD/IDs[24,27], other observational pragmatic evidence-based studies have focused on behavior categorization and contingency awareness intervention and training. Two classroom-based observational studies analyzed the expressive behaviors of two children aged 7 and 13 years old (had developmental age of 4 months and 1 month, respectively). Ashida and Ishikura[28] were able to identify six major behavior and movement categories: eye movement, facial expression, vocalization, hand movement, body posture, body movement and non-communicative behaviors (others). In a follow-up study that focused on intentions, which showed that while one of the children showed many active movements of the arms, legs, and eyes, and expressed intentions and feelings through changes in gaze and smiles, the other one had limited movements of the head, neck, mouth, and eyes and expressed intentions and feelings through changes in line of sight. These suggest variations in sensory stimulation activities to encourage expression of feelings and intentions among these children[29]. The possibility of developing contingency awareness or cause-and-effect movement-environment learning to enable communication among individuals with PIMD has also been explored. Increasing alertness or focus of attention and gross body movement and elicit more positive affect was the aim of a single case with inter-and within-case replication study by van Delden and colleagues[30]. The levels of the three target outcome measures were compared during, before, and after the introduction of a remote-controlled interactive ball that responded to body movement, focus of attention and vocalizations of nine adults (aged 24 to 62 years old). Higher levels of alertness improved affective behaviors, and variable changes in the movements during interaction with the ball were only observed among two to three participants implying heterogeneity in individual characteristics and abilities of the target user group suggesting individualized interaction intervention protocols[30].

The closest germane to the present investigation is a case-study series conducted by Blain-Moraes and Chau[31] who attempted to train a 15-year-old adolescent with PIMD to voluntary control his four physiological autonomic nervous system (ANS) signals (electrodermal activity (EDA), skin temperature, cardiac and respiratory patterns) to enable interaction without motor movements. Although unsuccessful, ANS signal patterns revealed three main challenges of developing physiological signal-based access pathways for individuals with PIMD. They discussed in length that more than the unambiguous caregiver's interpretation of child responses and lack of contingency awareness among the participants, addressing the intrasubject variability of physiological signals is of utmost significance and must be addressed by assuming a constant baseline physiological state which are contextually affected by environmental factors such as season, emotional state, and time of day, before technologies that measure target outcomes can be developed[31].

Latest innovations in technology have enabled the field experiment and collection of wide variety of real-time, efficient, accurate and consistent data using smartphones and apps[32–34]. The development of an app especially designed to aid in the identification and categorization of behavior-related movements and in the simultaneous collection of associated sensor and online API-collected weather variable data was introduced in prior literature[25]. Proximity sensing and location data have also met great success in aiding the interaction and communication of children with intellectual or speech disabilities[35,36]. This was an initial step in developing a novel movement and behavior inference system to understand the context of the interaction and support the communication of children with PIMD/IDs[25]. To extend and provide more insights, this current study aimed to explore the main and seasonal interaction effects and the immediate or delayed effects of weather indices, proximity sensing, and time-derived data (environment measures) on the movements and behaviors of children with PIMD/IDs.

As evidence suggest on physical activity and movements, potential significant effects of variations in relative humidity or precipitation, daylength, temperature, and wind speed indices on upper or lower body or limb movements and vocalizations of children with PIMD/IDs were hypothesized. Fluctuations in relative humidity, temperature, atmospheric pressure and UV light indices and wind direction would also have potential varying effects on the response, affective, or physiological behaviors consistent from the findings of previous similar investigations. Further, seasonal interaction and current or delayed effects of indoor or outdoor weather indices and child profile factors (e.g., age and gender) affecting the target movement and behavior outcome measures would also be significantly revealed in the multilevel models congruent with previous investigations. This study is exploratory in terms of the effects of the proximity sensing location data and the children condition to the variations in movements and behaviors of children with PIMD/IDs.

Methods

Participants

Twenty child-caregiver dyads were recruited at a special needs school. The children had an average age of 11 ± 06 years, ranging from 8–16 years (3rd grade to 1st year of high school) who were mostly males (n = 14; 70%) and had either PIMD (n = 16; 80%) or severe or profound ID diagnoses. Their caregivers who have been supporting them for years, had utmost familiarity, comprehensive schema, and particularly capable of interpreting their movements and behaviors. This study was part of a project protocol that was approved by the Ethics Committee of the Faculty of Education, Ehime University (approval number: R2-18) and all methods were performed in accordance with the relevant ethical guidelines and regulations[37,38]. The parents or caregivers of all participants provided their consent for the child's participation in this study by signing a written informed consent form. They were also informed that their participation in the study was voluntary and that they may stop their participation at any time. All data that contain participant information or identity were coded and blurred, respectively, and are stored in a password-protected network server database and computer for their protection and privacy.

Data collection

All child-caregiver dyads were observed in multiple single-subject face-to-face sessions targeting typical child movements and behavior contexts in natural dyadic caregiver- or peer-directed interactions during morning greetings, lunchtime, and break time (from 8 am to 1pm). The previously developed ChildSIDE app was utilized to record the caregivers' interpretations of the target outcomes with associated environment data (proximity, time, and indoor and outdoor weather indices). For retrospective inter-rater agreement outcome categorization analyses, one videotape recorder (VTR) in a tripod positioned two meters from the participants was used to record the upper, lower body and limb movements and behaviors manifested in all dyadic interactions relating to the intentions of the children. There were 105 sessions conducted with a total of 30-hours video recording time. Video-recorded sessions were generally 18.5 minutes in length (ranged from 0.37 to 54 minutes, SD of 12.5 minutes per session). One to 15 sessions per child (with an average of five sessions per child) were conducted in 16 days with one-week intervals over a 5-month period between September 2019 and February 2020.

Measures and preprocessing

Movement and behavior outcomes

The obtained 291 individual behavior data were subjected for inter-rater agreement Kappa statistics analyses after the exclusion of 7 test data, 73 undetected, had no associated environment data. Independent behavior expert raters retrospectively analyzed the video recordings at slow speeds frame-by-frame. Individual behavior data was coded and categorized to produce the outcome measures. The categorizations employed inter-rate agreement procedures with Kappa statistics computation to reach consensus based on fair (0.21–0.40) to almost perfect (0.81–0.99) agreement levels.

Upper and lower body and limb movements extracted from each individual behavior data were then categorized into six categories. *Eye movements* included gazing at people and things (especially unfamiliar faces), tracking the movements of people and things in linear fashion, changing line of sight different from gazing and tracking, and voluntary blinks. Movements that involved smiling, showing facial expression, or being surprised, frowning, sticking out tongue (other than smile) on concentrating or listening on different stimuli were categorized as *facial expressions*. Vocalization or producing sound was considered as both major and minor category. Pointing hand or finger towards an object or the action of reaching or chasing after reaching the target (not pointing hand or finger), and grabbing, hitting, pushing, or raising hands were categorized as *hand movements*. *Body movements* comprised of head or upper body moving close to a person or an object, touching people and things with hands and body which do not include unintentional ones, and movement of any part of the upper body (shaking, bending, moving mouth, etc.) including head and neck, and upper or lower limbs. Stereotypical or movements occur in certain repetition (finger sucking, shaking hands, rocking) or self-and others- injurious behaviors (e.g., biting finger and hitting someone) and other movements with no meaning were all categorized as *non-communicative movements*.

Behavior outcome categories were based on the indicators, codes, or categories of the Attuning Theory: engagement (joint attention), assent, emotions, interest, and negative attuning (refusal). Griffiths and Smith[39] discussed in length and great detail how people with severe or PIMD communicate suggesting that it is regulated by the process of attuning which describes how they move towards or away from each other cognitively and affectively. It consists of seven discrete but dynamically interrelated categories namely: *setting, being, stimulus, attention, action, engagement, and attuning*. These occur in an environment or *setting* which is described as the total context of a place that influences the individuals' *action* or their feelings or state of mind (their *being*), which influences how each person behaves (*stimulus)* or attend to each other (*attention*) and the nature of the interaction (*engagement*). In this study, we used the structure (anti and pro and negative and positive), typology (from screaming to harmony), indicators (looking at each other, movement towards each other, smile, close physical contact, gaze, expression, etc.) and codes (concentration, interest, and support) to categorize the manifestations of the behaviors of children with PIMD/IDs.

The first category focuses on the *engagement (joint attention) or calling* behaviors which may be directed to the same focus aiming to get the attention of the caregiver or teacher manifested verbally (greetings, vocalizations) or non-verbally (smiling, staring, pointing). The attuned agreement between the dyad demonstrated when one partner carries out an action or asks a question and the other respond in a clear affirmative manner is termed *assent or response*, manifested by saying "yes" or raising, waving, or clapping hands or nodding head. The mostly non-verbal expressions of *emotions* in the context of harmony (mutual satisfaction), pleased (contentment), pleasure (intense and direct satisfaction) or feelings of being happy, excited, perception of fun, and being upset (tension) and distressed (interim level of anti-attuning) or feelings of being angry, worried, troubled etc. (e.g., smile, moving or opening mouth, shaking head vertically or body, looking away, etc.). Another category is *interest* which is demonstrates an obvious attention and interest in (attuning to) the action, and the result of the interplay of attention and action is that the attuning level of the dyad. It is manifested in verbal (e.g., "let me see", "yes!", "what's that?") or non-verbal (e.g., pointing, raising hands, standing up, nodding, etc.) behaviors that hint interest in an object, person or action or doing an action. The behaviors that are manifested through verbal (e.g., "no", "don't like", "dislike" or "end") or non-verbal actions and vocalizations (e.g., closes mouth, sticks out tongue, turns face away) to express refusal or disagreement, or the dyads do not accede to the wishes of the other so the interplay between the dyad is negative, thus *negative attuning*. New categories were also developed as required. *Selecting* behaviors were mostly non-verbal actions or gestures (e.g., pointing, tapping, reaching) to express decision or desire to choose between or among objects. Verbal (e.g., saying "rice", "sleepy", "thirsty", etc.) and non-verbal (e.g., closing eyes, not opening mouth) vocalizations and actions to express functions or desires relating to normal physical or bodily responses were categorized as *physiological responses*. Behaviors with no shared meaning or interpretation like rocking the body in a sitting position, rolling onto back and shakes the whole body, looking backwards or moving face up and down were termed *unknown.* Lastly, *positive* attuning is a state where the dyads are attuned and understands each other, and both agreed as to what is happening and what should happen. However, individual behavior data relating to positive behavior manifestations were excluded due to insignificant frequency size.

Environment measures

Hourly real-time mean indoor and outdoor weather indices values, and timestamp-derived data associated with each individual movement data across the study period (fall: September 23rd to December 21st ; winter: December 22nd to March 20th, 2020) are shown in Figs. 1 and 2. Indoor weather indices values were acquired from The IoT Smart Module Sensor Network Module Evaluation kit, a multifunction Bluetooth sensor (ALPS Sensor: UV/ambient light, pressure, temperature, and relative humidity) ultracompact module in real-time (Fig. 1). The current real-time local outdoor temperature values (°C), atmospheric pressure (hPa), humidity (%), cloudiness (%), wind direction (degrees), wind speed (meters/second), sunrise and sunset times and date-stamped current time were transmitted from the OpenWeatherMap API, an online service that uses a highly reliable numerical weather prediction model from several data sources (global: NOAA GFS 0.25 and 0.5 grid sizes, NOAA CFS, ECMWF ERA; weather stations: METAR stations, users'stations, companies' stations; and weather radar data and satellite data).

Considered as relatively low index values (0 to 2 mW/cm2), the average (0.07 mW/cm^2) and the minimum (0.03 mW/cm^2) hourly indoor UV-A (0 to 20.48 mW/cm2) (solar radiation penetrating windows) index values were the same during fall and winter. Similar trend was found in the index values of ambient light (0 to 81900 Lx), defined as natural or artificial source of light (e.g., open window, fluorescent or light-emitting diode (LED) light) in a room which is measure by illuminance level (Lx). The average illuminance level during fall and winter were nearly the same (ranged from 322 to 335 Lx). However, a sudden increase in UV-A and ambient light on November 12th at 11 am resulted to a maximum UV-A index value of 0.64 mW/cm^2 and 3771.5 Lx during fall, 0.52 mW/cm^2 UV-A and 3,130 Lx higher than during winter (0.13mW/cm2 and 641 Lx). Usually ranges from 300 to 1100 hPa, atmospheric pressure or barometric pressure is an indicator of weather wherein high-pressure system leads to cloudiness, wind, and precipitation, while high pressure systems usually lead to fair and calm weather. The average (1010 to 1022 hPa), minimum (1005 to 1017 hPa), and maximum (1016 to 1027 hPa) atmospheric pressure index values were nearly identical indoor and outdoor (with 10 hPa difference) and during fall and winter (1 to 3 hPa difference). In both season, higher temperature levels (average: 19 to 22°C; range: 13.5 to 30°C) were recorded indoors compared to outdoors (average: 9.8 to 16°C; range: 4.9 to 27.6°C). For relative humidity (0 to 100 RH%) or the amount of water (moisture) vapor in the air relative to the temperature, an inverse pattern was observed. Humidity levels were higher outdoors (average: 55 to 64.9RH%; range: 43 to 90 RH%) than indoors (average: 49.5 to 58.4RH%; range: 40.5 to 88.4 RH%). Seasonal variations in humidity levels indoor and outdoor were also observed recording higher levels during fall (average: 58.5 to 64.9RH%; range: 43 to 90 RH%) than winter (average: 49.5 to 55.6RH%; range: 40.6 to 72.1 RH%). Cloudiness or cloud cover, which refers to the fraction (%) of the sky covered by clouds signals the presence of either high or low-pressure system. Cloudiness levels were almost the same during fall and winter seasons, with an average of 59 to 60% (range: 20–75%). Measured by degrees (0 to 380°) spanning four compass points (NE, SE, SW, and NE) wind direction is defined as the direction the wind is coming from. It was observed that almost 73% of the time, the wind was blowing from the northeast (NE), followed by the northwest (NW) direction (14.5%). Almost equal average, minimum, and maximum wind speed (how fast the air is moving past a certain point, measured as meters/second) index levels were recorded during fall and winter (4.14 to 4.17; range 0.83 to 9.73).

Daylength, the total number of hours between the sunrise and sunset times were nearly constant (0.1 to 0.8 hours) during fall (average: 10.88 hours, range: 9.9 to 12.1 hours) and winter (average: 10.7; range: 10.1 to 11.3 hours). While time variable categories (10 to 11am, 11 to 12 pm, etc.,) were derived from the current time stamps, location data were derived from iBeacons. iBeacon is a technology based on BLE proximity sensing that provides proximity-based app services, and coarse-grained indoor location positioning and navigation transmits proximity measurements based on the Received Signal Strength Indicator or RSSI (signal strength relevant to the receiving device which ranges from − 26 to − 100 inches) and an iBeacon name which was used to identify 18 indoor locations (e.g. playroom, classroom, music room, etc.,). Prior to each session, one iBeacon device and one ALPS sensor was placed 2 meters (m) (actual distance) from the app with an estimated mean distance of 2.18m, mean error of 0.18m, and with an RMSE (root mean square error) of 0.41m.

Data preprocessing

The app-based data acquisition infrastructure continuously sampled real-time time-stamped movement and behavior data with simultaneous proximity sensing location and weather indices (hourly change rates) and transmitted to a third-party database service provider. Prior to analysis, missing single or multiple proximity (iBeacon; n = 45) and indoor (UV range n = 98) weather index values in each session were replaced with the nearest non-missing within-session data (proximity), or with an estimated value (using the mean) of the nearest known or non-missing data values using the k-Nearest Neighbor (k-NN) imputation (k = 14). Missing outdoor weather indices (n = 14; wind direction n = 35) were obtained from the online weather data source to include all observations with a complete set of environmental data (complete cases) and avoid relatively large errors in multilevel models.

Most importantly, to minimize multicollinearity in multilevel linear modeling, significant and highly correlated (> 0.70) indoor and outdoor indices were identified (Table 1). Indoor UV was highly correlated with indoor ambient light (r 0.94, p < .001). As expected, outdoor atmospheric pressure index was highly correlated with the indoor atmospheric pressure index (r 0.85, p < .001), while outdoor index of temperature was highly correlated with both temperature (r 0.75, p < .001) and humidity (r 0.74, p < .001) indoor indices. Thus, because of this and the lack of time-offset values, indoor weather indices values (except for UV), were discarded subjecting only the outdoor indices values and UV for multilevel linear modeling and temporal analyses. Complete hourly observed values of outdoor weather indices (atmospheric pressure, temperature, humidity, wind speed, and wind directions) > 24 hours prior to each session were also obtained from Open WeatherMap API to evaluate possible current or time-offset delayed effects of weather variables to the movement and behavior outcomes. Current weather index values (0-offset model) that were matched to the observation session starting hours (8–9 am) were lagged by offsetting it 24 times.

Before predictor variables were entered to the models, all continuous (indoor UV, outdoor atmospheric pressure, temperature, humidity, cloudiness, wind speed, and daylength) including the 24-hour temporal offsets of outdoor indices, and dummy coded (transformed) categorical (wind directions: northeast, southeast, southwest, northwest; seasons: fall and winter; time: 10 to 11am, 11 to 12 pm, and 12 to 1 pm) weather variables were centered to reduce multicollinearity issues and *posthoc* analyses for seasonal interaction effects.

Table 1. Weather measure correlations.

		1	2	3	4	5	6	7	8	9	10
1	Ind_UV	1	**0.94*****	-0.06	0.02	-0.21	0.02	-0.04	-0.11	0.17	0.02
2	Ind_AL	**0.94*****	1	0.02	-0.01	-0.32*	0.08	-0.09	-0.15	0.09	0.01
3	Ind_AP	-0.06	0.02	1	-0.37	-0.41**	**0.85*****	-0.44**	-0.56***	-0.15	0.37
4	Ind_temp	0.02	-0.01	-0.37	1	0.37*	-0.27	**0.75*****	0.33*	-0.17	-0.17
5	Ind_hum	-0.21	-0.32*	-0.41**	0.37*	1	-0.41**	**0.74*****	0.47***	0.21	-0.06
6	Out_AP	0.02	0.08	**0.85*****	-0.27	-0.41**	1	-0.45***	-0.65***	-0.22***	0.38***
7	Out_temp	-0.04	-0.09	-0.44**	**0.75*****	**0.74*****	-0.45***	1	0.43***	0.12***	0.02
8	Out_hum	-0.11	-0.15	-0.56***	0.33*	0.47***	-0.65***	0.43***	1	0.21***	-0.33***
9	Cloud	0.17	0.09	-0.15	-0.17	0.21	-0.22***	0.12***	0.21***	1	-0.07
10	WindSp	0.02	0.01	0.37*	-0.17	-0.06	0.38***	0.02	-0.33***	-0.07	1

Note: Ind = indoor; Out = outdoor; UV = ultraviolet; AL = ambient light; AP = atmospheric pressure; temp = temperature; hum = humidity; Cloud = cloudiness; WindSp = wind speed; *p < 0.05, **p < 0.01, ***p < 0.001

Statistical analysis

The main, seasonal interactions, and current and delayed effects of indoor and outdoor weather measures on the movement and behavior outcomes were analyzed using hierarchical linear modeling (HLM) computed by the R function “glmer” in lmerTest package. These data were repeatedly observed in each child and collected simultaneously in each location (classroom, playroom, music room, etc.) thus providing hierarchical structure nested within children (age [in years], gender [male or female], conditions [profound ID or PIMD], and education levels [elementary, junior high school or senior high school]) (level 1) and location (classrooms, music room, playroom, etc.) (level 2). In this two-level model, the total variance of movement and behavior outcome variables are decomposed into children and location levels variance which provides information on between-children and location differences. In analyzing the null model using random intercept-only model where each model had two random-effects (children level indicator and location data level indicator) accounted for variability among children and location characteristics using this formula:

Level 1:

$$y_{ij} = \beta_{0ij} + r_{ij}$$
$$r_{ij} \sim N\left(0, \sigma^2\right)$$

where y_{ij} represents the outcome y for level one unit i nested (children level indicators) in level two unit j (location data level indicators) and is equal to $\beta_{0ij,}$ (a level one intercept) and r_{ij}(residual or unexplained variance) (Anderson D., 2012).

Level 2:

$$\beta_{0ij} = \gamma_{00} + \mu_{0i} + \mu_{0j}$$
$$\mu_{0i} \sim N\ (0, \tau_{i00})$$
$$\mu_{0j} \sim N\ (0, \tau_{j00})$$

At level 2, the $\beta_{0ij} or$level 1 intercept, is set as the outcome in a new regression equation with two components γ_{00}(the level 2 intercept), and $\mu_{0i} and \mu_{0j}$ (random parameters) which is the level 2 residual variance. The level 2 random parameter allows higher-level unit variation of the model. Subsequent models were then compared with a null or baseline model to capture the degree dependence of the variance at level 1 on group membership at the second level using the equivalent of intraclass correlation coefficient (ICC) for outcomes in *poisson* distribution, the difference between the lower and upper limits in a 95.4% range that included expected values of the outcome that vary by groups:

$$Indicator_i = \exp(\gamma_{00} + 2\sqrt{\tau_{i00}}) - \exp(\gamma_{00} - 2\sqrt{\tau_{i00}})$$

$$Indicator_j = \exp(\gamma_{00} + 2\sqrt{\tau_{j00}}) - \exp(\gamma_{00} - 2\sqrt{\tau_{j00}})$$

Similar with ICC, if the value of the difference is > 1 (that is, the expected value of the frequency of the outcome differs by > 1 between the upper and lower limit) in either level 1 (included children profile) and or level 2 (if the difference is > 1, children profile was not included), hierarchical linear models were performed suggesting that the data varied by children and or location of each movement and behavior outcomes. Otherwise, if there was < 1 difference values in both indicator levels, general linear models were performed. All predictor variables were then entered into the model followed by Variance Inflation Factor (VIF) estimation to reduce the impact of multicollinearity. Predictors with > 5 VIF were excluded and was repeated until there were no more variables with > 5 VIF in the model.

In addition to the evaluation of the main effects of explanatory variables (time, indoor [UV] and outdoor [UV, atmospheric pressure, temperature, humidity, cloudiness, windspeed, wind directions, daylengths, and seasons] variables on the outcomes:

y = a + b1*x1 + b2*x2

models were run with paired interaction between each of the children profile (when the ICC is > 1) and weather variables that were included in the main effect models, and season (fall and winter). The assume model is that

y = a + b1*x1 + b2*x2 + b3*x1*x2

where x1*x2 is the interaction variable and b3 is the regression coefficient of the interaction. Where interactions were statistically significant (P < 0.05), simple slope analyses were consequently carried out. Similar analysis steps were performed to evaluate possible current or time-offset delayed effects (0-24-hours) of outdoor weather variables indices variations on movements and behavior outcomes.

Results

Main And Seasonal Interaction Effects Of Weather Indices

Results of the hierarchical linear two-level models fitting and simple slope analyses on the main and seasonal interaction effect estimates of the relevant children profile and weather indices, and time variables on children's movements revealed several significant and contrasting findings (Table 2). Outdoor humidity levels revealed a significant positive seasonal interaction effect (0.86, p < 0.05), and the consequent simple slope analysis implies that children also tend to have more body movements during winter (0.66, SE: 0.33, P < .05) than fall. While cloudiness wind speed levels revealed significant seasonal interactions effect estimates (0.88 and 1.32, respectively) on body movement outcome, simple slope analysis found inconclusive results. Children's profile did not seem to have any significant effect on children movement except for diagnosis (-1.13, p < 0.05) demonstrating increased body movements suggesting more head or upper body including head and neck and upper or lower limbs movements were observed among children who had profound intellectual disabilities (IDs) than those who had PIMD diagnosis. Outdoor humidity levels also had significant main effect to vocalizations, which suggests that lower levels of outdoor humidity increased vocalizations among the children by 0.37 (p < 0.01). However, seasonal interactions effect estimates (0.63, p < 0.05) suggests otherwise, where greater humidity level index during fall season is predictive of decreased vocalizations (-0.37, SE: 0.13, p < 0.01). Vocalizations seem to also be significantly affected by the robust interaction effect estimate between season and UV level index (2.88, p < .001), indicating increased production of sound and vocalizations when UV level is greater during winter as compared to fall. As expected, there were significant positive effects of weather indices related to clear skies or dry weather such as rising atmospheric pressure levels (0.79, p < 0.001) and longer daylength hours (1.24) to frequent pointing hand or finger, and grabbing, hitting, pushing, or raising hand movements. Interestingly, similar fair-weather conditions indicated by rising outdoor atmospheric pressure level variations in fall (0.79) and winter (1.65) also increased hand movements among the children. Fluctuations in cloudiness levels (main), and robust interaction between wind speed and season (2.05) had significant effects to eye movements and facial expressions, respectively, signifying low cloud cover weather condition is predictive of more eye movements (-0.47) while higher wind speed level led to a greater extent of facial expressions among the children during winter (1.65, SE: 0.84, p < 0.05).

Consistent significant and positive main and seasonal interaction effect estimates of weather indices and timestamp-derived data were found predictive of assent (response) behavior outcome (Table 3). This implies that children demonstrated a clear affirmative manner and attuned agreement to their caregiver during lunchtime (12 to 1 pm) (1.15, P P < .05) and winter season (1.15, P < .001). Also predictive of increased assent behavior outcomes were weather indices related to well-lit and warmer rooms based on the significantly strong seasonal interaction effect estimates on high indoor UV index (3.48, p < 0.05) and outdoor humidity (0.89) during winter (2.61, SE: 1.18, p < 0.05 and 1.01, SE: 0.42, p < 0.05), respectively. Significantly high estimate effects (> 2.49) of elevated UV index levels also predicted persistent engagement behaviors with their caregivers and getting their attention verbally (e.g., greetings, vocalization) or non-verbally (2.84, SE: 0.81, p < 0.001), and more expressions of decisive behaviors or desire to choose between or among objects (3.42, SE: 1.60, p < 0.05) during winter. Warmer or more

Table 2
Hierarchical linear model (HLM) coefficients and standard errors of the main and interaction effects (season) analysis on the movement outcomes.

	Eye Movements		Facial expressions		Vocalizations		Hand movements		Body movements[a]		Non-comm.	
	C	SE	C	SE	C	SE	C	SE	C	SE	C	SE
Age (years)									-0.28	0.23		
Condition (PIMD)[b]									-1.13	0.49*		
Indoor ultraviolet (UV) (mW/cm2)	0.36	0.23	-0.50	0.59	0.23	0.43	-0.54	0.34	-0.50	0.56	-1.94	2.41
Outdoor atmospheric pressure (hPa)	-0.15	0.20					0.79	0.19***	-0.15	0.20	N/A	N/A
Outdoor humidity (%)	-0.16	0.19	-0.27	0.20	-0.37	0.13**	0.38	0.22	-0.20	0.14	N/A	N/A
Cloudiness (%)	-0.47	0.17**	0.10	0.27	-0.24	0.14	0.12	0.18	-0.10	0.16	-0.03	0.64
Wind speed (meters/second)	-0.47	0.29	-0.39	0.53	-0.54	0.29	-0.98	0.34**	-0.28	0.26	N/A	N/A
Daylength (hours)	N/A	N/A	0.34	0.29	N/A	N/A	1.24	0.43**	N/A	N/A	N/A	N/A
Season (winter)[c]	-0.37	0.36	0.23	0.47	-0.51	0.37	-0.45	0.37	-0.31	0.32	-2.00	2.03
Season_age (years)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.12	0.38	N/A	N/A
Season_condition (PIMD)[b]	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-1.20	0.74	N/A	N/A
Season_indoor ultraviolet (UV) (mW/cm2)	1.22	0.73	-0.14	1.50	2.88	0.79***	-0.88	0.97	0.91	1.04	-4.70	7.60
Season_outdoor atmospheric pressure (hPa)	-0.33	0.38	N/A	N/A	N/A	N/A	0.87	0.42*	0.43	0.35	N/A	N/A
Season_outdoor humidity (%)	-0.09	0.39	0.69	0.52	0.63	0.28*	0.55	0.39	0.86	0.31*	N/A	N/A
Season_cloudiness (%)	0.16	0.38	0.89	0.89	0.25	0.33	0.44	0.47	0.88	0.39*	0.05	1.71
Season_wind speed (meters/second)	0.50	0.62	2.05	0.95*	-0.08	0.62	-0.10	0.57	1.32	0.55*	N/A	N/A
Season_daylength	N/A	N/A	-0.79	1.07	N/A	N/A	0.95	0.77	N/A	N/A	N/A	N/A

Non-comm. = non-communicative; C = coefficient; SE = standard error; N/A = not included in the final model due to high (≥ 5) VIF; [a] = the expected value of the frequency of the outcome differs by > 1 between the upper and lower limit in level 1 (children profile) and level 2 (location); [b] reference: profound intellectual disability condition; [c] = reference: fall.

Table 3
Hierarchical linear model (HLM) coefficients and standard errors of the main and interaction effects (season) analysis on the behavior outcomes.

	Engagement (calling)[a]		Assent (response)		Emotions		Interest		Negative attuning[a]		Selecting		Physiological response		Unknown	
Children profile	C	SE	C	SE	C	SE	C	SE	C	SE	C	SE	C	SE	C	S
Indoor ultraviolet (UV) (mW/cm2)	0.35	0.41	-0.88	0.80	N/A	N/A	-1.12	0.63	-1.11	1.60	0.69	0.43			0.04	1
Outdoor atmospheric pressure (hPa)	N/A	N/A	0.30	0.23	-0.05	0.32	0.88	0.28**	N/A	N/A	-0.29	0.34	0.04	0.53	N/A	N
Outdoor temperature (°C)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	-0.89	1
Outdoor humidity (%)	-0.35	0.21	0.12	0.19	0.16	0.30	0.10	0.25	0.43	0.28	-0.43	0.31	0.37	0.48	N/A	N
Cloudiness (%)	-0.10	0.20	0.10	0.22	-0.41	0.30	0.23	0.26	-0.84	0.45	-0.18	0.31	-0.46	0.60	N/A	N
Wind speed (meters/second)	-0.33	0.37	N/A	N/A	N/A	N/A	-1.05	0.43*	1.27	0.53*	N/A	N/A	0.75	0.75	N/A	N
Season (winter)	-0.52	0.67	1.15	0.40***	-0.46	0.57	-0.50	0.60	0.75	0.86	-0.51	0.68	-0.96	1.02	2.68	1
Time (10 to 11 am)	N/A	N/A	0.71	0.44	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N
11 to 12 pm	N/A	N/A	0.27	0.46	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N
12 to 1 pm	N/A	N/A	0.99	0.46*	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N
Season_indoor ultraviolet (UV) (mW/cm2)	2.49	0.81**	3.48	1.38*	N/A	N/A	-2.22	1.67	2.46	3.37	2.71	1.29*	N/A	N/A	1.32	3
Season_outdoor atmospheric pressure (hPa)	N/A	N/A	-0.71	0.41	0.12	0.65	-0.34	0.51			0.12	0.63	0.22	1.12	N/A	N
Season_outdoor temperature (°C)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.51	1
Season_outdoor humidity (%)	-0.20	0.55	0.89	0.40*	1.50	0.72*	-0.18	0.55	0.21	0.66	-0.03	0.72	0.32	1.12	N/A	N
Season_cloudiness (%)	-0.25	0.44	-0.13	0.49	-0.68	0.78	-0.03	0.50	2.43	1.11*	0.58	0.80	1.35	1.77	N/A	N
Season_wind speed (meters/second)	-0.34	0.80	N/A	N/A	N/A	N/A	0.10	0.77	-0.11	1.13	N/A	N/A	-0.75	1.87	N/A	N
Season_time(10 to 11 am)	N/A	N/A	-0.57	0.94	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N
Season_time(11 to 12 pm)	N/A	N/A	0.25	0.90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N
Season_time(12 to 1 pm)	N/A	N/A	-1.24	0.91	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N

C = coefficient; SE = standard error; N/A = not included in the final model due to high (≥ 5) VIF; [a] = the expected value of the frequency of the outcome differs by < 1 between the upper and lower limit in level 1 (children profile) and level 2 (location), thus coefficients and standard errors were computed in general linear models (GLM); [b] = reference: northeast; [c] = reference: fall.

humid outdoor weather conditions due to increasing humidity levels (1.50) during winter was also found to predict numerous actions and communications that display mutual satisfaction, pleasure, or being upset or distressed among the children (1.66, SE: 0.83, $p < 0.05$). Gentle breeze and calmer and fair-weather conditions due to descending wind speed (-1.05) and increasing atmospheric pressure (0.88) indices led to recurring interest behaviors among the children demonstrating an obvious attention and interest in (attuning to) in an object, person or action or doing an action. As expected, although the simple slope analyses showed insignificant seasonal interaction effect estimates of cloudiness index, inclement weather conditions brought by increased cloud cover (2.43, $p < 0.05$) and moderate to strong breeze (1.27) are predictive of escalated negative attuning states among children expressing refusal or disagreement verbally (e.g., “no”, “don’t like”, “dislike” or “end”) or non-verbal actions and vocalizations (e.g., closes mouth, sticks out tongue, turns face away).

Outdoor weather indices 24-hour temporal offsets

Effect estimate (Z values) of the current and 24-hour temporal offsets of outdoor weather indices (atmospheric pressure [AP], temperature [Temp], humidity [Hum], cloudiness [cloud], wind speed [WindSp], and wind directions [WindDir]: northeast [NE], southeast [SE], southwest [SW], and northwest [NW]) on the movements and behavior outcomes are shown in Figs. 3 and 4. Wind-related indices values responded more frequently at current and several time lags affecting variations in eye movements among the children (Fig. 3a). Fluctuating wind speed from hour 0 (-2.33) through hour 7 (-2.01 to 3.90, $p < 0.05$), and wind blowing mainly from and to NE, SE, and NW (-2.84 to 3.78, $p < 0.05$) had significant effects to eye movements. Children also had more eye movements when warmer (-2.53) yet less humid (-2.78), and gentle to moderate wind speed (3.51) blowing from and to different directions (-3.27 to 2.44, $p < 0.05$) as revealed by the significant delayed effect temperature, humidity, wind speed, and direction estimates Z values during hours 9 to 12. Towards the end of the 24-hour time period (hours 19 to 23), more humid (2.05) with clearer skies (-2.08), fluctuating levels of wind (-2.28) more frequently blowing from and to SE and NW (-2.48 to 6.63, $p < 0.05$) also led to delayed increased or varied frequencies of eye movements among the children.

High and current outdoor atmospheric pressure (2.51), humidity (2.90), and high cloud cover (2.02) and lower temperature (-2.36), suggestive of relatively fair and drier weather conditions were predictive of more facial expressions among children (Fig. 3b). Children seemed to also have more facial expressions brought by the delayed effect (hours 6 and 7) of less humid (-2.29), clearer skies (-2.02) with gentle to moderate wind blowing form and to SW and NW (-1.95 to -2.52). However, delayed effects (hours 9 through 11) of increased cloudiness (2.22), temperature (3.13), wind speed (3.21), indicative of warmer weather with gentle to moderate breeze blowing to the SE (-3.46) were predictive of increased facial expressions. Interestingly, the unpleasant or stormy and humid weather throughout the last quarter of the time-offset analysis period (hours 19 to 24), when more frequent wind was blowing from the NE and SE (-3.65 to 5.50, $p < 0.05$), high cloud cover levels during hour 21 (2.18) and high humidity levels during the 24th hour (1.98) also led to an expected delayed effects on the recurrence in facial expressions among the children.

Robust atmospheric pressure effect estimates Z value (6.21, $p < 0.001$), lower temperature (-3.66), cloudiness (-3.15), wind speed (-2.00), and wind directions (-3.47 to 2.37, $p < 0.05$) signifying more pleasant and clearer skies with gentle wind blowing from and to SE, SW, or NW had significant immediate and delayed (hours 1 to 3) effects to vocalizations among children (Fig. 3c). Warmer (-3.66), less humid (-2.72 to 3.71, $p < 0.01$) but cloudy (2.13 to 3.97, $p < 0.05$) weather also had significant delayed (hours 4 through 12) effects to vocalizations. During the same time period, vocalizations were also significantly affected by gentle to moderate wind (3.02 to 4.64, $p < 0.01$) blowing from and to all four directions as revealed by the varying wind-related indices effect estimates (-3.58 to 4.64, $p < 0.05$). There were consistent significant delayed (hours 14 to 24) effect estimates of wind direction index values (with robust Z value when the wind was blowing from SE during the 20th hour: 10.28, $p < 0.011$), lower cloud cover levels (hour 14: -2.70) and higher humidity (3.64) were also found leading to vocalizations among the children.

Fair (3.67) and cooler (-2.71) weather had significant immediate effects to the increased hand movements (Fig. 3d). However, the increasing effect estimates in cloudiness levels (-2.38 to 2.92, $p < 0.05$) and negative effect estimates in wind direction (SW and NW: -2.76 to -4.04, $p < 0.01$) indices suggesting stormy weather conditions (hours 2 to 6) had significant delayed effects to hand movements. Predictive of increased hand movements were time-offset (delayed) less humid (hours 6 and 11: -2.51 to 2.57, $p < 0.01$), clearer skies (hour 18: -2.21). The fluctuating delayed (7th to 20th time-offset period) effect estimates of wind direction indices (NE, SE, and SW: -2.79 to 3.99, $p < 0.05$) and the alternating low and high wind speed index values (-4.24 to 4.76, $p < 0.05$) were also found significant. Warmer (3.14) and more humid (4.36) weather conditions also had delayed effects (24th hour) to the increased hand movements among the children.

Figure 3e shows that more humid (5.60) yet less warm (-2.43) weather conditions with breeze blowing from or to NE and SE (-2.68 to 2.53, $p < 0.01$) were predictive of immediate increase in body movements among the children. However, less humid (hour 7 and 11: -3.37 to -3.84, $p < 0.001$), low atmospheric pressure (-3.13), fluctuating wind speed levels (-5.08 to 3.32, $p < 0.05$) and more frequent wind activity from different directions (-3.34 to 4.66, $p < 0.05$) from hours 3 through 17, suggestive of humid and inclement weather condition had significant delayed effects to variations in body movements. Nearly similar conditions resulted from high temperature (4.03), humidity (4.57), and cloudiness (2.19), and varied wind direction indices (NE and NW: -4.16 to 2.04) delayed (hours 21 to 24) effect estimates were also predictive of body movements among the children. For non-communicative movements, inclement weather-related indices seem to be predictive of stereotypical or repetitive or self-and others- injurious movements among the children. Cloudiness was significant at the 1st, 3rd, and 9th hours (-2.70 to 2.12, $p < 0.05$), while wind speed was significant during the 9th, 13th, 19th, and 20th (-3.62 to 2.50, $p < 0.05$) (Fig. 3f). The wind blowing to and from NE (hours 2 and 7: 2.57 and − 2.86, $p < 0.01$), and from the SE (hours 11, 14, and 21: 2.22 to 3.32, $p < 0.05$) were also found significant predictors of delayed non-communicative movements.

Children tend to engage and exhibit more joint attention in the dyadic interactions when there were clear skies or fair weather conditions brought by the immediate effects of high atmospheric pressure levels (2.42, $p < 0.05$) and low cloud cover levels at hour 1 (-2.06, $p < 0.05$) and delayed effects of cloud cover and wind speed at hour 20 (-3.07, $p < 0.001$; 2.38, $p < 0.05$) and high humidity levels during the 24th hour (2.60, $p < 0.01$) (Fig. 4a). However, inclement weather conditions indicated by high wind speed index levels at hour 12 (2.62, $p < 0.01$), high cloud cover at hours 4 and 9 (2.48, 1.99, $p < 0.05$), and wind blowing mainly from the NW (2.56, $p < 0.01$) and SE (3.02, $p < 0.001$) were predictive of engagement behaviors.

High (5.13, $p < 0.001$) and low (at hours 6 and 18: -2.46, 2.49, $p < 0.01$) humidity index levels had immediate and delayed effects on children demonstrating more attuned agreement with their caregiver by responding to questions or signals in a clear affirmative manner (Fig. 4b). Elevated cloudiness levels at hour 21 (2.53, $p < 0.01$), wind speed at hour 22 (2.88, $p < 0.001$), and wind blowing from or to SW and NW directions at hour 22 (-2.99 and 2.17, $p < 0.05$) were also significant. Varying significant effect estimates of wind speed (-3.17, $p < 0.001$) and other wind direction indices (NE and SE: -2.33 to 2.65, $p < 0.05$) during hours 2 and 16 were also found significant.

Children expressed more feelings of being happy, pleasure, excited, perception of fun, angry, worried, or troubled due to the delayed effects of low temperature index levels (hour 2: -2.79, $p < 0.01$) (Fig. 4c). From the 10th and 11th hours, high temperature (3.18, $p < 0.001$) and cloudiness (3.62, $p < 0.001$) and low humidity (-2.21, $p < 0.05$) indices effect estimates were also significant. During the same time (9th and 10th), the wind blowing from and to NE and SE directions (-2.06 and 2.31, $p < 0.05$) were also found significant. Extreme significant and delayed effects (24th hour) of decreasing cloud cover (-2.06, $p < 0.05$) and wind speed (-2.16, $p < 0.05$) indicative of clear and calm weather conditions were also found predictive of changes in emotional expressions among the children.

While atmospheric pressure and temperature had positive immediate (hour 0: 3.02, $p < 0.001$) and delayed effects (hour 21: 2.40, $p < 0.05$) respectively, led to increase demonstration of an obvious attention and interest in (attuning to) an object, person or action or doing an action among the children, variations in cloudiness (-4.59 to 3.22, $p < 0.05$), wind speed (-2.70 to 2.79, $p < 0.05$) and wind directions (NE and SE: -3.63 to 3.34, $p < 0.05$) index levels had significant effect estimates across the 24-hour period (Fig. 4d).

Low atmospheric pressure (-2.97, $p < 0.001$) and cloudiness (-2.54, $p < 0.05$), high humidity levels (2.15, $p < 0.05$), and wind activities (hour 1, from or to the SE: -1.97, $p < 0.05$), suggestive of unpleasant or stormy, significantly led to an immediate increase in negative attuning behaviors (do not accede to the wishes of the other to express refusal or disagreement) among the children (Fig. 4e). High wind speed level not significant until hour 3 (-2.20, $p < 0.05$), however, it had delayed fluctuating effects during hours 10 through 12 (-2.30 to 3.25, $p < 0.05$) and hour 20 (2.24, $p < 0.05$). During the same period, low humidity level was also significant (-2.34, $p < 0.05$). Wind direction indices were less frequently predictive of negative attuning behaviors. It was nearly the same with selecting behaviors (-2.71 to 2.77, $p < 0.05$), and among the outdoor weather indices, only wind speed had immediate (-2.23, $p < 0.05$) and delayed (hour 6 and 16: 2.26 and 1.94, $p < 0.05$) effect on the non-verbal actions or gestures to express decision or desire to choose between or among objects among the children (Fig. 4f). Figure 4g shows that among the outdoor weather indices, only the temperature and wind direction indices (NE, SE, and SW) had the significant delayed effects (hour 2 for NE: 3.43, $p < 0.001$; from hour 11 through hour 15: -2.66 to 2.24, $p < 0.05$) to variations in the occurrence of vocalizations and actions to express functions or desires relating to normal physical or bodily responses among the children. Besides the delayed effect of high cloudiness level (hour 24: 2.25, $p < 0.05$), the current (SW: 2.64, $p < 0.05$) and delayed (hour 11, 17 and 23 through 24: -1.98 to 2.99, $p < 0.05$) effects of wind direction indices were predictive of changes in behaviors with no shared meaning or interpretation (Fig. 4h).

Discussion

The fluctuations in outdoor atmospheric pressure, humidity, cloudiness, wind speed indices levels, including season, daylength and time (12 to 1 pm) as revealed by the hierarchical and general linear models, were predictive of variations in eye, hand, and body movements, vocalizations, as well as assent, interest, and negative attuning behaviors of children with PIMD/IDs. The findings also demonstrated that seasonal interaction effect estimates, and subsequent simple slope analyses indicate increasing index values in indoor UV, humidity, and cloudiness during winter were also found significantly affecting vocalizations, hand and body movements, facial expressions, engagement, assent, emotions, negative attuning and selecting behaviors. On the other hand, hand movements and vocalizations were significantly affected by increasing atmospheric pressure and decreasing humidity during fall. Furthermore, while varying current outdoor temperature, atmospheric pressure, humidity, and cloudiness indices levels had significant immediate effects to variations in movement and behavior outcomes, time-offset effect estimation values of wind-related indices (speed and directions) had significant delayed effects at several time lags. Overall, the individual and seasonal interaction effects, and the combinations or patterns of significant immediate and delayed effect estimates of fluctuating weather indices across the 24-hour time lag were suggestive of either fair and calm or inclement weather conditions affecting movements and behaviors of children with PIMD/IDs.

Main and seasonal interaction effect estimates, and temporal analyses proved outdoor atmospheric pressure positively affecting the increase in hand movements among the children with PIMD/IDs in any season, and interest behaviors. There are also evidence attesting its robust positive immediate effects on the increased facial expressions, vocalizations, hand movements, and engagement behaviors. These findings and the high correlated outdoor and indoor values (0.85, $p < 0.001$) consistently present evidence that children with PIMD/IDs exhibited more behaviors and movements directed to an obvious attention and interest or attuning signifying more engaged interactions with the caregiver when there were higher atmospheric pressure levels indicative of clear and fair-weather conditions. On the other hand, this substantial weather indicator index also seems to have an inverted relationship with movement and behavior outcomes, revealing that lower atmospheric pressure index levels indicative of stormy or inclement weather condition, had significant immediate effects to increased expressions of refusal or disagreement in dyadic interactions leading to negative attuning behaviors. Consistent with these findings, previous studies suggest that decreasing atmospheric pressure which causes constricted capillaries thus reducing oxygen to the brain, frequently causing migraine attacks, increased risk for epileptic seizures and depressive symptoms, or more cardiac or cerebrovascular complications associated with decrease in blood pressure among adults[12,13,40]. Others experience ear pressure sensations, head compressions and trigger headaches[41], increased schizophrenia hospital admissions[16] and changes in wellbeing, activity, and mood due to atmospheric pressure levels fluctuations[42]. Increased scared emotions, nervousness, being upset, irritation associated with atmospheric pressure level fluctuations[5].

Multilevel models found no main nor seasonal interaction effects of temperature levels, while on the other hand, multilevel temporal analyses found fluctuations in temperature levels, as revealed by effect estimates, were predictive of immediate or delayed occurrence of movements or behaviors among the children with PIMD/IDs. Positive effect estimate indicating high temperature levels at several time lags had delayed yet robust significant effects (> 1.99 Z-values) to facial expressions, vocalizations, hand and body movements, and emotions, interest, and physiological response behavior outcomes. With its highly correlation with indoor temperature and indoor humidity levels, (> 0.74, $p < 0.001$), it is also noticeably evident that the continuous decrease in temperature levels from several time lags resulted to high-pressure area at current time, suggestive of relatively less warm and fair-weather conditions, were found predictive of immediate increase in facial expressions, vocalizations, and hand movements. These findings may imply that children with PIMD/IDs had delayed yet more responses to warmer temperatures exhibiting appetitive or reactive instincts ranging from hunger or thirst, and motor reactions, to expressing emotions, interests, or curiosity, which in turn, seemingly mediated by immediate or current cooler and clement weather conditions. With increased blood flow on the surface of the skin promoting heat dissipation by sweat evaporation, increased heart rate and dehydration, rising temperature levels have been associated physical activity and emotions among children[3,5,43]. After adjusting for individual covariates (age and sex), warmer temperature (every 5C increase) and dryer weather were associated with increased in moderate-to-vigorous physical activity (MVPA) (by > 67 minutes) among 6–7-year-old children[3]. Remmers et al.[44] had similar conclusion that temperature was the strongest predictor of MVPA. Higher temperature was also positively associated with alertness among younger children[5], and in a longitudinal individual-level study, adjusted multilevel models revealed strong evidence for long-term exposure to increasing ambient temperature is associated with higher aggressive behaviors of children and adolescents in urban areas across the 3-year study period[45].

Moreover, our results also demonstrated distinct patterns indicative of a reverse relationship between atmospheric pressure and temperature affecting significant immediate increase in occurrences in facial expressions, vocalizations, and hand movements among the children with PIMD/IDs when there were decreasing temperature and increasing atmospheric pressure index levels. While high temperature levels positively correlated with alertness and hostile negative emotions, irritation being positively associated with fluctuations in atmospheric pressure, Lagace-Seguin and Coplan[5] also found that decreases in atmospheric pressure and increases in temperature significantly affected activity level, while the opposite trend predicted scared emotions in children. In adults, while lower atmospheric pressure increases risk for depressive symptoms among males, higher air temperature (> 14.2°C) predominant during May to September had a protective impact[46].

Subsequent slope analysis and significant multilevel main and seasonal interaction effect estimations of outdoor humidity index levels revealed that lower levels of outdoor humidity significantly led to increased vocalizations during fall while higher humidity index values positively affecting body movements, assent (response), and emotion behaviors during winter. This seasonal variation in humidity levels may seem correspond to the higher average and range recorded during fall (average: 64.9RH%; range: 43 to 90 RH%) compared to winter (average: 55.6RH%; range: 43.00 to 72.1 RH%), proposing children with PIMD/IDs responded more to fair or comfortably humid (30 to 60 RH%) environment during cooler or colder seasons exhibiting attuned agreement by responding affirmative manner, and expressing feelings that range from mutual satisfaction to being distressed (interim level of anti-attuning) manifested by vocalizations or body movements. Employing similar multilevel linear analyses, Ciucci and colleagues[7] who also investigated the effects of weather variables to child affective and behavior states and activity levels across different seasons, also found seasonal variations in humidity levels. On winter days, when outdoor humidity is higher, children showed more negative affects (frustration and aggression) while on summer, increasing humidity levels led to significant reduction in activity levels among the children[7].

Apart from increasing atmospheric pressure index levels, temporal analysis results also indicated that increased outdoor humidity levels also considerably contributed to immediate increase in negative attuning behaviors among the children with PIMD/IDs. Regarding movement outcomes, besides lower temperature levels, high outdoor humidity level also led to an immediate increase in facial expressions and body movements. Further, across the 24-hour time period, time-offset effect estimates of outdoor humidity and temperature suggest that increasing temperature and decreasing humidity index levels had delayed significant effects to eye movement, facial expressions, vocalizations, body movements, and emotions. These findings were of particular interest disclosing three substantial evidences: the relationship between humidity and negative emotional states among children, the inverse relationship between humidity and temperature index levels, and the positive relationship between humidity and atmospheric pressure, affecting negative emotions, behavioral states, and activity levels among children. Lagace-Seguin and Coplan[5] had congruent findings specifying decreases in humidity levels significantly predicted negative emotions such as irritability and hostility among children. Ciucci and colleagues[6] had the same results concluding higher humidity levels as one of the main predictors of children's affective and behavior outcomes such as frustration, aggression, and negative feelings. Regarding the relationship between temperature, atmospheric pressure, and humidity, Lagace-Seguin and Coplan[5] also found decreases in atmospheric pressure and humidity and increases in temperature led to significant increase in activity levels, while decreases in temperature and increases in atmospheric pressure and humidity predicted scared emotions in children. A separate multiple regression analysis also indicated that changes in humidity and atmospheric pressure levels were associated with irritation, nervousness, and being upset.

Light-related indices, daylength and indoor UV had consistent positive effects to movements and behavior outcomes of children with PIMD/IDs. Daylength led to significant increase in hand movements while indoor UV had robust effects to increase in vocalizations, engagement (calling), assent, and selecting behaviors. These suggest that children exhibited more engaged or joint attention, responses, and decision or desire to choose between or among objects manifested verbal or non-verbal movements in dyadic interactions when there were longer hours from sunrise to sunset and increased exposure to natural light source inside the classrooms. Through modulating circadian rhythm and sleep and activating emotion-processing brain regions, and suppression of melatonin production, UV light, illuminance, daytime light have been investigated focusing on its potential non-image forming indirect or direct regulating effects to mood or behavior[9,47,48]. Among children, these light-related indicators have been studied investigating its effects to or associations with physical activities, sedentary behaviors, socialization skills, cognitive abilities, attitudes, and energy levels in classroom settings. Children were physically more active (less sedentary behavior) when there were better visibility and more hours of daylight (late afternoon and early evening) or longer daylengths hours[2,3,49,50]. Regarding social behaviors, children who are prone to higher levels of negative affect have increased prosocial behaviors when there is increased amount of sunshine[4]. More recently, when compared with students in non-daylit classrooms, the social behaviors, and cognitive skills of children in classroom exposed to daylight were higher and more developed[51]. Being highly correlated with indoor UV levels (0.94, $p < 0.001$), indoor ambient lighting, especially higher correlated color temperature lighting positively impacted alertness, attitude, and energy level in classroom setting[52].

Fluctuations in cloudiness and wind speed had significant main and seasonal interaction effects to the movements and behavior outcome measures. While decrease in these two weather indices affected eye and hand movements, and interest behaviors, its increasing levels led to significant increase in negative attuning behaviors. The increasing level trend in these indices also had significant seasonal interaction effects to increased facial expressions in winter. Although simple slope analyses results had inconclusive results, seasonal interaction effect estimates for body movements and negative attuning behaviors were also significant. These suggest that children with PIMD/IDs had lesser movements and less likely to demonstrate an obvious attention and interest in (attuning to) object, person or action or doing an action, and more likely to exhibit verbal (e.g., "no", "don't like", "dislike" or "end") or non-verbal actions and vocalizations (e.g., closes mouth, sticks out tongue, turns face away) to express refusal or disagreement, when it was cloudy with moderate to strong breeze, indicative of precipitation from an incoming low atmospheric pressure system. While rising wind speed and rainfall were associated with depressive symptoms and panic episodes among adults[8,46,53], cloud cover, precipitation, and wind speed have been associated with levels of physical activities and emotions among children. Increase in cloud coverage and precipitation ranging from light to heavy levels were negatively associated with daily step counts and compared to dry days, primary school children also had fewer MVPA and more sedentary behaviors on rainy days[54–57]. Decrease in accelerometer (counts per minute)-measured physical activity and MVPA were also associated with increased precipitation and wind speed[2,58]. In a series of correlation analyses, wind speed was negatively associated with positive emotions of being active and determined and was positively associated with negative emotion of being scared[5]. The overall pattern of results of correlation analyses between emotions and changes in weather variables, wind speed was found to be positively associated with nervousness among the children.

A further novel finding is that the time-offset effect estimate values of wind directions at several time lags were also found significant. There was a predominance in significant effect estimates of wind blowing from and to the southeast (SE) affecting current or delayed variations in most of the movements and behaviors of children with PIMD/IDs although the wind was blowing from and to the southeast 14% of the time. Surprisingly, a time series case study in a patient with anxiety disorder had similar findings. Bos, Hoenders, and de Jonge[8] found that energy levels were significantly less when the wind blew from the southeast. It remains unclear to which degree the occurrence or variations of movements and behaviors of children with PIMD/IDs are attributed to wind activity or blowing wind from and to the southeast. However, we assume the potential association of wind direction with the fluctuations in cloud cover and wind speed indices, in concert, are major indicators of inclement weather conditions. Thus, the occurrence and variations in the movements and behaviors of children with PIMD/IDs in general, are affected by an incoming low atmospheric pressure system or inclement weather conditions. Although multilevel temporal analyses found no distinct patterns in significant immediate and delayed effect estimates of cloud cover, wind speed, and wind direction indices to support this assumption.

Contrary to the hypothesized exploratory notions of the random effects of proximity sensing data and child gender and age on the occurrence and variations in movements and behavior outcomes among children with PIMD/IDs, children's condition was the only found significant accounting for the variability in body movements. The proximity sensing data proved insignificant findings on its effect to movement and behavior outcomes since the children were recruited from the same school and the sessions were limited to classroom settings. Regarding children condition, although not as intense, the negative effect estimate value suggests that children with severe or profound intellectual disabilities (IDs) carried out more head or upper body and movement of any part of the upper body (shaking, bending, moving mouth, etc.) including head and neck, and upper or lower limbs than children with PIMD. This basic condition-related difference may be attributed to the absence of neuromotor dysfunctions and sensory problems among children with PID, which impair understanding or expressing verbal language and consequent difficulties in interactions among children with PIMD[18,20]. Moreover, there was an apparent increase in assent (response) behaviors among children with PIMD/IDs from 12 to 1 pm, indicating increased attuned agreement demonstrated doing an action or responding to actions by saying "yes" or raising, waving, or clapping hands or nodding head between the dyads during lunchtime. This clearly provide evidence that the behaviors of children with PIMD/IDs are contextually affected by environmental factors such as the time of the day. This also adds support to Blain-Morales and Chau[31] on the perceived importance of time of the day in investigating the intrasubject variability of physiological signals and states among children with PIMD.

To obtain an adequate interpretation and generalization of the potential main, seasonal interaction, and the immediate and delayed effects of fluctuations in weather indices levels, child condition, and time of the day as feasible predictors of occurrence and variations in movements and behaviors of children PIMD/IDs, some methodological limitations should be considered. First is the relatively inadequate length, number, and seasonal coverage of the sessions. Even though we consider performing 105 observational pragmatic evidence-based sessions a main strength of this study, they were relatively short (average of 18.5 minutes in length), relatively small (the average session per dyad is five completed in 16 days), and only covers 2 seasons (5-month period), to manifest the main and seasonal interaction effects of weather indices to the movement or behavior outcomes. Another limitation is the lack of 24-hour time offset values of indoor weather indices. Although some of the indoor and outdoor weather indices were significantly correlated, the temporal analyses were only based on outdoor weather indices which makes it difficult to exclude the confounding effects of indoor weather indices to the significant current or delayed effect outdoor weather indices estimates. Third, an apparent limitation also arises from the target outcome categorization that involves merging varied movement and behavior manifestations into one category. For example, emotions behavior category had no subdomains to indicate either positive or negative emotions were affected by fluctuating weather index levels. Lastly,

the children were recruited from the same school and the sessions were limited to classroom setting which explains the insignificant findings on the effect of location data to movement and behavior outcomes. This might have confounded the results and that the data did not provide hierarchical structure nested within location, and the total variance of movement and behavior outcome variables were decomposed into children level providing between-children variances only.

In conclusion, the fluctuations in outdoor atmospheric pressure, humidity, cloudiness, wind speed indices levels, including season, daylength and time (12 to 1 pm) were predictive of variations in eye, hand, and body movements, vocalizations, as well as assent, interest, and negative attuning behaviors of children with PIMD/IDs. Seasonal interaction effect estimates, and subsequent simple slope analyses indicate increasing index values in indoor UV, humidity, and cloudiness during winter were also found significantly affecting vocalizations, hand and body movements, facial expressions, engagement, assent, emotions, negative attuning and selecting behaviors. On the other hand, hand movements and vocalizations were significantly affected by increasing atmospheric pressure and decreasing humidity during fall. Furthermore, while varying current outdoor temperature, atmospheric pressure, humidity, and cloudiness indices levels had significant immediate effects to variations in movement and behavior outcomes, time-offset effect estimation values of wind-related indices (speed and directions) had significant delayed effects at several time lags. Overall, the individual and seasonal interaction effects, and the combinations or patterns of significant immediate and delayed effect estimates of fluctuating weather indices across the 24-hour time lag were suggestive of either fair and calm or inclement weather conditions affecting movements and behaviors of children with PIMD/IDs.

In conclusion, fluctuations in outdoor atmospheric pressure, humidity, cloudiness, wind speed indices levels, including season, daylength, and time (12 to 1 pm) were predictive of variations in movements and behaviors of children with PIMD/IDs. Further, children with severe or profound intellectual disabilities (IDs) exhibited more head or upper body including head and neck, and upper or lower limbs than children with PIMD. Findings also demonstrated that children with PIMD/IDs exhibited more vocalizations, hand and body movements, facial expressions, engagement, assent, emotions, negative attuning and selecting behaviors when there were increasing indoor UV, humidity, and cloudiness index levels during winter. On the other hand, more hand movements and vocalizations were observed when there were increased atmospheric pressure and decreased humidity during fall. Outdoor temperature, atmospheric pressure, humidity, and cloudiness indices levels had significant immediate effects to variations in movement and behavior outcomes, time-offset effect estimation values of wind-related indices (speed and directions) had significant delayed effects at several time lags. These findings support the hypothesis that variations in movements and behaviors of children with PIMD/IDs are affected by seasonal variations and current or delayed fluctuating levels of weather indices. This also contributes to the emerging investigations proving physical activity, movements, behaviors, or affective states were sensitive to the levels and changes in weather indices. This provides basis for opportunities of meaningful interactions and to structure communication interventions, educational and learning programs and outcomes, defining the level and the timing of activities, type and level of support and level of understanding of children with severe or profound intellectual disabilities and multiple disabilities.

Declarations

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Author Contributions

V.R.D.M.H. validation, formal analysis, writing-original draft and review and editing, visualization; T.K. conceptualization, methodology, funding acquisition, project administration, supervision, writing-review and editing, resources; A.T. validation, formal analysis, data curation, writing-review and editing; Y.F. methodology, validation, formal analysis, investigation, data curation, writing-review and editing; S.S., E.O., T.S. conceptualization, software, resources, project administration, writing-review and editing.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Additional information

Competing interests

The author(s) declare no competing interests.

References

1. Turrisi, T.B. *et al.* Seasons, weather, and device-measured movement behaviors: a scoping review from 2006 to 2020. Int J Behav Nutr Phys Act **18**, 24 (2021).
2. Harrison, F. *et al.* Weather and children's physical activity; how and why do relationships vary between countries?. Int J Behav Nutr Phys Act **14**, 74 (2017).
3. Kharlova, I. *et al.* The weather impact on physical activity of 6–12 year old children: A clustered study of the health oriented pedagogical project (hopp). Sports (Basel) **8**:9 (2020).
4. Lagacé-Séguin, D. G., & d'Entremont, M.R. L. Weathering the preschool environment: Affect moderates the relations between meteorology and preschool behaviors. Early Child Development and Care, **175**, 379–394 (2005).
5. Lagacé-Séguin, D.G., & Coplan, R.J. Winter weather go away, come again another day! Meteorology and mothers' perceptions of children's emotions during the winter season. Can J Res Child Educ **8**, 39–50 (2001).
6. Ciucci, E. *et al.* Weather daily variation in winter and its effect on behavior and affective states in day-care children. Int J Biometeorol **55**, 327–337 (2011).
7. Ciucci, E. *et al.* Seasonal variation, weather and behavior in day-care children: a multilevel approach. Int J Biometeorol **57**, 845–856 (2013).
8. Bos, E.H., Hoenders, R., & de Jonge, P. Wind direction and mental health: a time-series analysis of weather influences in a patient with anxiety disorder. BMJ Case Rep. (2012).
9. Veleva, B.,van Bezooijen, R., Chel, V., Numans, M.,& Caljouw, M. Effect of ultraviolet light on mood, depressive disorders and well-being. Photodermatol. Photoimmunol. Photomed. *34*, 288–297 (2018).
10. Lickiewicz, J., Piotrowicz, K., Hughes, P. P., & Makara-Studzińska, M. Weather and Aggressive Behavior among Patients in Psychiatric Hospitals-An Exploratory Study. International journal of environmental research and public health, *17*, 9121 (2020).
11. Sarran, C., Albers, C., Sachon. P., & Meesters Y. Meteorological analysis of symptom data for people with seasonal affective disorder. Psychiatry Res. **257**:501–505 (2017).
12. Okuma, H., Okuma, Y., & Kitagawa, Y.. Examination of fluctuations in atmospheric pressure related to migraine. Springerplus. **18**,790 (2015).
13. Rakers, F. *et al.* Weather as a risk factor for epileptic seizures: A case-crossover study. Epilepsia. **58**,1287–1295 (2017).
14. Salib, E., & Sharp, N. Relative humidity and affective disorders. Int J Psychiatry Clin Pract. **6**,147 – 53 (2002).

15. VanBuskirk, S.E., & Simpson, R. Meteorological Variables and Behavior of Learners With Autism. Focus on Autism and Other Developmental Disabilities, *28*, 131–137 (2013).
16. Jahan, S., & Wraith, D. Immediate and delayed effects of climatic factors on hospital admissions for schizophrenia in Queensland Australia: A time series analysis. Environmental Research **197**, 111003 (2021).
17. Oeseburg, B., Dijkstra, G. J., Groothoff, J. W., Reijneveld, S. A., & Jansen, D. E. Prevalence of chronic health conditions in children with intellectual disability: a systematic literature review. Intellectual and developmental disabilities, **49**, 59–85 (2011).
18. van Timmeren, E.A., van der Putten, A.A.J., van Schrojenstein Lantman-de Valk, H.M.J., van der Schans, C.P., Waninge, A. Prevalence of reported physical health problems in people with severe or profound intellectual and motor disabilities: a cross-sectional study of medical records and care plans. J Intell Disabil Res, **60**, 1109–1118 (2016).
19. Nijs, S., & Maes, B. Social Peer Interactions in Persons with Profound Intellectual and Multiple Disabilities: A Literature Review. Education and Training in Autism and Developmental Disabilities. *49*,153–165 (2014).
20. Nijs, S., Vlaskamp, C., & Maes, B. Children with PIMD in interaction with peers with PIMD or siblings. Journal of Intellectual Disability Research **60**,28–42 (2016).
21. Nieuwenhuijse, A.M., Willems, D.L., van Goudoever, J.B., Echteld, M.A., & Olsman, E. Quality of life of persons with profound intellectual and multiple disabilities: A narrative literature review of concepts, assessment methods and assessors. Journal of Intellectual & Developmental Disability. **44**,261–271 (2019).
22. van der Putten, A.A.J., Bossink, L.W.M., Frans, N., Houwen, S., & Vlaskamp, C. Motor activation in people with profound intellectual and multiple disabilities in daily practice. Journal of Intellectual & Developmental Disability 42,1–11(2017).
23. Hostyn, I., Daelman, M., Janssen, M.J., & Maes, B. Describing dialogue between persons with profound intellectual and multiple disabilities and direct support staff using the scale for dialogical meaning making. Journal of Intellectual Disability Research. **54**,679–90(2010).
24. Chadwick, D., Buell, S., & Goldbart, J. Approaches to communication assessment with children and adults with profound intellectual and multiple disabilities. J Appl Res Intellect Disabil. **32**,336–358(2019).
25. Herbuela, V.R.D.M. *et al.* Integrating behavior of children with profound intellectual, multiple, or severe motor disabilities with location and environment data sensors for independent communication and mobility: app development and pilot testing. JMIR Rehabil Assist Technol. **8**,e28020 (2021).
26. Wessels, M.D., & van der Putten, A.A.J. Assessment in people with PIMD: Pilot study into the usability and content validity of the Inventory of the personal Profile and Support. Cogent Psychology. **4**,250–260 (2017).
27. Brady, N. C. *et al.* Development of the communication complexity scale. American Journal of Speech-Language Pathology. 21, 16–28 (2012).
28. Ashida, K., & Ishikura, K. Creating a category table of expressions in children with severe motor and intellectual disabilities. The Journal of School Education, **25**, 75–82 (2013).
29. Ashida, K., & Ishikura, K. The understanding of expression for children with severe motor and intellectual disabilities: The analysis using the category table of expressions. The Journal of School Education. **28**,55–61 (2015).
30. van Delden, R. *et al.* Alertness, movement, and affective behaviour of people with profound intellectual and multiple disabilities (PIMD) on introduction of a playful interactive product: Can we get your attention? Journal of Intellectual and Developmental Disability. **45**, 66–77(2020).
31. Blain-Moraes, S., & Chau, T. Challenges of developing communicative interaction in individuals with congenital profound intellectual and multiple disabilities. J Intellect Dev Disabil. **37**,348–59 (2012).
32. Zhang, J., Calabrese, C., Ding, J., Liu, M., & Zhang B. Advantages and challenges in using mobile apps for field experiments: A systematic review and a case study. Mobile Media Commun. **6**,179–196(2017).
33. Njuguna, H.N., *et al.* A comparison of smartphones to paper-based questionnaires for routine influenza sentinel surveillance, Kenya, 2011–2012. BMC Med Inform Decis Mak **14**,107(2014).
34. King, J.D., *et al.* A novel electronic data collection system for large-scale surveys of neglected tropical diseases. PLoS One. **8**,e74570(2013).
35. Karita, T. Development of a Communication Aid App with iOS Devices to Support Children/Persons with Speech Disabilities Improvement in Obtaining Positioning Information with iBeacon as Near Field Radio Communication Technology. J. Adv. Comput. Intell. Intell. Inform. **21**,371–377(2017).
36. Irvin, D. W., Bard, A., Wallisch, A., & Little, L. M. Measuring Social Communication in the Community: Novel Tools for Advancing Family Participation. The American journal of occupational therapy: official publication of the American Occupational Therapy Association. **72**, 7206205060p1–7206205060p7(2018).
37. World Medical Association. World Medical Association Declaration of Helsinki Ethical Principles for Medical Research Involving Human Subjects. JAMA. **310**,2191–2194 (2013).
38. European Medicines Agency. ICH Topic E6 (R1) Guideline for Good Clinical Practice Step 5 Note for Guidance on Good Clinical Practice; CPMP/ICH/135/95: London, UK (2002).
39. Griffiths, C., & Smith, M. You and me: The structural basis for the interaction of people with severe and profound intellectual disability and others. Journal of Intellectual Disabilities. **21**,103–117(2017).
40. Charach, L., Grosskopf, I., Karniel, E., & Charach, G. A Meteorological Paradox: Low Atmospheric Pressure-Associated Decrease in Blood Pressure Is Accompanied by More Cardiac and Cerebrovascular Complications: Five-Year Follow-Up of Elderly Hypertensive Patients. Atmosphere. **13**, 235(2022).
41. Funakubo, M., Sato, J., Mizumura, K., Suzuki, N., & Messlinger, K. Craniofacial sensations induced by transient changes of barometric pressure in healthy subjects – A crossover pilot study. Cephalalgia Reports. 4,1–10(2021).

42. Sharafi, R., Bogdanov, V., Gorlov, D. & Gorgo, Y. The influences of meteorological factors on the health and functional state of human. Health. **5**, 2068–2076(2013).
43. No, M., & Kwak, H. B. Effects of environmental temperature on physiological responses during submaximal and maximal exercises in soccer players. Integrative medicine research, *5*, 216–222(2016).
44. Remmers, T., *et al.* Weather and Children's Physical Activity Patterns. Medicine & Science in Sports & Exercise. **49**,922–929(2017).
45. Younan, D., *et al.* Environmental Determinants of Aggression in Adolescents: Role of Urban Neighborhood Greenspace. J Am Acad Child Adolesc Psychiatry. **55**,591–601(2016).
46. Brazienė, A., *et al.* Relationship between Depressive Symptoms and Weather Conditions. International Journal of Environmental Research and Public Health. **19**,5069(2022).
47. Li, Y., *et al.* Effects of illuminance and correlated color temperature of indoor light on emotion perception. Sci Rep. **11**,14351(2021).
48. Milosavljevic, N. How Does Light Regulate Mood and Behavioral State? Clocks & sleep. *1*,319–331(2019).
49. Goodman, A., Paskins, J., & Mackett, R. Day Length and Weather Effects on Children's Physical Activity and Participation in Play, Sports, and Active Travel. Journal of physical activity & health, 9,1105–16(2012).
50. Goodman, A., *et al.* Daylight saving time as a potential public health intervention: an observational study of evening daylight and objectively-measured physical activity among 23,000 children from 9 countries. Int J Behav Nutr Phys Act **11**,84(2014).
51. Yacan, S. D. Impacts of Daylighting on Preschool Students' Social and Cognitive Skills, submitted for the Degree of Master of Science, University of Nebraska-Lincoln (2014).
52. Morrow, B.L., & Kanakri, S.M. The impact of fluorescent and led lighting on students attitudes and behavior in the classroom. Adv Pediatr Res 5,15(2018).
53. Bulbena A., *et al.* Panic anxiety, under the weather*? Int J Biometeorol*. **49**,238 – 43(2005).
54. Harrison, F., *et al.* The impact of rainfall and school break time policies on physical activity in 9–10 year old British children: a repeated measures study. Int J Behav Nutr Phys Act. **8**, 47 (2011).
55. Harrison, F., *et al.* The changing relationship between rainfall and children's physical activity in spring and summer: a longitudinal study. Int J Behav Nutr Phys Act **12**, 41 (2015).
56. Rahman, S. Effects of weather on physical activity among school children in Alberta, Canada. *A thesis submitted for the degree of Master of Science in Epidemiology School of Public Health, University of Alberta* (2017).
57. Lewis, L.K., *et al.* At the Mercy of the Gods: Associations Between Weather, Physical Activity, and Sedentary Time in Children. Pediatr Exerc Sci. 28,152 – 63(2016).
58. Edwards N.M., *et al.* Outdoor Temperature, Precipitation, and Wind Speed Affect Physical Activity Levels in Children: A Longitudinal Cohort Study. J Phys Act Health. **12**,1074–81 (2015).

Figures

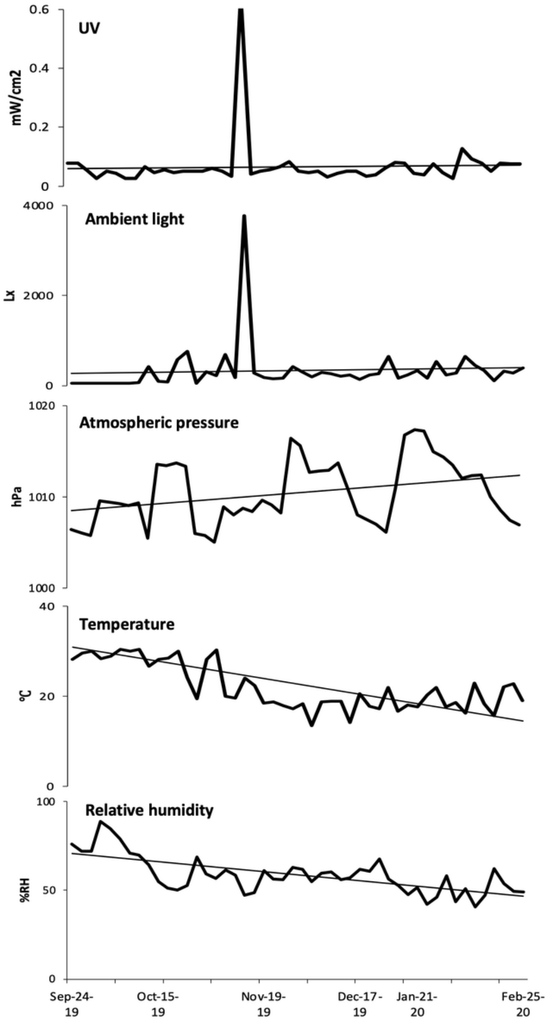

Figure 1

Hourly mean indoor weather indices across the study period

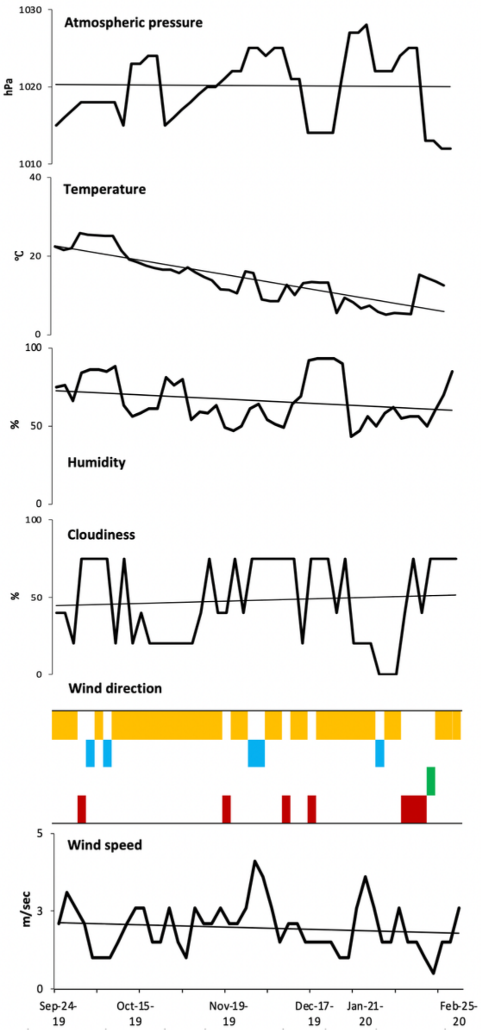

Figure 2

Hourly mean outdoor weather indices across the study period. NE = northeast; SE = southeast; SW = southwest; NW = northwest.

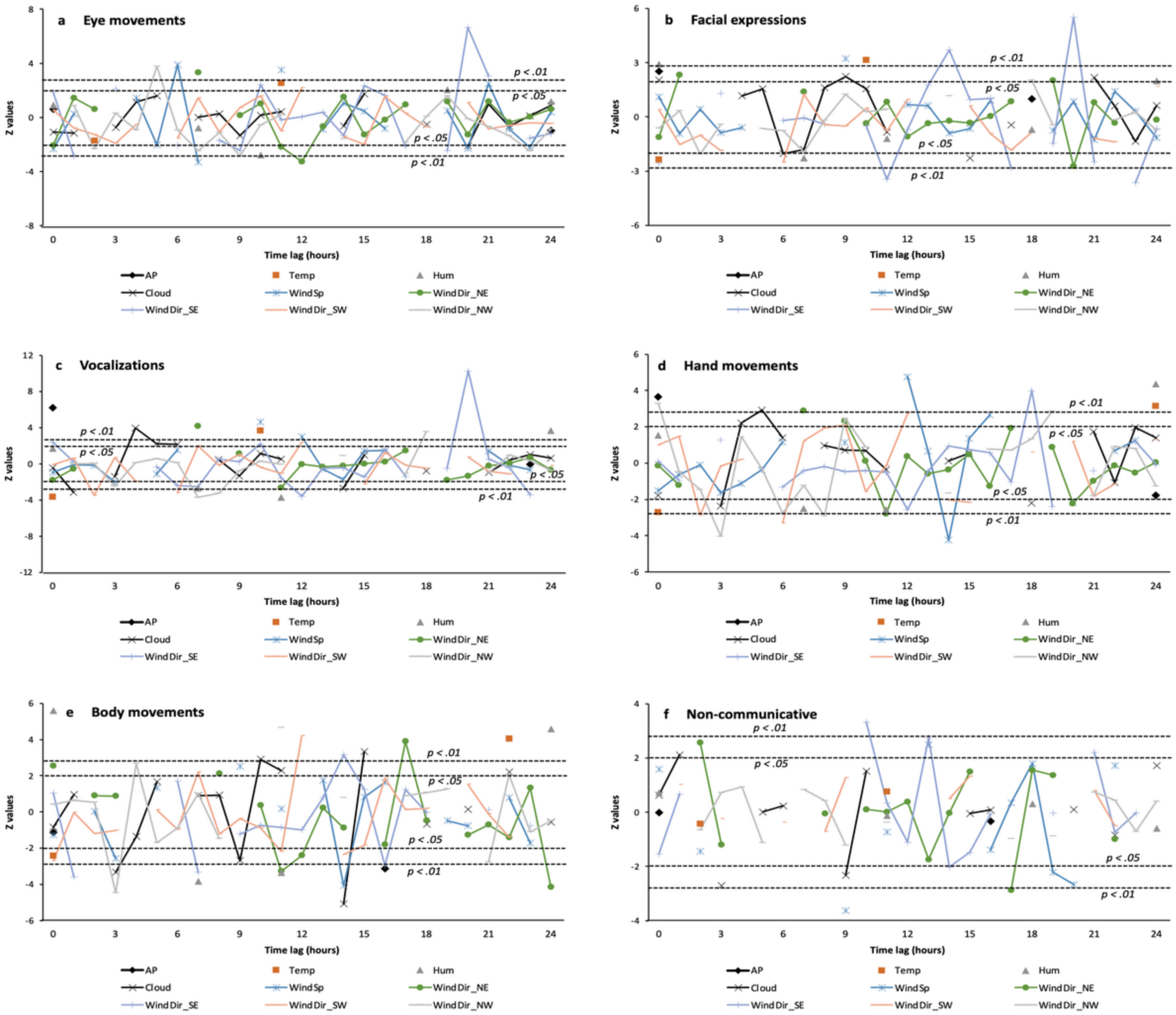

Figure 3

The main effect estimates (Z-values) of outdoor weather indices across 24-hour analysis time period on the movement outcomes. AP = atmospheric pressure; Temp = temperature; Hum = humidity; Cloud = cloudiness; WindSp = wind speed; WindDir = wind direction; NE = northeast; SE = southeast; SW = southwest; NW = northwest.

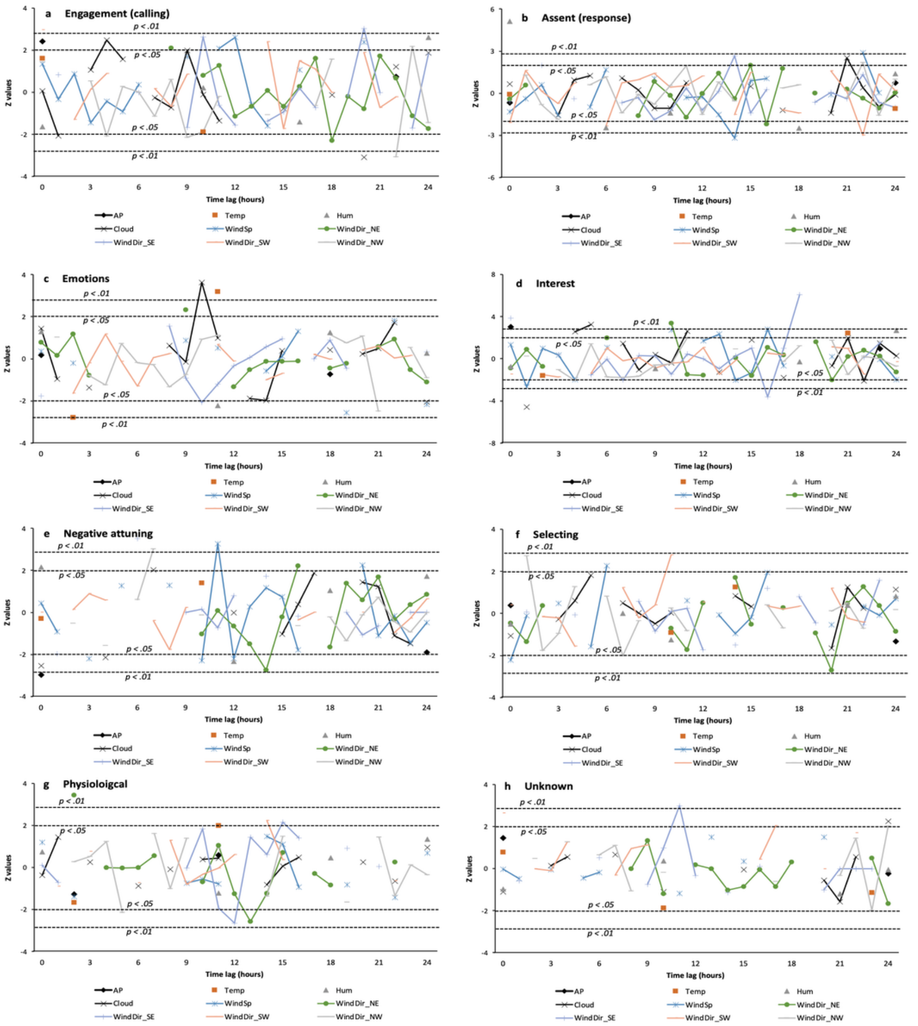

Figure 4

The main effect estimates (Z-values) of outdoor weather indices across 24-hour analysis time period on the behavior outcomes. AP = atmospheric pressure; Temp = temperature; Hum = humidity; Cloud = cloudiness; WindSp = wind speed; WindDir = wind direction; NE = northeast; SE = southeast; SW = southwest; NW = northwest.