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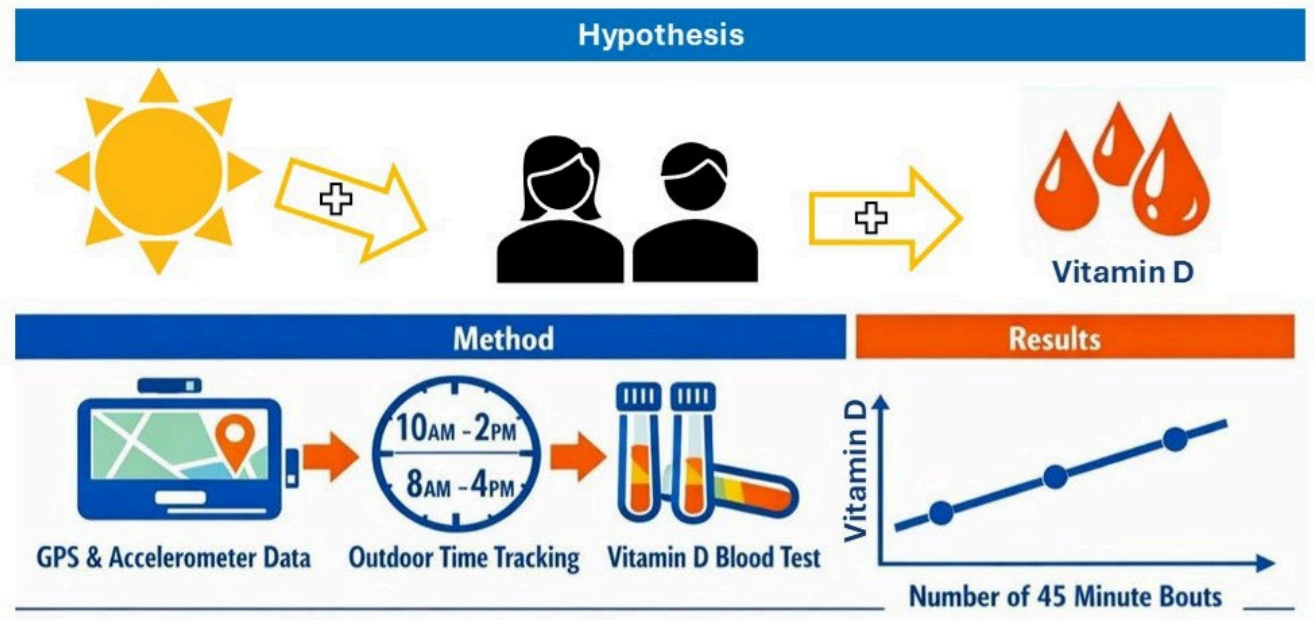
Graphical Abstract



Highlights:

- GPS data used to measure outdoor time for vitamin D synthesis assessment.
- Novel method links outdoor exposure patterns to serum vitamin D levels.
- Greater outdoor time associated with higher vitamin D.
- GPS-derived measures could expand UVB exposure assessment capabilities.

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GPS-derived outdoor time and associated vitamin D status

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Abstract: **Background:** Vitamin D is essential for health and sunlight (ultraviolet radiation band B (UVB) radiation) is a major source. However, individual sunlight exposure is difficult to measure, limiting our ability to identify people at risk of deficiency and to design effective interventions. Therefore, to address limitations of self-reported data, we developed and assessed a method that uses global positioning system (GPS) data to generate individual outdoor time measures relevant to vitamin D synthesis and compared these with serum vitamin D levels. **Method:** GPS and accelerometer sensors were used to measure time spent outdoors in San Diego adults (n = 130) for an average of 12.6 days. Three categories of outdoor time measures were generated including total outdoor time, number of outdoor "bouts" (distinct periods of outdoor time), and number of days with outdoor bouts. Within these categories, outdoor time was assessed between 10 am–2 pm (peak UVB) and a broader time UVB-relevant time window 8 am–4 pm. Satellite derived daily Ultraviolet (UV) data were used to generate UV weighted versions of the total outdoor time and number of outdoor bout measures. Participants also completed 24-hour food recalls and provided fasting blood samples. Adjusted generalized linear regression models were estimated for associations of each exposure measure with serum vitamin D level. **Results:** Across all GPS-derived exposure metrics, point estimates were consistently positive, indicating a uniform directional pattern in which greater outdoor time was associated with higher serum vitamin D concentrations, although most confidence intervals included the null. In sensitivity analyses excluding participants who reported taking vitamin D supplements, this pattern persisted. Two measures of longer outdoor exposure provided stronger evidence of an association: the number of 45-minute bouts between 10 am and 2 pm (β = 4.36, 95% CI 0.32 to 8.40) and the number of days with a 45-minute bout (β = 4.38, 95% CI 0.16 to 8.59). In both cases, the confidence intervals did not include the null. More days with shorter bouts also showed a relatively large point estimate, though with substantial imprecision. UV-weighted exposure metrics did not outperform the simpler GPS-derived time-based measures. **Conclusion:** GPS-derived outdoor time measures, including those weighted by satellite-derived daily UV, demonstrated consistent positive associations with vitamin D levels, with the strongest evidence observed for longer exposures during peak UVB periods. These findings indicate that simple, time-based GPS metrics and their UV-weighted variants may provide practical and informative indicators of UVB-relevant exposure patterns in real-world settings.

Keywords: vitamin D; sunlight; UVB radiation; GPS; dynamic exposure; mobility; cancer; cardiovascular disease; mHealth

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1. Introduction

Vitamin D is an essential nutrient for healthy body function [1] with insufficient vitamin D being linked to conditions such as rickets, osteomalacia [2] cardiovascular disease and cancer [3]. Despite clear health benefits, lack of vitamin D is of global concern. For example, there are worldwide reports on widespread prevalence of vitamin D insufficiency and deficiency [4–7] .

Sunlight is required for the first step of active vitamin D synthesis [8]. When solar ultraviolet radiation band B (UVB) reaches the skin, it converts 7-dehydrocholesterol—a chemical present in the skin—to previtamin D3. Through a series of steps, this is converted to 25-hydroxyvitamin D3, the main form used in serum testing [3]. The quantity of vitamin D synthesized as a result of sunlight depends on environmental and individual factors that determine first whether UVB radiation reaches the skin and then vitamin D synthesis [9]. Environmental factors include the angle of the sun, which is determined by the time of day, season and latitude, cloud cover which generally reduces surface Ultraviolet (UV) radiation atmospheric effects such as ozone and aerosols, and albedo (*i.e.*, surface reflectance) [8–12]. At a smaller scale, environmental characteristics that provide shade, such as buildings and tree canopy, will also influence how much UV radiation reaches the skin [13–15]. Individual factors relevant to vitamin D synthesis include skin type, clothing coverage, sunscreen use, genotype, and age [8,9,11,12,16]. Individual behavior is also key. Not only do individual choices affect aspects such as clothing and sunscreen use, they also affect the daily mobility patterns that determine outdoor location, timing and duration, and thereby UVB exposure.

Vitamin D-effective UV irradiance follows a well-characterized action spectrum and is strongly driven by the duration and timing of exposure to unshaded outdoor environments. Photobiology research demonstrates that time spent outdoors during periods of sufficient solar elevation is a primary determinant of cutaneous vitamin D synthesis, even when intensity varies due to cloud cover, shade, or atmospheric conditions [2,17–19]. This supports the use of outdoor time as a proxy for UVB-relevant exposure in population studies.

An individual's UVB radiation exposure from the sun has been assessed in different ways. Portable ultraviolet radiation (UVR) dosimeters provide direct quantitative data on personal ultraviolet radiation exposure. For example, polysulphone film dosimeters, characterize cumulative exposure [20,21]. In comparison electronic dosimeters, often attached with a wrist band collect time-stamped data, allowing estimation of the magnitude, frequency and duration of UVB exposure [22–25]. Dosimetry approaches allow good characterization of individual exposures, though also have limitations such as lack of ability to account for sunscreen/clothing, inability to distinguish between type of radiation, and cost and burden to deploy and process [26].

An alternative approach is to estimate UVB exposure based on measures of outdoor time. Outdoor time is relevant for several reasons. First, being outdoors is a prerequisite for vitamin D synthesis since indoor sunlight exposure does not typically result in vitamin D synthesis as glass and plexiglass absorb solar UVB radiation [12,27]. Second, daily mobility patterns are embedded in a variety of built and natural environments which can potentially influence UVB exposure. Finally, understanding the spatiotemporal patterning of outdoor time (location, duration, timing, frequency and consistency) is important since regular, short doses of solar UVB at specific times of day are the most effective and efficient way of increasing vitamin D [9,28], and can also minimize the risk of detrimental effects of sunlight such as sunburn and skin cancer [29,30]. Some population-level studies of vitamin D have assessed outdoor time through surveys. These outdoor time measures can be relatively coarse, for example, only assessing overall outdoor time such as total hours of outdoor physical activity [31] or comparing indoor versus outdoor sportspeople [32]. Other vitamin D studies have assessed outdoor time with greater spatiotemporal specificity, for example measuring average daily outdoor time [33,34], outdoor time by season [35], average frequency of outdoor activity per week in the past 3 months [34], activity window (before 8 am, 8 am–4 pm, and after 4 pm) [34], or time outdoors on a typical day off (between 9 am–12 pm, 12–3 pm and 3–6 pm) [36]. Yet outdoor time measures in vitamin D studies have traditionally relied on self-report data which can be subject to recall bias [37–40] and a tendency for participants to round and over-report time estimates [41].

Recent Global Navigation Satellite System (GNSS)-assisted approaches have also explored using raw satellite signals to estimate individual-level UV exposure in real time, including in shaded environments [42]. These methods highlight growing interest in leveraging mobile devices for passive UV exposure assessment.

To the best of our knowledge no study with the aim of relating outdoor time with circulating vitamin D levels has objectively measured when and for how long participants are outdoors. Yet such an approach could allow for low-burden, cost-effective estimation of time spent outdoors through mobile devices currently carried by most of the population.

In this study, we develop several global positioning system (GPS)-derived vitamin D-specific outdoor time measures based on current understanding of optimal times and durations for vitamin D synthesis. We then establish which of these is most closely associated with vitamin D levels in a sample cohort after adjusting for individual factors associated with vitamin D. Our research questions are:

Is there a relationship between GPS-measured outdoor time and vitamin D levels in free-living adults?

After adjusting for individual factors associated with vitamin D, which measures of outdoor time (e.g., our new vitamin D-specific outdoor measures versus total time spent outdoors) are more closely associated with vitamin D levels?

We hypothesize that GPS-based measures of outdoor time will show measurable associations with vitamin D levels, and that these associations will be more pronounced for temporally specific outdoor bouts compared to total time spent outdoors.

2. Methods

2.1. Study data

The current study draws on a subset of participants from the Community of Mine Study, details for which have been published elsewhere [43]. Briefly, this cross-sectional study enrolled participants 35 to 80 years of age in San Diego County, California from 2014 to 2017. The study purpose was to better understand associations between environmental exposures and cancer risk in a diverse cohort of adults living in San Diego County, with targeted enrichment for Hispanics/Latinos. Participants filled out detailed questionnaires, completed two 24-hour food recalls, gave fasting blood and urine samples, and wore GPS and accelerometer sensors for two weeks. Participants without at least 4 valid days of sensor data were asked to re-wear devices for an additional 7 days. Of the 602 participants who completed the Community of Mine study, measurement of serum vitamin D was conducted in a subset of 146 individuals who participated in an ancillary study "Nucleotides to Neighborhoods" and had complete data collection and, thus, were eligible to be included in the current study. This subsample was demographically similar to the full Community of Mine sample [44]. All participants provided written informed consent and ethics approval was obtained from the University of California San Diego Institutional Review Board (protocol #140510).

2.2. UV data

Time series of daily UV data for San Diego (2014–2017) were obtained from the Tropospheric Emission Monitoring Internet Service (TEMIS) [45]. TEMIS provides estimates of UV irradiance that reaches the Earth's surface in a day and takes cloud cover into account [45]. TEMIS computes three UV doses that align with three different action spectra and associated health effects: erythema (sunburn) of the skin, vitamin D production in the skin and DNA-damage. Since our study is focused on vitamin D production, we used vitamin D UV dose (UVDVF), which was provided in kJm^{-2}.

2.3. Sensor data processing and outdoor time assessment

Sensor data was generated from two sensors worn on the hip during waking hours over a two-week period: a GT3X+ ActiGraph accelerometer (ActiGraph, LLC; Pensacola, Florida) and a Qstarz GPS device (Qstarz International Co. Ltd., Taipei, Taiwan). The GPS data was used to assess outdoor time and the accelerometer data was only used to define wear time.

The Qstarz GPS has an industry reported accuracy of 3 m with similar accuracy found in independent validation, however large jumps in location can happen due to signal scatter [46]. Additionally, signal interference can cause large gaps of missing GPS data. Imputation was performed to fill in missing GPS data (Mean: 8.8%; SD: 17.7%) using a previously validated algorithm [47]. The Personal Activity and Location Measurement System (PALMS) was used to clean GPS data of scatter, lone GPS fixes (single fix between two gaps in data), excessive speed fixes over 130 km/hr, and fixes with large elevation change over 1000 m [48].

PALMS was also used to aggregate GPS and raw 30 Hz accelerometer data to the minute level, stitch the sensor data together based on time stamp, identify non-wear time, and classify minutes into movement categories including stationary, walking, and in-vehicle. Source code for the original PALMS system can be found at https://github.com/MD2Korg/md2k-PALMS. Non-wear time was defined as 90 minutes of consecutive zeros with a 2-min threshold with accelerometer data using the validated Choi algorithm [49]. Valid days were defined as having at least 10 hours of accelerometer measured wear time; on average participants for this study had an average of 12.6 valid wear days of combined GPS and accelerometer data.

Outdoor time was determined using the PALMS system. PALMS characterizes each GPS point as being outdoors or indoors using the signal-to-noise ratio (SNR). A SNR of ≥ 250 was classified as outdoor time, while < 250 was classified as indoor time. This is based on the principle that indoor environments will have a lower SNR due to interference from building materials [50,51]. The cut-point of 250 was selected based on previous sensitivity analyses indicating that it provides an appropriate balance between sensitivity and specificity [50]. Time classified as in-vehicle was excluded since UVB, which is needed for vitamin D synthesis, cannot penetrate automobile glass windows [12,27].

2.4. Outdoor time measures

A total of 26 outdoor time measures were created from GPS derived outdoor data organized in three categories:

Outdoor time: Total GPS measured outdoor time during the study (hours). This is intended to replace self-reported survey data commonly used in outdoor time assessment.

Number of outdoor bouts: Total number of outdoor bouts (*i.e.*, distinct periods of outdoor time) over the study period. These bouts were defined based on the timing and times of day that provide the greatest opportunity to synthesize vitamin D from UVB [17,52–54].

Number of days with outdoor bouts: Total number of days with at least one outdoor bout. This category of measures was intended to capture the regular accumulation of outdoor time that is better for vitamin D synthesis. For example, in terms of vitamin D synthesis, '10 outdoor bouts in 1 day' is distinct from '1 outdoor bout every day for 10 days.'

Two daylight time windows were generated for each measure. These included a broad daylight time window (8 am–4 pm) that includes times of day with lower UVB radiation and a narrow window (10 am–2 pm) of peak UVB radiation and therefore, the optimal time for vitamin D synthesis.

Outdoor bouts were first calculated using four different durations: 10, 20, 30 and 45 minutes of consecutive outdoor time. The selected durations represent a range of exposures and enable sensitivity analyses. They were derived from sunshine exposure guidelines [55] and align with evidence from

laboratory and observational studies. For instance, a laboratory study of skin samples indicated that about 15 minutes of exposure to noon equatorial UVB results in an equilibrium between 7-dehydrocholesterol and pre-vitamin D3, suggesting 15 minutes as an adequate bout threshold, although this may differ based on individual characteristics such as skin tone or environmental characteristics such as seasonality [52]. One estimate of time required for an adequate vitamin D dose in San Diego at noon (latitude: 32 degrees) is 9 minutes in summer and 49 minutes in winter [56]. Alternate estimates for locations at 29 degree latitudes range from 3–10 minutes in summer and 10–48 minutes in winter for skin phototypes II, III, IV and V [17], which are the most likely phototypes based on our sample and the most prevalent in the United States [17].

2.5. UV weighted outdoor time measures

All outdoor time measures were weighted by UV data:

UV weighted outdoor time: For each participant, the outdoor time measures for each day of data collection was multiplied by the satellite derived UV data for that day. These daily weighted outdoor times were then averaged and summed for each participant.

UV weighted number of outdoor bouts: For each participant, the number of outdoor bouts in each day was multiplied by the satellite derived UV data for that day. These were then averaged for each participant.

2.6. Vitamin D assay

Participants were asked to fast for 12 h prior to a clinical visit for a 45 mL blood draw, a minimum fast of 9 h was required. The clinical visit occurred one week after GPS data collection commenced (*i.e.*, midway through GPS data collection). Blood used for serum preparation was allowed to clot at room temperature for 30 minutes, then held on ice for an additional 30 minutes before centrifugation at 4 °C for 10 minutes. Serum was aliquoted and stored at –80 °C prior to analysis.

High-performance liquid chromatography (HPLC) method was used to separate and quantify 25(OH)D2 and 25(OH)D3 on an Agilent Technologies (Palo Alto, California) 1100 series LC at the UC San Diego Moores Cancer Center Biobehavioral Shared Resource. Vitamin D metabolites were extracted from 400 µL serum samples based on methods previously published by Heath *et al.* [57]. To monitor the HPLC method performance, the laboratory participates in the international Vitamin D External Quality Assessment Scheme (DEQAS) proficiency survey [58], and more recently, the newly inaugurated National Institute of Standards and Technology (NIST) vitamin D quality assurance exercise. We routinely used one in-house serum pool and four additional purchased quality control samples covering the analytical range from 6.0–150 ng/mL. The batched sample results were accepted only if these internal quality control results were within 2 standard deviations of the assigned values.

Acknowledging that there is debate regarding the definition of vitamin D deficiency and insufficiency [59], in this study we define sufficient vitamin D as >75 nmol/L [60], insufficient as 50–75 nmol/L, and deficient as < 50. In the absence of clear guidance this cutoff was an arbitrary choice, noting that we only use these categories in descriptive statistics. Vitamin D sufficiency was coded as 0 for deficiency, 1 for insufficiency, and 2 for sufficiency. Changes in 25 hydroxyvitamin D levels are detectable within 24 hours after UVB exposure [61], with maximal levels occurring at 1–2 weeks [62]. The half-life of 25 hydroxyvitamin D is approximately two weeks [63].

2.7. Covariates

Demographic covariates were collected via surveys and included age, sex, education, race and ethnicity. Daily vitamin D (mcg) intake from diet (continuous) was estimated using two 24-hour, multiple-pass food recalls (one collected on a weekday and one on a weekend day) using the Nutrition Data System for Research (NDSR) versions 2015 and 2016 [64]. Vitamin D supplementation was recorded during clinical visits when participants were asked to bring in all medications and supplements that they take regularly. GPS wear time was the total number of GPS recorded minutes regardless of location or time of day. Table 1 provides covariate details.

Table 1. Covariates.

Covariate	Coding and categories	Reference group	Functional form in model
Age	Continuous	N/A	Linear term
Sex	Binary: male, female	Male	Dummy variable
Education	Categorical: no completed college degree, college degree, graduate education	No completed college degree	Dummy variable
Race	Binary: white, other	White	Dummy variable
Ethnicity	Binary: other, Latino or Hispanic	Other	Dummy variable
Daily vitamin D intake (mcg)	Continuous	N/A	Linear term
Vitamin D supplementation	Binary: no, yes	No	Dummy variable
GPS wear time (hours)	Continuous	N/A	Linear term

2.8. Statistical analysis

Descriptive statistics were calculated for the full sample and for the vitamin D insufficient and sufficient sub-samples. T-test and chi-squared tests compared mean sample characteristics between vitamin D sufficient and insufficient participants.

Continuous exposures were z-standardized to facilitate comparability of effect estimates. Separate generalized linear models (GLM) with robust standard errors were used to

determine the relationship between each transformed outdoor exposure measure (independent variable) and vitamin D levels (Gaussian model, link function: 'identity'). Two versions of each model were estimated. Model 1 included only the independent and dependent variables. Model 2 adjusted for age, sex, education, race, ethnicity, dietary vitamin D intake, supplementation with vitamin D, and GPS wear time (to account for the varying number of hours and days that participants wore the GPS unit). Since vitamin D supplementation can influence serum 25(OH)D [65] and therefore potentially mask associations with outdoor behavior we also repeated the modelling for the sample of participants who did not use vitamin D supplements.

Analyses were conducted using complete case data. Beta-coefficients and 95% confidence intervals were reported. Statistical analyses were performed in R version 4.4.3 [66] and figures produced with ggplot2 [67].

3. Results

3.1. Sample

Of the 146 eligible participants, 12 were excluded due to missing race data and three for missing vitamin D supplement data, and one for implausible dietary vitamin D. The final analytic sample size was 130.

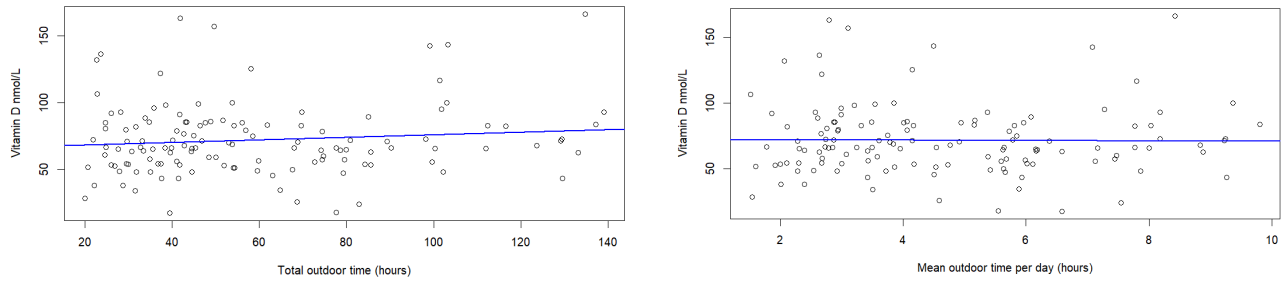
Final sample characteristics are shown in Table 2. Participants were on average 60.2 years old and predominantly white (86.9%), with 36.6% Hispanic and 51.5% male. One participant was African American. Approximately one third (36.2%) of participants took vitamin D supplements and on average participants consumed 3.9 mcg of vitamin D daily. Serum circulating vitamin D was on average 71.9 nmol/L. Eighty three (63.8%) participants were vitamin D insufficient (50–75 nmol/L) or deficient (< 50 nmol/L) compared to 70.3% in US adults [5]. The only statistically significant differences between vitamin D sufficient, insufficient and deficient participants were levels of serum vitamin D and vitamin D supplementation. All participants had valid GPS data (median: 13 days) and, on average, wore the units for a total of 14.5 hours daily.

Figure 1 presents scatter plots illustrating the relationships between total time spent outdoors, mean daily outdoor time, and serum Vitamin D levels. There is a slight positive association between total outdoor time and serum Vitamin D, with higher cumulative outdoor exposure corresponding to marginally higher Vitamin D levels. In contrast, no apparent relationship is observed between mean time outdoors per day and serum Vitamin D.

Table 2. Analytical sample characteristics and comparison of participants, including categorization by vitamin D sufficiency (sufficient: > 75 nmol/L; insufficient: > 50 and <= 75 nmol/L; deficient: <= 50 nmol/L).

	Total sample (n = 130) Mean (SD)	**Sufficient (n = 47) Mean (SD)**	**Insufficient (n = 62) Mean (SD)**	**Deficient (n = 21) Mean (SD)**	**t-test p-value**
Age (years)	60.2 (10.3)	63.0 (9.8)	58.8 (10.0)	58.4 (11.5)	0.065
Dietary VitD (mcg)	3.9 (4.6)	2.9 (2.3)	4.8 (6.0)	3.5 (3.1)	0.095
Total VitD (nmol/L)	71.9 (26.9)	98.7 (24.2)	62.8 (6.9)	39.0 (10.6)	**< 0.001**
Total GPS wear time (hours)	183.8 (40.8)	191.2 (43.4)	182.2 (38.5)	172.1 (39.9)	0.189
Mean daily GPS wear time (hours)	14.5 (1.2)	14.5 (1.2)	14.4 (1.1)	14.6 (1.4)	0.874
	n (%)	n (%)	n (%)	n (%)	chi^2 p-value
Sex					
Male	67 (51.5)	19 (40.4)	34 (54.8)	14 (66.7)	0.104
Ethnicity					
Hispanic/Latino	48 (36.6)	14 (29.8)	24 (38.7)	8 (38.1)	0.603
Race					
White	113 (86.9)	33 (87.2)	55 (88.7)	17 (80.9)	0.658
Education (highest qualification)					
No completed college degree	45 (34.6)	18 (38.3)	19 (30.6)	8 (38.1)	0.766
College degree	39 (30.0)	12 (25.5)	22 (35.5)	5 (23.8)	
Graduate degree	46 (35.4)	17 (36.2)	21 (33.9)	8 (38.1)	
VitD supplementation					
Yes	47 (36.2)	27 (57.4)	18 (29.0)	2 (9.5)	**< 0.001**
Month of sample					
January	2 (1.5)	2 (4.3)	0 (0.0)	0 (0.0)	0.657
February	11 (8.5)	5 (10.6)	4 (6.5)	2 (9.5)	
March	1 (0.8)	1 (2.1)	0 (0.0)	0 (0.0)	
April	2 (1.5)	1 (2.1)	1 (1.6)	0 (0.0)	
May	39 (30.0)	12 (25.5)	21 (33.9)	6 (28.6)	
June	16 (12.3)	5 (10.6)	7 (11.3)	4 (19.0)	
July	17 (13.1)	9 (19.1)	6 (9.7)	2 (9.5)	
August	26 (20.0)	8 (17.0)	16 (25.8)	2 (9.5)	
September	5 (3.8)	1 (2.1)	2 (3.2)	2 (9.5)	
October	9 (6.9)	3 (6.4)	4 (6.5)	2 (9.5)	
November	2 (1.5)	0 (0.0)	1 (1.6)	1 (4.8)	
December	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	

Results from t-tests and chi^2 tests are shown ($\alpha = 0.05$).



(a) (b)

Figure 1. Levels of serum vitamin D plotted against: **(a)** Total outdoor time; **(b)** Mean outdoor time per day.

3.2. Outdoor time measure results

Table 3 summarizes the GPS-derived outdoor time measures. Participants recorded an average of 58.7 outdoor hours (SD: 30.5) over the two-week study period, with an average of 30.6 hours in daylight (8 am–4 pm) and 15.3 hours during the optimal time for vitamin D synthesis (10 am–2 pm). As expected, more bouts were recorded within larger time windows (8 am–4 pm) and for shorter bout definitions. Similarly, the number of days with at least one bout ranged from 2.5–8.1 with higher numbers for the wider time window and shorter bout definitions. The differences between participants with sufficient, insufficient and deficient vitamin D were not statistically significant ($\alpha = 0.05$).

Table 3. Outdoor time measure characteristics, including categorization by vitamin D sufficiency (sufficient: > 75 nmol/L; insufficient: > 50 and <= 75 nmol/L; deficient: <= 50 nmol/L). The data and measures are at the participant level.

	Total sample (n =130) Mean (SD)	Sufficient (n = 47) Mean (SD)	Insufficient (n = 62) Mean (SD)	Deficient (n = 21) Mean (SD)
Outdoor time (hours)				
Total hours outdoors	58.7 (30.5)	59.4 (32.9)	59.3 (29.7)	55.1 (28.5)
Total hours outdoors (8 am–4 pm)	30.6 (17.3)	31.0 (17.3)	31.6 (18.3)	27.0 (14.4)
Total hours outdoors (10 am–2 pm)	15.3 (9.4)	15.6 (9.6)	15.8 (9.9)	13.5 (7.6)
UV weighted outdoor time				
Mean UV weighted daily outdoor time	29.4 (20.9)	25.6 (18.9)	30.9 (21.8)	33.3 (21.8)
Mean UV weighted daily outdoor time (8 am–4 pm)	15.7 (11.8)	13.1 (9.4)	17.4 (13.2)	17.1 (11.9)
Mean UV weighted daily outdoor time (10 am–2 pm)	8.4 (6.4)	6.9 (5.4)	9.4 (7.3)	8.8 (5.6)
Number of outdoor bouts				
Number of 10 min bouts (8 am–4 pm)				
Number of 20 min bouts (8 am–4 pm)	19.9 (15.8)	20.0 (15.8)	21.0 (17.2)	16.5 (11.1)
Number of 30 min bouts (8 am–4 pm)	11.4 (10.4)	11.0 (9.4)	12.5 (11.8)	8.8 (8.0)
Number of 45 min bouts (8 am–4 pm)	5.8 (6.5)	5.6 (5.9)	6.7 (7.6)	4.0 (3.9)
Number of 10 min bouts (10 am–2 pm)				
Number of 20 min bouts (10 am–2 pm)	11.1 (10.4)	11.2 (11.0)	11.6 (10.9)	9.5 (6.9)
Number of 30 min bouts (10 am–2 pm)	6.4 (6.9)	6.2 (6.8)	7.0 (7.5)	4.9 (4.4)
Number of 45 min bouts (10 am–2pm)	3.2 (4.4)	3.3 (4.4)	3.6 (4.9)	2.0 (1.9)
UV weighted number of outdoor bouts				
UV weighted number of 10 min bouts (8 am–4 pm)				
UV weighted number of 20 min bouts (8 am–4 pm)	124.2 (124.3)	108.9 (114.2)	138.2 (140.3)	117.3 (91.3)
UV weighted number of 30 min bouts (8 am–4 pm)	70.4 (80.5)	59.2 (65.6)	81.6 (94.3)	62.0 (63.4)
UV weighted number of 45 min bouts (8 am–4 pm)	36.8 (48.7)	30.6 (42.0)	43.7 (57.0)	30.0 (32.4)
UV weighted number of 10 min bouts (10 am–2 pm)				
UV weighted number of 20 min bouts (10 am–2 pm)	67.1 (77.6)	57.0 (73.5)	74.0 (85.9)	68.9 (59.3)
UV weighted number of 30 min bouts (10 am–2 pm)	38.4 (53.2)	31.9 (48.1)	44.5 (61.2)	35.1 (35.8)
UV weighted number of 45 min bouts (10 am–2 pm)	20.2 (33.8)	18.3 (32.1)	23.3 (39.3)	15.4 (15.8)
Number of days with outdoor bouts				
Number of days with a 10 min bout (8 am–4 pm)				
Number of days with a 20 min bout (8 am–4 pm)	8.1 (3.6)	8.5 (3.6)	8.0 (3.9)	7.4 (2.8)
Number of days with a 30 min bout (8 am–4 pm)	6.1 (3.9)	6.3 (3.9)	6.3 (4.0)	5.0 (3.1)
Number of days with a 45 min bout (8 am–4 pm)	3.9 (3.5)	3.9 (3.5)	4.2 (3.8)	3.1 (2.5)
Number of days with a 10 min bout (10 am–2 pm)				
Number of days with a 20 min bout (10 am–2 pm)	6.0 (3.8)	6.0 (3.9)	6.1 (4.0)	5.6 (3.1)
Number of days with a 30 min bout (10 am–2 pm)	4.2 (3.5)	4.2 (3.5)	4.4 (3.6)	3.4 (2.7)
Number of days with a 45 min bout (10 am–2 pm)	2.5 (2.8)	2.6 (3.0)	2.7 (3.1)	1.8 (1.5)

3.3. Associations between outdoor time and vitamin D

Table 4 and Figures 2 and 3 present the results from linear regression models of associations between the GPS-derived outdoor time measures and vitamin D levels (assessed using serum collected midway through GPS tracking).

In fully adjusted models across all exposures examined, all point estimates were positive, indicating a consistent directional association between greater outdoor exposure and higher serum vitamin D concentrations. Although most confidence intervals included the null, the overall pattern suggested a weak but uniform positive relationship across exposure definitions. UV-weighted exposure metrics did not outperform the simpler GPS-derived time-based measures.

In sensitivity analyses excluding participants who reported taking vitamin D supplements, the overall pattern remained consistent. Two measures of longer outdoor exposure provided stronger evidence of an association: the number of 45-minute bouts between 10 am and 2 pm (β = 4.36, 95% CI 0.32 to 8.40) and the number of days with a 45-minute bout (β = 4.38, 95% CI 0.16 to 8.59). In both cases, the confidence intervals did not include the null. Results also suggest that for this subsample, more days with short bouts may be associated with higher vitamin D levels, as indicated by a relatively large point estimate despite an imprecise confidence interval β = 5.61 95% CI −0.27 to 11.48).

Table 4. Results from linear regression models of associations between outdoor time and vitamin D levels.

	Whole sample (n = 130)		Sample who did not supplement vitamin D (n = 83)	
z-scores	Model 1 β (95% CI)	Model 2 β (95% CI)	Model 3 β (95% CI)	Model 4 β (95% CI)
Outdoor time (hours)				
Total hours outdoors	2.96 (−1.68, 7.60)	2.18 (−2.98, 7.34)	1.54 (−2.88, 5.96)	2.97 (−1.95, 7.89)
Total hours outdoors (8 am–4 pm)	2.84 (−1.73, 7.40)	2.35 (−2.51, 7.20)	2.82 (−1.30, 6.93)	3.74 (−0.74, 8.22)
Total hours outdoors (10 am–2 pm)	2.51 (−2.04, 7.06)	2.53 (−2.19, 7.25)	3.15 (−0.94, 7.23)	3.86 (−0.53, 8.24)
UV weighted outdoor time				
Mean UV weighted daily outdoor time	−1.41 (−6.36, 3.55)	1.09 (−3.68, 5.86)	−1.26 (−5.75, 3.24)	0.24 (−4.35, 4.82)
Mean UV weighted daily outdoor time (8 am–4 pm)	−1.45 (−6.65, 3.75)	1.50 (−3.70, 6.71)	−0.37 (−5.22, 4.47)	0.92 (−4.15, 5.99)
Mean UV weighted daily outdoor time (10 am–2 pm)	−0.91 (−6.51, 4.68)	1.50 (−4.26, 7.26)	0.04 (−5.18, 5.25)	0.79 (−4.72, 6.30)
Number of outdoor bouts				
Number of 10 min bouts (8 am–4 pm)	2.37 (−2.18, 6.93)	2.50 (−2.31, 7.31)	1.77 (−2.42, 5.96)	3.01 (−1.51, 7.53)
Number of 20 min bouts (8 am–4 pm)	2.65 (−1.95, 7.25)	3.02 (−1.75, 7.80)	1.58 (−2.53, 5.68)	2.98 (−1.50, 7.45)
Number of 30 min bouts (8 am–4 pm)	2.10 (−2.57, 6.77)	2.95 (−1.84, 7.7.4)	1.66 (−2.36, 5.68)	3.29 (−1.05, 7.64)
Number of 45 min bouts (8 am–4 pm)	2.34 (−2.28, 6.97)	3.60 (−1.15, 8.34)	1.85 (−2.07, 5.77)	3.52 (−0.74, 7.78)
Number of 10 min bouts (10 am–2 pm)	1.68 (−2.89, 6.25)	2.11 (−2.60, 6.83)	1.60 (−2.59, 5.80)	2.49 (−1.99, 6.97)
Number of 20 min bouts (10 am–2 pm)	2.17 (−2.40, 6.73)	2.54 (−2.14, 7.22)	1.90 (−2.19, 5.98)	2.97 (−1.48, 7.42)
Number of 30 min bouts (10 am–2 pm)	1.56 (−3.08, 6.20)	2.43 (−2.26, 7.12)	2.27 (−1.70, 6.24)	3.79 (−0.50, 8.09)
Number of 45 min bouts (10 am–2 pm)	2.61 (−1.93, 7.15)	3.76 (−0.78, 8.29)	2.69 (−1.10, 6.47)	**4.36 (0.32, 8.40)**
UV weighted number of outdoor bouts				
UV weighted number of 10 min bouts (8 am–4 pm)	0.67 (−4.06, 5.40)	2.03 (−2.65, 6.70)	0.48 (−3.71, 4.67)	1.33 (−3.04, 5.71)
UV weighted number of 20 min bouts (8 am–4 pm)	0.79 (−4.03, 5.60)	2.40 (−2.36, 7.17)	0.40 (−3.75, 4.55)	1.34 (−3.04, 5.71)
UV weighted number of 30 min bouts (8 am–4 pm)	0.61 (−4.22, 5.44)	2.63 (−2.15, 7.42)	0.82 (−3.24, 4.87)	1.99 (−2.32, 6.30)
UV weighted number of 45 min bouts (8 am–4 pm)	1.20 (−3.59, 6.00)	3.27 (−1.50, 8.04)	1.23 (−2.76, 5.22)	2.36 (−1.88, 6.61)
UV weighted number of 10 min bouts (10 am–2 pm)	0.24 (−4.48, 4.96)	2.07 (−2.58, 6.72)	0.63 (−3.47, 4.73)	1.16 (−3.09, 5.41)
UV weighted number of 20 min bouts (10 am–2 pm)	0.37 (−4.36, 5.10)	2.02 (−2.68, 6.1)	0.51 (−3.53, 4.55)	1.03 (−3.25, 5.31)
UV weighted number of 30 min bouts (10 am–2 pm)	0.28 (−4.41, 4.98)	2.19 (−2.44, 6.81)	1.09 (−2,82, 5.00)	2.06 (−2.09, 6.20)
UV weighted number of 45 min bouts (10 am–2 pm)	1.28 (−3.28, 5.85)	2.97 (−1.42, 7.37)	1.74 (−2.00, 5.48)	2.81 (−1.07, 6.70)
Number of days with outdoor bouts				
Number of days with a 10 min bout (8 am–4 pm)	**4.67 (0.10. 9.24)**	2.13 (−3.48, 7.73)	3.93 (−0.59, 8.45)	5.61 (−0.27, 11.48)
Number of days with a 20 min bout (8 am–4 pm)	4.33 (−0.23, 8.89)	2.96 (−1.91, 7.83)	1.86 (−2.50, 6.22)	2.69 (−2.24, 7.63)
Number of days with a 30 min bout (8 am–4 pm)	3.79 (−0.76, 8.34)	3.23 (−1.45, 7.92)	1.51 (−2.87, 5.89)	3.06 (−1.71, 7.83)
Number of days with a 45 min bout (8 am–4 pm)	3.14 (−1.43, 7.72)	3.62 (−1.04, 8.28)	1.84 (−2.30, 5.97)	3.43 (−0.98, 7.85)
Number of days with a 10 min bout (10 am–2 pm)	3.35 (−1.17, 7.88)	2.30 (−2.59, 7.20)	2.26 (−2.12, 6.65)	3.13 (−1.83, 8,10)
Number of days with a 20 min bout (10 am–2 pm)	2.47 (−2.11, 7.05)	2.40 (−2.28, 7.08)	1.78 (−2.47, 6.04)	2.55 (−2.04, 7.15)
Number of days with a 30 min bout (10 am–2 pm)	2.27 (−2.34, 6.88)	2.53 (−2.19, 7.24)	2.40 (−1.79, 6.58)	3.99 (−0.56, 8.54)
Number of days with a 45 min bout (10 am–2 pm)	3.02 (−1.52, 7.57)	4.14 (−0.42, 8.70)	2.55 (−1.37, 6.47)	**4.38 (0.16, 8.59)**

All exposure variables were entered into models as z-scores. Bolded estimates indicate $p < 0.05$.
Models 1 and 3 are unadjusted.
Models 2 and 4 adjust for: age, education, sex, education, race, ethnicity, dietary vitamin D, Vitamin D supplementation, and GPS wear time.

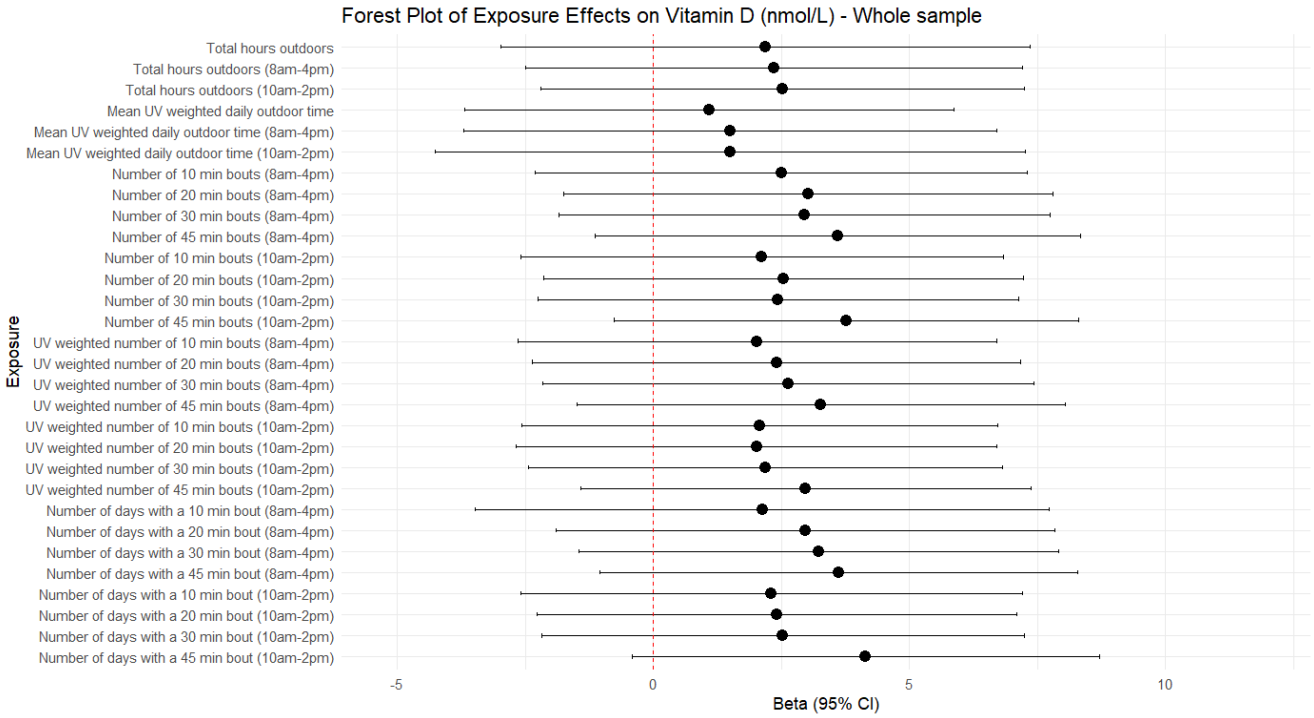


Figure 2. Point estimates and 95% confidence intervals from the fully adjusted models of associations between outdoor bouts and vitamin D levels for the whole sample (n = 130). Models adjusted for age, education, sex, education, race, ethnicity, dietary vitamin D, Vitamin D supplementation, and GPS wear time. Each exposure has been transformed to it's z-score.

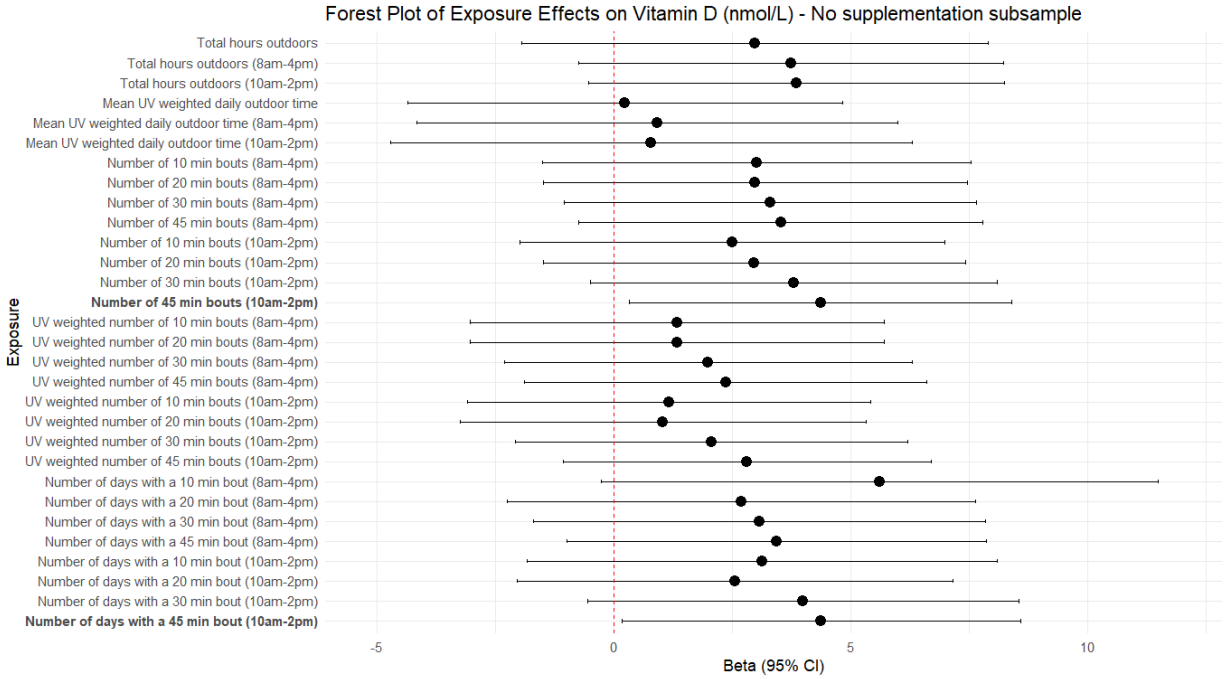


Figure 3. Point estimates and 95% confidence intervals from the fully adjusted models of associations between outdoor bouts and vitamin D levels for the subsample who did not take vitamin D supplements (n = 83). Models adjusted for age, education, sex, education, race, ethnicity, dietary vitamin D, Vitamin D supplementation, and GPS wear time. Each exposure has been transformed to it's z-score. Bolded estimates indicate $p < 0.05$.

4. Discussion and conclusion

4.1. Principal findings

Our study demonstrated the use of GPS sensor data to calculate novel outdoor time measures related to vitamin D synthesis from sunlight. The findings provide partial support for our hypothesis that GPS-measured outdoor time is associated with serum vitamin D, with stronger associations for temporally specific outdoor bouts than for total outdoor time. The results suggest the measures may be a promising way to characterize outdoor time relevant to sunlight-related vitamin D synthesis. Across all exposure metrics, point estimates were consistently positive, suggesting a uniform pattern in which greater outdoor exposure was associated with higher serum vitamin D, although most confidence intervals included the null. Notably, measures that captured both the timing and length of outdoor exposures during peak UVB hours showed some evidence of stronger associations with vitamin D than broader measures of UV weighted measures of total outdoor time. In sensitivity analyses excluding vitamin D supplement users, this pattern persisted. Two measures capturing longer outdoor periods during the peak UVB window (10 am–2 pm) showed stronger evidence of an association. There was also some indication that more days with shorter bouts may be related to higher vitamin D levels, reflected in a relatively large but imprecise point estimate. The modest sample size likely contributed to this imprecision and may have limited our ability to detect more subtle associations. Overall, these findings suggest that GPS-derived measures can offer additional information about individuals' outdoor behavior, which may be useful when assessing an individual's vitamin D status.

4.2. Interpretation

To the best of our knowledge no one has explored the potential of GPS data to better assess outdoor time relevant to vitamin D synthesis, although others have recently explored using strength of GPS signal as a proxy for UV light intensity [68]. Our approach provides a methodology to assess real-world outdoor time exposures that capture the complexities of everyday life. This contrasts with laboratory studies, which, while essential for mechanistic understanding of the UVB dose necessary to synthesize vitamin D [69,70], do not account for people's real-world experience. Our approach also allows for relatively low cost, objective assessment of time outdoors. This is a potential improvement on the methodology used by epidemiological studies, which predominantly assess self-reported time in the sun and so are considered poorly measured [71].

Use of GPS and accelerometer sensors has other benefits. These sensors are commonly used to measure many health-related contexts and behaviors such as physical activity and active travel [72–76]. As such, a sensor-based solution to outdoor time assessment would enable analysis of other contexts and behaviors of interest. For instance, being active outdoors could also benefit increased physical activity, and mental health improvements from being active in nature [77]. Sensor-based measurement approaches will better enable researchers to assess these potential co-benefits of outdoor time.

A second benefit of sensor derived exposure metrics is that GPS and accelerometers are also included in smartphones. This enables the use of smartphone-based apps to track and suggest interventions to improve outdoor time and UVB exposure while minimizing harmful UVB overexposure and sunburn [78]. Others have tested a smartphone app for this purpose [79]. However, it appears they did not incorporate temporal variations throughout a day or assess bouts or number of days with bouts over time. Since timing of exposure to sunlight during the day is critical, our approach incorporating spatio-temporal variability has the potential to improve smartphone-based monitoring and interventions [78].

Our proposed measures demonstrate the potential of a GPS-sensor based approach to measure outdoor time relevant to vitamin D synthesis. However, we acknowledge that our study was limited to participants sampled from San Diego, CA and this may limit the generalizability of the findings. Firstly, people in different locations have varying cultures of sun protection use (such as use of sunscreen and protective clothing) and may have different clothing coverage day-to-day due to social, cultural and religious factors. Additionally, most participants in this study identified as white. For the same UVB exposure, people with more melanin in their skin produce less vitamin D [80]. Thus, these findings may not be generalizable to other populations. Further, the findings may not be generalizable to other geographic areas as the amount of UVB and thus Vitamin D production will be affected by factors such as latitude, altitude, cloud cover patterns, surface conditions (such as the presence of snow which can reflect UVB), air pollution (which may "scatter" and thus reduce the penetration of UVB rays [81]. Although 25-hydroxyvitamin D has a half-life of about two weeks, serum levels integrate UV exposure over several months [82]. Our two-week GPS monitoring therefore captures only recent outdoor behavior and may not reflect the longer-term exposure window that contributes to 25(OH)D. This mismatch in time frames could help explain the modest associations observed and may also have contributed to the wide confidence intervals, as capturing only a brief period of behavior introduces exposure misclassification.

In our analyses, UV-weighted measures and unweighted outdoor time had similar associations with serum vitamin D, likely reflecting the limited spatial and seasonal variation in UVB within this setting. In regions with greater variability in UVB, UV-weighting may offer additional discriminatory value.

Future research should test this approach in a larger sample and in different locations. Measures could be enhanced by using time windows that better align with diurnal UV patterns, including an indoor-outdoor transition time window, considering alternate measures such as percentage of days with an outdoor bout, and calculating weighted measures (e.g., giving higher weights to measures closer to noon).

Additionally, there is substantial opportunity to incorporate other sensor data (e.g., satellites) to assess UVB exposure more precisely by including spatiotemporal UVB variations, and the impact of different built environment characteristics such as tree canopy and buildings. Further, combining the use of GPS derived time outdoors with dosimetry data from polysulphone badges or electronic dosimeters could be used to establish, for different populations, whether time outdoors could be used as proxy for UVB exposure and an indicator of vitamin D status. This may vary by context, for example, for people living in dense urban areas with many urban canyons which block sunlight [83], or in areas with very high levels of tree canopy, time outdoors may not be a good reflection of UVB exposure.

4.3. Limitations

A limitation of our study is the cross-sectional design, which means we are unable to draw conclusions about causality. As this was a secondary analysis we did not have data on individual factors that would affect the amount of UVB reaching the skin, such as skin area exposed, clothing coverage or its ultraviolet protective factor (UPF) [84], sunscreen use and its coverage or level of sun protection factor (SPF) [85], use of parasols and obstruction of sun by shade-generating structures. We also lacked data on some individual factors which would impact how much vitamin D was generated from sunlight (e.g. skin type, genotype for known variants impacting vitamin D metabolism [86]). Having this data available for our participants would make the generalizability of our findings on the GPS-derived outdoor time—vitamin D relationship clearer. Additionally, there was a small sample size, which may have limited our ability to detect relationships between outdoor time and vitamin D, and there may be residual confounding due to factors such as occupation, (a potential indicator of long-term outdoor exposure), body weight [87] which may affect both outdoor time and vitamin D metabolism) and sunbed use [88]. Another disadvantage is the use of total serum vitamin D (comprising D2 and D3) as a measure. Future research would ideally assess relationships between outdoor time metrics and vitamin D3, since D2 is not affected by sun exposure. We also were limited to only two days of data on non-supplement dietary intake of vitamin D and self-report of supplementation, including dose and regularity.

Although we included UV-weighted exposure metrics, these did not show stronger associations with vitamin D than the GPS-derived measures. Future work should explore whether integrating GPS-based behavior patterns with more refined UVB weighting improves predictive performance.

Further, given that we evaluated 26 models, the Type I error may be inflated, and thus we cannot rule out the possibility of false positive results. However, the 26 independent (main effect) variables in our models are all different ways of assessing a single underlying exposure, namely, vitamin D-specific outdoor time, and thus represent similar (and correlated) constructs. Hence, a Bonferroni correction would be too stringent and is unwarranted. Notably, the two exposures for which we observed statistically significant associations in fully adjusted models, all involved long bouts.

Fixed clock-time windows (e.g., 8 am–4 pm and 10 am–2 pm) do not fully reflect seasonal variation in day length or the shifting timing of solar noon, which may introduce some temporal misalignment between outdoor time and actual UVB availability. The UV-weighted outdoor-time measure used in this study partly addresses this issue by incorporating daily UV radiation data, thereby capturing diurnal and seasonal variation in UV intensity more accurately than unweighted time windows. Nonetheless, some imprecision is likely, particularly in periods with rapid seasonal changes in daylight.

Finally, our use of a 250 SNR threshold to classify indoor *versus* outdoor time had limitations. This threshold has been previously validated and shown to have good sensitivity and specificity. Comparing with information on environment obtained from a body-worn camera, an SNR threshold of 250 has been shown to have a sensitivity of 79.4% and a specificity of 84.1% for classifying indoor compared with outdoor time [50]. Another study found this threshold had a sensitivity of 82% and a specificity of 88% [89]. However, we were not able to test other thresholds, and this threshold may not be transferable to other studies due to ongoing changes in GNSS receiver capabilities and constellation availability since our study [90]. A further limitation is that a fixed SNR threshold may misclassify window-side or partially obstructed environments, where partial satellite reception produces intermediate signal patterns [91,92]. Such borderline contexts are therefore at risk of systematic misclassification, representing a potential source of exposure error.

Utilizing more accurate models to differentiate indoor/outdoor time would benefit future research in this area. For example, the MicroTrac model uses geocoded rooftop borders of indoor locations and GPS data and has been shown to have 99.5% accuracy, although building rooftop boundaries would be prohibitively time-consuming in larger studies [93]. Machine learning approaches that use clusters of GPS points in combination with building footprints and lux data also show potential [94]. More recently, indoor/outdoor detection algorithms that leverage smartphone sensor data have demonstrated strong performance, as they integrate multiple signals (e.g., GNSS, Wi-Fi, accelerometry) to improve classification accuracy [92,95,96]. Such approaches may offer better transferability as GNSS receiver capabilities and satellite constellations continue to evolve.

4.4. Conclusion

This study provides one of the first demonstrations that GPS-derived outdoor time has potential to be used as a predictor of vitamin D status in a population-based setting. We developed and applied a method that integrates GPS-based outdoor time with daily UV measurements and examined its association with circulating 25(OH)D.

The observed pattern of results reinforces this potential. GPS-derived measures showed uniformly positive associations with 25(OH)D, and those reflecting longer outdoor periods during peak UVB hours provided the clearest evidence of

an association. These findings suggest that behaviorally grounded, time-based GPS measures can characterize outdoor patterns relevant to vitamin D status in real-world settings, and may offer useful contextual information when interpreting population level UVB exposure.

Future work should incorporate additional modifiers of UVB exposure (e.g., cloud cover, shade, surface reflectance), evaluate improved indoor/outdoor classification methods, and validate these approaches across different devices, seasons, and populations. Such refinements will be essential for developing more accurate and generalizable tools for understanding individual outdoor time and UVB exposure in epidemiological research and may also lay groundwork for future integration into mobile-health tools.

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Data availability statement

The data that support the findings of this study contain sensitive personal health information and precise GPS locations. To protect participant privacy and comply with ethical guidelines, these data are not publicly available. However, datasets may be available from the senior author upon reasonable request and subject to institutional review board approval.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used Co-pilot only for polishing/editing, *i.e.* light use, to help make some sentences more readable. The authors take full responsibility for the content of the manuscript.

Authors' contribution

Conceptualization, SM, MMJ; methodology, SM, JY, KC, RC, CT, SZ, DDH, DDS and MMJ; formal analysis, SM, JY, CT, SZ and DDH; resources, SM, DDH, DDS and MMJ; data curation, JY, CT, SZ, DDH and MMJ; writing—original draft preparation, SM and MMJ; writing—review and editing, SM, JY, KC, RC, CT, SZ, SA, DDH, DDS and MMJ. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

Suzanne Mavoa holds the position of Associate Editor for *International Journal of Environmental Epidemiology* and has not peer reviewed or made any editorial decisions for this paper.

Ethical statement

The study was performed in accordance with the Declaration of Helsinki and approved by the name of the University of California San Diego Institutional Review Board (protocol #140510). All participants gave written informed consent.

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