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Comparison of global positioning system (GPS) tracking and parent-report diaries to characterize children's time–location patterns

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Respondent error, low resolution, and study participant burden are known limitations of diary timelines used in exposure studies such as the National Human Exposure Assessment Survey (NHEXAS). Recent advances in global positioning system (GPS) technology have produced tracking devices sufficiently portable, functional and affordable to utilize in exposure assessment science. In this study, a differentially corrected GPS (dGPS) tracking device was compared to the NHEXAS diary timeline. The study also explored how GPS can be used to evaluate and improve such diary timelines by determining which location categories and which respondents are least likely to record "correct" time–location responses. A total of 31 children ages 3–5 years old wore a dGPS device for all waking hours on a weekend day while their parents completed the NHEXAS diary timeline to document the child's time–location pattern. Parents misclassified child time–location approximately 48% of the time using the NHEXAS timeline in comparison to dGPS. Overall concordance between methods was marginal ($\kappa = 0.33$–0.35). The dGPS device found that on average, children spent 76% of the 24-h study period in the home. The diary underestimated time the child spent in the home by 17%, while overestimating time spent inside other locations, outside at home, outside in other locations, and time spent in transit. Diary data for time spent outside at home and time in transit had the lowest response concordance with dGPS. The diaries of stay-at-home mothers and mothers working unskilled labor jobs had lower concordance with dGPS than did those of the other participants. The ability of dGPS tracking to collect continuous rather than categorical (ordinal) data was also demonstrated. It is concluded that automated GPS tracking measurements can improve the quality and collection efficiency of time–location data in exposure assessment studies, albeit for small cohorts.
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Introduction

When dealing with transient peaks of environmental contaminants, knowing whether or not a person is in a particular microenvironment is the first step toward determining if exposure may occur (Klepeis et al., 2001; McCurdy and Graham, 2003). Time–location has been measured using self-report diary instruments for many years (Robinson, 1988; Wallace et al., 1987, 1991; Freeman et al., 1993, 1999). One of the most widely used diaries for human exposure assessment in the US is the National Human Exposure Assessment Survey (NHEXAS). Approximately 600 people in four EPA regions participated in this survey between 1994 and 1999 (Echols et al., 1999; Freeman et al., 1999; O'Rourke et al., 1999; Robertson et al., 1999; Whitmore et al., 1999; Quackenboss et al., 2000; Freeman et al., 2001). The diary timeline, which was one component of the larger survey, was designed to provide data whose resolution was comparable to the temporal resolution of the environmental and human samples collected (Freeman et al., 1999). EPA's Consolidated Human Activity Database (CHAD) is another example of research using self-report diaries, in this case to collect extremely detailed and regionally-specific time–location data (EPA, 2005). The issue with a CHAD-type diary for most exposure assessments is that it requires extreme vigilance on the part of the respondent. This problem is even greater when a parent must report time–location for a child.

Time–location of children has been measured by parental-report using the same NHEXAS diary timeline used for adult self-report (Dorre, 1997; Freeman et al., 2001; Pellizzari et al., 2003). Dorre (1997) investigated a group of 52 children aged 2–3 years. The Minnesota Children's Pesticide Exposure Study utilized the NHEXAS diary to assess, among other things, children's time–location over 1 week (Freeman et al., 2001; Pellizzari et al., 2003). Parents

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completed the diary for children between 3 and 4 years old, and parents aided completion of the diary for children ages 5–9 years. Neither study reported problems with completion of diaries. The NHEXAS diary timeline instructions direct participants to estimate partial-hour (15 min) fractions for location categories, but do not provide much structure to do so. Thus, the resolution of a person's true time–location is potentially low. The NHEXAS diary timeline also has somewhat low spatial resolution because it defines only seven location categories. The diary was designed this way "to facilitate participant responses" and to correspond with "compartments" the questionnaire addresses in terms of exposures (Freeman et al., 1999). The resolution of a diary timeline may also be limited by recall bias, although this has not been documented for the NHEXAS diary. Some type of measure independent of the diary is needed to illuminate recall bias, such as the "shadow sensor" prototype developed by Moschandreas and Relwani (1991) that distinguished between indoor and outdoor locations.

Validity and reliability testing of the NHEXAS time/activity diary was published prior to its extensive use (Freeman et al., 1999). Validity of the diary questions was checked by comparison with related questions outside the diary. Validity (as well as completeness) of the timeline component was measured by checking that all time, in hours and minutes, added up to 24 h. Reliability of the diary was measured by looking for consistency of responses. Reliability/consistency of the timeline component was checked by having a duplicate question about time in a particular location (time in transit) on both a questionnaire and the timeline. The responses were compared, and reported times were highly correlated between questionnaire and timeline ($r = 0.811$–0.922, $P < 0.001$). However, true accuracy of the timeline was not tested. Accuracy testing requires independent observations of a person's time–location and activities for a means of comparison with the self-reported timeline data. For example, such independent observations may be gathered by having a researcher follow a subject and record activities (Seixas et al., 2001; Neitzel and Yost, 2002), or by using video or other records to corroborate responses. Diary timeline accuracy would be best tested by using a "gold standard" that continuously and unobtrusively measures the accuracy of reported time–location. However, since no "gold standard" for human time–location is available, a best available proxy "gold standard" is needed. Global positioning system (GPS) tracking devices are arguably the best available "gold standard" for this purpose.

GPS tracking devices that record individuals' location data are fast becoming a part of everyday life. Low-resolution GPS watches are used by athletes to track velocity and position (Suunto, Vantaa, Finland; Timex, Middlebury, CT, USA; Casio, Tokyo, Japan), and by parents to protect children in case of abduction or getting lost (Wherify, Redwood Shores, CA, USA). Higher resolution GPS tracking telephones are used to enhance the safety of workers in remote locations (Benfon, Salo, Finland). GPS has been used for several studies involving human time–location measurements (Lyon et al., 1998; Larsson et al., 2001; Phillips et al., 2001; Elgethun et al., 2003). The highest resolution GPS instruments use a process called differential correction to improve accuracy. The advantages of a differential-corrected global positioning systems (dGPS) method for logging time–location are that resolution is high and bias is minimal. The dGPS personal activity logger (GPS-PAL) instrument validated by University of Washington researchers achieved a resolution of 3.2 m root mean square (RMS) while logging every 5 s (Elgethun et al., 2003).

The purpose of this paper is threefold: (1) compare the GPS-PAL dGPS method to the parent-reported NHEXAS diary timeline; (2) test if GPS can be used to refine a diary by determining the child and household factors that might affect accuracy of diary reporting in specific time–location categories; and (3) demonstrate a new approach for exposure assessment, using dGPS to replace categorized data with continuous positional data.

Methods

Study Population

All human subjects protocols were approved by the University of Washington Human Subjects Review Board. The study was conducted in the late spring and early summer since children in northern climes are likely to go outside during this season and have frequent movement between indoors and outdoors. A total of 35 families living in the city limits of Seattle were recruited from Early Head Start Programs in the spring of 2003. A letter was sent home to parents (in Spanish, Vietnamese and English) from four Early Head Start centers, and researchers attended evening meetings at centers to explain the study to parents. Early Head Start was chosen to afford access to lower-income (150% poverty level and below) and minority population in the region, and access to a well-defined age group (3–5 years old). A total of 15 enrolled families spoke Spanish only or Spanish primarily, and all materials and interviews were given in Spanish to these families. One child per family was enrolled.

NHEXAS Timeline and GPS Methods

One parent in each family filled out the NHEXAS diary timeline for her/his child (Figure 1). The NHEXAS time–location diary and the protocol for training interviewers and administering the diary were obtained from one of the diary's authors (N Freeman, EOHSI, Rutgers University, Piscataway, NJ, USA; current affiliation U. Florida, Gainesville, FL, USA). The timeline and supporting materials were printed in both Spanish and English. The original diary has seven time–location categories. In this study, two categories,

	Location	Morning	Afternoon	Evening	Early Morning (Night time)	Amount of Time
Day 1	Inside at Home	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
Day of Week	Inside at Work and School	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
	Inside at Other	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
DATE	Outside at Home	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
	Outside at Work and School	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
___/___/___	Outside at Other	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min
	In Transit	5 6 7 8 9 10 11	12 1 2 3 4 5	6 7 8 9 10 11	12 1 2 3 4	___Hrs___Min

Total Daily Time Expenditure must add to 24 Hrs

Figure 1. Single day NHEXAS Diary Timeline (English version). Spanish version was identical in format. Respondents participated on weekend days only and thus did not include "Inside at Work and School" and "Outside at Work and School" in their responses.

"Inside Work or School" and "Outside Work or School" were eliminated because the subjects were 3–5 year old children who participated on a non-school weekend day. The remaining five categories were: "Inside at Home" (INHOME), "Inside at Other" (INOTHER), "Outside at Home" (OUTHOME), "Outside at Other" (OUTOTHER), and "In Transit" (TRANSIT). In addition to the diary timeline, University of Washington researchers administered a questionnaire regarding housing characteristics, family demographics, and income to determine if these factors influenced either responses to the diary or compliance with the GPS protocol. Lightweight portable GPS-PAL dataloggers (Elgethun et al., 2003) were worn by children in vests. The vest allows for optimal placement of an antenna on the horizontal shoulder surface. GPS-PALs were set to record data once every 5 s.

On the first home visit, researchers spent approximately 45 min explaining the purpose of the study, how to fill out the diary, how and when to turn on the GPS-PAL, and administering the questionnaire. Researchers had parents fill out a practice diary and corrected errors in notation, per NHEXAS guidelines. The practice diary and notes were kept by the parents as a guide for filling out the diary on the study day. Parents were asked to record time–location every 15 min. The respondent parent was instructed to report the child's time–location in real-time, or as close to real-time as possible. The respondent parent was instructed to observe the child for the entire period, as opposed to relying on the child's account of time–location. Families participated on weekends only to maximize the number of hours of parental supervision. The period of participation was 24 h. The GPS-PAL was worn for all waking hours. Parents turned the GPS-PAL on and put the vest on the child when s/he awoke in the morning. The second home visit was usually the day after participation. Researchers reviewed the diary with the parents and had them make appropriate corrections if the total time did not add up to 24 h. Researchers asked parents to verify the time the GPS-PAL vest was put on the child, the time the GPS-PAL vest was taken off, and to report if the child ever left the house without the GPS-PAL vest on. Leaving the house without the vest on (or forgetting to turn on the GPS-PAL) and participating on a non-weekend day excluded the child from analysis.

The completed diaries were totaled according to NHEXAS protocol. For each subject, total time reported for each location category, at specific time of day, was entered into a database. GPS-PAL data were likewise binned into these categories after being post-processed to improve resolution using differential correction measurements obtained from the National Geodetic Survey Continually Operating Reference Station (CORS) program. Processed GPS paths were mapped onto 1 m resolution City of Seattle orthophoto maps using GIS software (ArcGIS v.8.3, ESRI, Redlands, CA, USA) and location by time was recorded. Recording involved magnifying the map many times to determine the outline of homes, then creating a polygan around each home so that points inside were differentiated from points outside. The same procedure was used for buildings other than the home into which the child entered. Points inside polygans were coded as "Inside at Home" or "Inside at Other". Similarly, a polygan was drawn around each child's yard. If there was no yard, a patio or shared outdoor space belonging to an apartment building, such as a courtyard, was considered the same as a yard. These points were coded "Outside at Home". In a few cases when building or yard boundary could not be seen clearly in aerial images, researchers went to the location and took ground measurements and photographs. Measurements and photographs were then used to help delineate boundaries in the GIS. Being "In Transit" was determined by the child's GPS path velocity. Elapsed time of movement at velocities exceeding that possible on foot (>5 m/s) was coded "In Transit". Remaining points were coded "Outside at Other".

To demonstrate the ability of the GPS-PAL to record continuous data, the data set was also kept in its original format (latitude/longitude recorded approximately every 5 s). These data were plotted as an hourly average of distance and direction from a "tether" location. In this case, the tether was an air monitoring station in Seattle proximal to the children's homes.

A key assumption of this study is that the GPS-PAL method is what will be defined here as a "best practical standard". "Best practical standard" in this case means the GPS-PAL affords good resolution and reception while still being completely portable and wearable for children. Based on a previous validation study (Elgethun et al., 2003), this is defensible provided the child keeps the vest on, and that parents are compliant with the protocol.

Only the hours between 0900 and 2100 were included in analyses. Some morning periods shortly after 0900 and evening periods shortly before 2100 had no GPS data, either due to reception, early bed time, or sleeping in. It was thus sometimes necessary to insert proxy GPS data for early evening and morning hours if the child went to bed early or slept in, if the child lived in a building that blocked GPS reception, or both. For all children, it was verified (via parental interview) that the child did not leave the home without the vest on, and that the GPS-PAL was turned on before leaving the home. Missing time periods were coded as "Inside at Home" unless the first logged point was far away (>1 km) from the home.

Criteria for Inclusion

If a subject's first logged point for the day for was >1 km from home, the subject did not meet the criteria for inclusion in the study (although none were excluded for this reason). Subjects were included in analyses if their GPS logged more than 6 h during the 12 h period from 0900 to 2100 on the day of participation, and if the GPS device was used on the weekend. Four children did not meet these inclusion criteria: one family participated on a weekday instead of a weekend; one family forgot to turn on the GPS device; two children did not log the minimum 6 h on the GPS device. Thus, a total of 31 subjects met the study criteria and were included in the analyses.

Statistical Analysis

κ measurements along with a test for significance were performed to compare the two methods (Armstrong et al., 1994; Rosner, 1995). The test for significance is a one-sided z-test with the null hypothesis $\kappa=0$, and the alternative hypothesis $\kappa>0$. (Negative values for κ have no significance). κ itself is a coefficient and not a statistic. κ is based on two proportions: proportion of concordance expected if methods are completely unrelated, and proportion of concordance observed between the two methods. A misclassification matrix is constructed such that the five time–location categories by each method are listed perpendicular to one another, creating a 25 square 5×5 grid (Tables 3 and 4). Similarly, a 2×2 matrix is created for each time-location category individually compared to all other categories in aggregate (Table 5). A matrix allows for a frequency of agreement to be calculated for each possible combination of reporting by the two methods. Cells that fall along the diagonal from upper left to lower right are in concordance (both methods rated the same). These determine the proportion of concordance observed (P_o). The proportion of agreement expected (P_e) is calculated under the null hypothesis of no association between the two measures.

The formula for the κ measurement is:

$$\kappa = \frac{(P_o - P_e)}{(1 - P_e)}$$

The influence of differences in gender, age, first language spoken, housing factors, family demographics, and income on reporting concordance was tested for two types of data by linear regression. The first type of data was sequential scoring concordance (κ or proportion measures). This was tested in two ways: by using frequency of reporting correctly in each time-location category as the dependent variable, and by using overall κ value as the dependent variable. The second type of data was overall time (sum) in each category. This was tested using Spearman rank correlation.

Results

The race/ethnicity distribution of the 31 children in this study was 14 Hispanic, seven African American, one Pacific Islander, two Native American, seven Caucasian; 16 children were male, 15 were female. Demographics of the study participants are shown in Table 1. Several families earned above 150% poverty level because their household income had risen since the time of child's enrollment in Head Start. Children's mothers completed the diary for all but one family (single father).

Table 2 shows where children spent their time during the 24 h weekend period, by both methods. For GPS time–location, the mean proxy time inserted for Inside at Home (accounting for morning periods shortly after 0900 and evening periods shortly before 2100 with no data) was 104 min. All subjects confirmed they had not left the home without the vest, nor had they forgotten to turn the GPS on. The NHEXAS diary responses under-reported time spent Inside at Home, and over-reported time spent in other places when compared to dGPS. On average, the GPS method recorded that children spent 76% of the 24-h study period in the home. There was a wide range of time spent in each location by children.

κ *results – sequential reporting concordance*

Table 3 contains data analyzed by a 15-min time interval. Table 4 contains data analyzed by a 1-h time interval. The numbers logged in the matrix are counts: that is, the number of times the parents classified child time–location into a certain category by diary and the number of times classified by GPS. Next to each counts value, in parentheses, is the proportion of the total number of counts. Guidelines for the evaluation of κ (Rosner, 1995) are listed below.

$k > 0.75$ excellent reproducibility
$0.4 < k < 0.75$ good
$0 < k > 0.4$ marginal

Table 1. Demographics of participating families ($n = 31$)

Household language	
English	61%
Spanish	39%
Parent's race/ethnicity	
Hispanic	45%
African American	23%
Caucasian	23%
Native American	6%
Pacific Islander	3%
Participating child	
Female	48%
Male	52%
Only child	23%
Median no. of siblings	1
Median age	4 years
Median income per Month	$970
Mother's occupation	
No mother in home	3%
Stay at home	52%
Unskilled labor	29%
Trade labor	3%
White collar	13%
Father's occupation	
No father in home	29%
Stay at home	6%
Unskilled labor	42%
Trade labor	10%
White collar	13%

$n = 31$ families.

The *P*-value for a *z*-test of the κ measurement can be significant whether or not the κ value denotes appreciable agreement between methods.

For both 15-min and 1-h interval data the Inside at Home time was the largest proportional to the total sampling time period (12 h). Consequently, Inside at Home had the greatest impact on κ. The greatest proportion of overall counts fell in the INHOME/INHOME cell. As this is one of the concordance cells, it influenced the overall κ value more than any other cell. This was also seen to be true in 2 × 2 analysis for each subject (Table 5).

While statistical significance of the *z*-test was observed for both 15-min and 1-h data, the κ values were 0.33 and 0.35, respectively. According to Rosner (1995), this implies *marginal* reproducibility. Notably the κ was almost the same regardless of the time interval resolution. This was likely due to the fact that there is sufficient lack of concordance regardless of time subdivision, or to a lesser extent due to the fact that fewer than 15% of subjects logged time–location in the diary at sub-hour intervals.

Table 5 shows the κ values generated by a simplified 2 × 2 matrix, where each location is compared to the aggregate of the other four categories. Inside at Home had the highest κ value of 0.443, considered "good" reproducibility. Outside at Home had the lowest κ value of 0.160. As stated above, it follows that Inside at Home had the greatest positive influence on the overall κ, particularly since the most time was spent overall in this category. Outside at Home had less influence on overall κ in the negative direction since little time was spent on average in this category.

Individual Child and Household Factors: Sequential Reporting Concordance, Linear Regression

Very few demographic variables were found to be predictors of concordance when tested using a linear regression model (Table 6). Mothers who stayed at home or worked an unskilled labor job had lower concordance between methods when κ was tested as the dependent variable. Access to a car

Table 2. Time (min) spent in each location category by dGPS and NHEXAS diary methods for one 24 h weekend period

	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT
dGPS					
Mean	1096	137	58	86	72
Range	642–1397	0–690	0–442	0–301	0–186
NHEXAS diary					
Mean	915	170	95	186	74
Range	420–1260	0–600	0–420	0–840	0–180
Difference	181	−33	−37	−100	−2
% Difference	17	−19	−39	−54	−3

$n = 31$ children
Age 3–5 years

Table 3. Frequency (proportion) matrix for all subjects comparing GPS-PAL method to NHEXAS diary method for 15 min time intervals ($n = 31$)

	GPS-PAL					
	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT	
NHEXAS						
INHOME	459 (0.308)	33 (0.022)	19 (0.013)	10 (0.007)	20 (0.013)	541 (0.364)
INOTHER	80 (0.054)	124 (0.083)	16 (0.011)	24 (0.016)	28 (0.019)	272 (0.183)
OUTHOME	120 (0.081)	18 (0.012)	38 (0.026)	20 (0.013)	12 (0.008)	208 (0.139)
OUTOTHER	109 (0.073)	62 (0.042)	30 (0.020)	115 (0.077)	43 (0.029)	359 (0.241)
TRANSIT	32 (0.022)	29 (0.019)	5 (0.003)	10 (0.007)	32 (0.022)	108 (0.073)
	800 (0.538)	266 (0.179)	108 (0.072)	179 (0.120)	135 (0.091)	1488

Proportion of concordance expected if methods unrelated = 0.274.
Proportion of concordance observed = 0.516.
$\kappa = 0.334$.
$P = 0.0000$.

Table 4. Frequency (proportion) matrix for all subjects comparing GPS-PAL method to NHEXAS diary method for 1 h time intervals ($n = 31$)

	GPS-PAL					
	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT	
NHEXAS						
INHOME	119 (0.320)	7 (0.019)	3 (0.008)	1 (0.003)	7 (0.019)	137 (0.368)
INOTHER	17 (0.046)	30 (0.081)	3 (0.008)	8 (0.022)	9 (0.024)	67 (0.180)
OUTHOME	28 (0.075)	6 (0.016)	12 (0.032)	5 (0.013)	3 (0.008)	54 (0.145)
OUTOTHER	28 (0.075)	16 (0.043)	7 (0.019)	29 (0.078)	8 (0.022)	88 (0.237)
TRANSIT	9 (0.024)	6 (0.016)	0 (0.000)	4 (0.011)	7 (0.019)	26 (0.070)
	201 (0.541)	65 (0.175)	25 (0.067)	47 (0.126)	34 (0.091)	372

Proportion of concordance expected if methods unrelated = 0.276.
Proportion of concordance observed = 0.530.
$\kappa = 0.350$.
$P = 0.0000$.

Table 5. Trends determined by 2×2 κ matrix analysis of 15 min data

	κ	Proportion of concordance[a]
INHOME	0.443	0.574
INOTHER	0.342	0.466
OUTHOME	0.160	0.352
OUTOTHER	0.318	0.642
TRANSIT	0.199	0.237

Overall $\kappa = 0.334$ (Table 3).
Total number of counts in all categories = 1488.
Number of subjects = 31.
For all κ measures, $P < 0.00001$ (z-test).
[a]Proportion of concordance = number of counts coded the same for both methods divided by the number of counts total by GPS-PAL (see Table 3).

was a predictor of higher κ. Fathers who stayed at home were not a predictor of higher overall κ, but did influence reporting concordance in the Inside at Home category based on regression analysis of the Inside at Home frequency of concordance (proportion of agreement). A child with siblings was predictive of higher overall concordance in the Outside at Home category based on regression analysis of the Outside at Home frequency of concordance.

Individual Child and Household Factors: Total Time and Rank Correlation

Table 7 shows the correlation between methods for total time spent in time–location category by child and household factors (Spearman rank sum). Note that the rank correlation only measures difference in total time in category, and is not a measure of sequential concordance of responses.

Given the assumption that the GPS method is a fair test of the NHEXAS diary timeline, it can be said that subjects with the factors listed below reported *total time in location* for the whole day more accurately than other subjects. This does not directly relate to concordance of sequentially correct answers. The following is a summary of the child and household factors that showed the *highest number* of significantly correlated time–location categories: English speaking household, three categories; Male child, two categories; Child with

Table 6. Trends determined by regression analysis of 15 min data

Significant independent variable	Dependent variable	Sig	Slope term
Mother's occupation			
Stay at home or unskilled labor	κ	0.02	−0.468
Access to a car			
Yes	κ	0.05	0.386
Father's occupation			
Stay at home	Freq. of concordance INHOME	0.03	0.416
Siblings			
Yes	Freq. of concordance OUTHOME	0.05	0.523

Both frequency of concordance in each time–location category and κ used as dependent variables. All demographic factors tested as independent variables (refer to Table 3).

siblings, four categories; Not in daycare on weekdays, three categories; Home with fenced outdoor area, three categories; Parent owns or uses a car, four categories; Mother's occupation unskilled labor, three categories; Father's occupation unskilled labor, two categories; Household income > $4000/months (highest bracket), two categories.

Demonstration of Continuous GPS-PAL Data

Results thus far have been based on categorical analysis. However, it is not necessary to reduce GPS data into categories. As shown in Figure 2, 25 of 31 subjects were outdoors or in transit during the hour between 1400 and 1500. Children's 1-h averaged distance and direction from an air monitoring station in Seattle are represented by one line for each child for this time period; the terminus of the line is the point representation of averaged location. Based on data from the Puget Sound Clean Air Agency, the highest daily 2.5 μm particulate matter (PM2.5) levels were recorded at this time of day on weekends during the study months of April and May 2003. The six subjects who were indoors the entire hour are not recorded on this figure, as the fraction of ambient PM2.5 penetrating from outdoors is unknown, and no measure of indoor contaminants was made.

Discussion

Compliance is a problem with all time–location data collection methods. The problem with a diary method is that the subject's parent may forget to fill in the diary as instructed, and may later fill in the time–location as a "best-guess". Even if the parent fills in the diary as instructed, adherence to protocol or documentation of specific time–location patterns may be challenging. Parents can have difficulty if the child is extremely active and visits many locations or spends very short time periods in each location. This is not unusual behavior, especially in the 3–5 year old age group studied here (Zartarian et al., 1997). Low literacy and language barriers also confound the successful completion of a diary, even when the researchers thoroughly rehearse the procedure with parents in their native language, as was done in this study. In contrast, compliance with the GPS-PAL method is solely limited by parents remembering to turn on the unit, and by children continuing to wear the unit while it is turned on. The former is verifiable, since the GPS time stamps the turn-on time. The latter cannot always be verified, but can be checked by asking parents, as was done in this study. This still introduces a potential recall problem that could be overcome by wiring a simple trip-switch if the vest is removed. The GPS-PAL method is not limited so inherently by recall bias as a diary, nor is it limited by low literacy and language barriers.

Overall, children spent a large portion of their weekend day Inside at Home. The NHEXAS diary responses under-reported time spent Inside at Home, and over-reported time spent in other places when compared to the dGPS measurement (Table 2). An integral part of this over-reporting is the default length of the diary time–location category. A child may only be in the car for 5 min, but the parent either consciously or unknowingly rounds up to 15 min (or more) when reporting in the diary. Parents were instructed to record every 15 min, but the format of the NHEXAS diary does not promote such vigilant recording. The numbers listed on the diary timeline are whole hours, even though the last column has a designation for hours and minutes. Another potential problem with NHEXAS timeline reporting is the variability of time between written entries. Time between entries for respondents was not recorded and cannot be determined directly from the NHEXAS timeline, which is a shortcoming of this study. Had this been recorded, it may have given insight into respondents' diligence of reporting. It should be noted that a better match-up between diary and GPS would be likely if a high resolution diary such as the US EPA Consolidated Human Activity Database

Table 7. Spearman rank correlation between methods for total time in time–location category by child and household factors ($n = 31$)

	INHOME	INOTHER	OUTHOME	OUTOTHER	TRANSIT
Household language					
English	0.448*	0.305	0.415	0.532*	0.692*
Spanish	0.365	0.240	0.127	0.404	−0.034
Child's gender					
Female	0.223	−0.040	0.215	0.425	0.581*
Male	0.450	0.530*	0.519*	0.467	0.292
Age					
3	0.277	−0.235	0.604	0.368	0.427
4	0.363	0.354	0.218	0.268	0.589
5	0.700	0.872	0.783	0.667	0.205
Siblings					
No	0.720	0.071	−0.490	0.536	−0.255
Yes	0.496*	0.319	0.469*	0.462*	0.514*
In daycare, weekdays					
No	0.421*	0.300	0.345	0.480*	0.465*
Yes	0.543	−0.203	0.893*	0.232	0.618
Home w/fenced area					
No	0.648*	0.110	−0.045	0.519	0.184
Yes	0.363	0.328	0.507*	0.460*	0.516*
Parent uses a car					
No	0.174	−0.369	0.679	0.589	0.955*
Yes	0.482*	0.477*	0.436*	0.603*	0.338
Mother's occupation					
Stay at home	0.180	0.154	0.049	0.239	0.315
Unskilled labor	0.695*	0.595*	0.592*	0.460	0.055
Trade labor	id	id	id	id	id
White collar	id	id	id	id	id
Father's occupation					
No father	0.036	−0.283	0.129	0.556	0.845*
Stay at home	−0.500	−1.000	id	−0.500	0.866
Unskilled labor	0.440	0.734*	0.176	0.644*	0.086
Trade labor	0.500	−0.866	0.866	0.500	0.866
White collar	0.051	0.700	0.800	−0.100	0.975*
Income per Month					
< $1000	0.344	0.306	0.067	0.497	0.842*
$1000–$2000	0.529	−0.050	0.477	0.428	0.196
$2000–$3000	−0.500	0.500	0.866*	id	−1.000
> $4000	0.949*	0.800	0.632	0.775	0.949*

id = insufficient data.
*Values are significantly correlated at $P < 0.05$.

(CHAD) diary had been used in this study. Such diaries can resolve as many as 40 different microenvironments (McCurdy and Graham 2003; EPA, 2005). However, the wide range of times spent in each location for all children in the current study (by both methods) emphasizes the problem with using surrogate time–location based on a database of sequential time/location patterns such as CHAD. It should be noted that for the aims of NHEXAS, higher time resolution was possibly not necessary, while for more refined exposure assessments, higher time-resolution is critical.

The κ measures (Tables 3–5) show that overall agreement of methods can be considered marginal, and that time spent Inside at Home has the greatest influence on the overall κ for two reasons: (1) the most time during the day is spent Inside

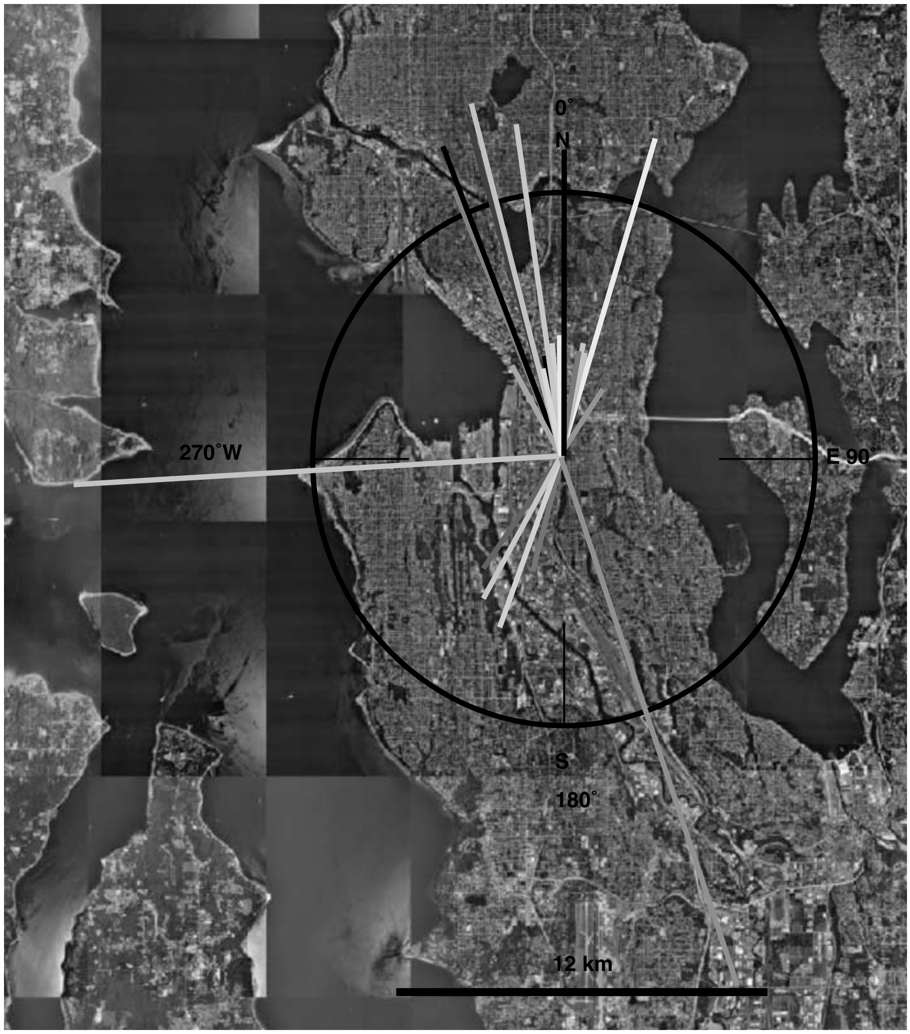

Figure 2. Mean distance and direction from an air monitoring station in Seattle during the peak hour of PM2.5 concentration. All subjects shown ($n = 25$) were outdoors. Six subjects were indoors where there was not GPS reception and are not shown. Time period over which mean values were calculated is 2–3 pm on a weekend day in April or May, 2003. This is the time of peak PM2.5 in Seattle for April and May on weekends. Distance and direction can be used to calculate exposure relative to PM2.5 readings from this station. The main source of PM2.5 is Interstate 5, which runs North–South approximately 0.5 km West.

at Home; (2) some of the time recorded as Inside at Home by GPS method is in fact proxy, since reception was often blocked until the subject left the home. These are notable limitations of GPS. The need for start time proxy data could be overcome by having the GPS time stamp when it is turned on, regardless of reception. A switch could also be wired such that the GPS would time stamp when the vest is zipped shut and zipped open so that removal of the vest would be logged by the GPS.

One purpose of this study was to evaluate GPS for detecting who has most trouble providing valid and consistent responses to the diary timeline, and to determine which location categories are most troublesome. This is important because timelines such as the NHEXAS diary timeline remain necessary for time–location characterization of large cohorts. GPS appears to hold promise for diary testing . Based on trends shown in Tables 5 and 6, changes or recommendations might be made to diaries and/or diary methods. For example, it was possible to determine that "Outside at Home" had the lowest κ, and "Inside at Other" was found to be least correlated with the GPS for total rank sum of time. Given these findings, researchers could coach parents to set a timer during times the child goes out the back door, or when they go into stores. When child and household factors were examined for comparisons of total time in location (Spearman rank correlation, Table 7), Spanish-speaking households were less likely than English-speaking households to reply accurately. English speakers reported total time In Home, Out at Other, and especially total time In Transit more accurately than Spanish speakers. Researchers could re-evaluate and test the Spanish version of the timeline or re-train Spanish-speaking interviewers based on this finding. Other findings included: presence of a fenced outdoor space at the home improved parent's reporting accuracy for the "Outside at Home" category (likely because observation is easier in a defined space); and parents who never had access to a car and thus primarily used public transportation were very accurate in their reporting of time spent in transit (likely because their travel was dictated by bus schedules). All the above findings would have been missed without comparison to a "best practical standard" such as the GPS-PAL.

Both affordability and practicality preclude the use of GPS for large cohorts. In addition, it should be noted that despite their shortcomings, diary timelines currently have the advantage over GPS of being less time-consuming to process, assuming categorical location data is the desired output. By the methodology used in this study, a 12-h dGPS data set for one child takes approximately four hours to process if categorical location is desired. On the other hand, the processing is reduced to approximately 1.5 h if true (continuous) location rather than ordinal location category is the desired output, as exemplified in Figure 2.

With GPS, it is not necessary to average or categorize time–location. Instead, GPS allows for delineation of hundreds or thousands of very small exposure environments and exposure intervals of only a few seconds. This means that peak, transient exposures can be recorded by specific time and location rather than being absorbed into a time-weighted average. Using continuous GPS data, it would be possible to address the question "for each child, how representative are the 1-h air data from the monitoring station in Figure 2?" It would be possible to test the hypothesis that the further away a child is, the less representative the station data is for estimating exposure. Similarly, distance from a PM2.5 source can be observed in Figure 2. Interstate five runs North–South less than 0.5 km West of the air station and is the major source of PM2.5 measured at the station. Children closer to this line source or more directly downwind from it may be expected to receive greater PM2.5 exposure than children farther away or upwind. Continuous GPS data provide the distance and direction information needed to make such estimates of exposure.

While a diary could record time spent outside in relation to PM2.5 data, the diary could not have captured the children's proximity to the monitoring station. Contaminant concentration is not uniform in all distances and directions from a monitoring station. With GPS, two advancements have been made. First, inherent problems with human-reported data are minimized, yielding higher resolution data. Second, proximity of moving human receptor to contaminants can be measured. With the automated collection of near-continuous (once every 5 s) dGPS data, researchers can now pinpoint where subjects are in relation to contaminants. This is particularly important in the case of a transient, spike release such as a pesticide spray event. Continuous sampling (once every second) is possible with the GPS-PAL and other dGPS instruments if required for a specific application. The only limitation on sampling interval is memory (byte) space. The only limitation on sampling period is battery life. As personal logging dosimeters for air toxics improve in resolution and decrease in size and weight, it is logical to expect that tandem time-synched contaminant monitoring and dGPS positional monitoring will become standard procedure.

Overall, the NHEXAS timeline misclassified child time–location approximately 48% of the time in comparison to the GPS-PAL. This study demonstrated that dGPS can be used to evaluate a diary timeline such as that used in the NHEXAS studies, and used to illuminate which categories fail to elicit accurate responses or which people are most likely to have trouble reporting using a diary. Most exciting is the ability of dGPS tracking to collect continuous rather than categorical data by way of automated rather than human reporting. With the elimination of categories and the automation of data collection, resolution and efficiency of time–location measurement is dramatically improved.

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