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► **To cite this version:**

Basile Chaix. How daily environments and situations shape behaviors and health: momentary studies of mobile sensing and smartphone survey data. *Health & Place*, 2020, 61, pp.102241. 10.1016/j.healthplace.2019.102241 . hal-03878489

HAL Id: hal-03878489

<https://hal.science/hal-03878489v1>

Submitted on 29 Nov 2022

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How daily environments and situations shape behaviors and health: momentary studies of mobile sensing and smartphone survey data

Basile Chaix

Sorbonne Université, INSERM, Institut Pierre Louis d'Epidémiologie et de Santé Publique
IPLESP, Nemesis team, Faculté de Médecine Saint-Antoine, 27 rue Chaligny, 75012 Paris,
France

Traditionally, studies of place and health in public health and epidemiology have examined cross-sectional associations between (often residential) environmental exposures and health outcomes, analyzing individuals as the statistical units of observation; or more rarely longitudinal associations between baseline environmental characteristics and changes in health outcomes, or between time-varying environmental exposures and outcomes over mid to long term periods.

Place and health studies have not relied until recently on the intensive monitoring of participants over consecutive days (Krenn et al., 2011). Such data collection design has existed for long in other research fields, such as health psychology and behavioral psychology where paper-based diaries have long been used (Armeli et al., 2000). It is mostly through GPS tracking that the continuous monitoring design was introduced in place and health research.

Analytically, the simplest use of GPS data is to aggregate the GPS points over the observation period and derive an overall shape, the daily path area, and to calculate exposure to environmental factors at that level as individual-level variables. This approach, which then correlates such exposures with individual-level outcomes, implies a significant data reduction (from tens thousands points to a unique value) and an elimination of the time dimension. In contrast, another analytical strategy is to generate repeated time-varying exposure and outcome variables, yielding a true space-time perspective in the analyses (Chaix, 2018). For the latter approach to make sense, not only environmental exposures but also behavioral or health outcomes must be disaggregated over time.

Accelerometers enable to collect data on physical activity over time, and Health & Place has published articles on place effects on physical activity using GPS receivers and

accelerometers (Chaix et al., 2013; Stewart et al., 2016). However, measurement strategies are needed to gather repeated data on other behavioral and health outcomes over GPS follow-up periods. Ecological momentary assessment (EMA) is one such key measurement approach, through smartphone-based surveys, to collect perceived environmental exposure, covariate, and outcome data. The combination of GPS tracking with EMA has been referred to as geographic or geographically-explicit EMA, or GEMA. While only a handful of GEMA studies have been published to date (Epstein et al., 2014; Kirchner and Shiffman, 2016), it is likely that GEMA, enriched with other sensors, has a unique contribution to make in the future of place and health research.

A review of selected EMA studies

To reflect on methods, this commentary briefly reviews selected article published in Health & Place that used EMA to gain insight on place influences on health.

Dunton and colleagues (Dunton et al., 2012) analyzed data from 94 children collected with mobile phones for EMA and accelerometers (but not GPS receivers) to examine whether children change their contexts for physical activity after a recent move to a smart growth community as compared to children in suburban communities. EMA over 4 days (20 prompts), conducted two times 6 to 12 months apart, permitted real-time assessment of whether children were currently physically active and where and with whom they engaged in physical activity. Among EMA surveys corresponding to current physical activity, multilevel models with EMA surveys as statistical units and an individual-level random intercept examined whether residing in a smart growth community was associated with the likelihood that physical activity occurred outdoor vs. at home, and nearby vs. further away from home; and whether the outdoor environment was perceived as supportive for physical activity. These

momentary analyses revealed that smart growth community children engaged in physical activity more often with friends and at a walkable location from home.

This study demonstrates that EMA is useful to investigate the situational predictors of behavior in addition to objective environmental factors that could have been captured with GPS tracking. Situational factors refer to transient circumstances in the visits of people to places (time and day, weather, purpose of the visit, time constraints, other people also visiting the place, mood, etc.). They are important to examine because they may interact with environmental factors, and such interactions should be considered to target interventions at the most relevant places and times. Without EMA implemented in a continuous tracking design, situational predictors such as being with friends when engaging in physical activity would have been assessed with massive measurement error. Replication of pioneering protocols of this kind might incorporate GPS tracking and automatically trigger questionnaires after detected accelerometer bouts of physical activity.

Another EMA article published in the journal (Beute and de Kort, 2018) was interested in the impact of nature and daylight (restorative environmental aspects) on mood and stress level in 57 depressed and non-depressed participants. EMA over 6 days (8 invitations per day) collected perceived data on daylight and nature with checklists. Data were appropriately analyzed with a three-level hierarchical model with survey responses nested within participants and day. For example, a random intercept and slope model demonstrated that the impact of self-reported exposure to nature on depressive symptomatology varied in magnitude across participants and that participant who felt most depressed benefitted most from nature exposure. Again, although combined GPS and geographic information system data would

yield crude information on surrounding nature, perhaps adding these data could have provided relevant complementary predictive information.

This ambitious study attempted to capture galvanic skin response with a wristwatch but data were deemed unreliable. However, building on this example, investigators should develop multisensor studies collecting data over various relevant channels, including objective environmental and physiologic, and subjective (self-report) data streams.

Another study published in *Health & Place* (Doogan et al., 2018) used EMA to investigate whether in rural settings distance from home to the nearest tobacco outlet and the presence of price promotions interactively influenced quantities of tobacco purchased. Over 7–10 days (once per year over 2 years), 54 combustible and 27 smokeless tobacco users reported information on smartphones after every tobacco purchase (products, quantity, use of price promotions) as soon as possible after the purchase. Associations with purchase quantity per purchase were modeled with each purchase as a statistical unit, with a random intercept accounting for the within-individual correlation. For example, it was shown that combustible users purchased an increased quantity of cigarette packs if they lived further away from an outlet and used a price promotion (synergistic effect). This study shows that stable residential environment factors (distance to the closest outlet) and momentary environmental factors (price promotion) can synergistically intervene to shape behavior.

All three EMA (but not GEMA) studies reviewed above undertook a momentary analysis of data, i.e., analyzed data at the momentary level of repeated surveys. Compared to the more traditional approach that examines static individuals, this novel perspective based on continuous monitoring brings the focus closer than ever of real-life conditions.

A review of selected GEMA studies

Health & Place also published some of the few GEMA studies. McQuoid et al. (McQuoid et al., 2019) collected location tracking data and smartphone EMA data in 17 participants aged 18-26 years in California over 30 days to explore the everyday smoking contexts and practices of bisexual individuals. The comprehensive EMA assessment included participants' initiated cigarette smoking reports, some of them leading to smoking surveys, complemented with random surveys to assess smoking and nonsmoking situations. EMA assessed contextual predictors (types of locations) but also situational predictors of smoking (i.e., transient circumstances contingent or connected to places): drinking/eating, other people smoking, presence of ashtrays, or tobacco advertisement. Thus this GEMA study was adequately designed to develop a predictive model of how momentary contextual and situational factors influence contemporaneous smoking, interestingly conceptualized as a place-embedded practice. However, this article only reported descriptive analyses of the GEMA data, as its aim was to conduct a qualitative analysis of participants' interviews commenting geographic clusters of smoking and nonsmoking.

Another GEMA study (Byrnes et al., 2017) collected data in 170 Californian teens aged 14-16 with GPS enabled phones over one month. EMA collected data 6 times per week over 3 days on risk behavior (alcohol consumption since the last text or right now; any action that could put them in trouble with law, school, or their parents since the last text) and on teens' perceptions of their environment (social disorganization and whether they could see an alcohol outlet nearby). Objective exposure to alcohol outlets and socioeconomic status in the census block group was spatially linked to each EMA survey. Environmental exposure and outcome data were then aggregated at the individual level, yielding, e.g., an average

socioeconomic score, average teen-reported social disorganization score, percentages of times where teens were aware of an alcohol outlet nearby or had used alcohol, etc. across all EMA surveys over one month. Thus, the data underwent a considerable reduction, leaving 170 (individual-level) statistical units for the analysis. This analysis for example demonstrated that teen-reported disorganization and low objective socioeconomic status of survey locations were positively associated with a higher percentage of surveys where teens reported alcohol use. This study could not develop a momentary analysis of data (with one statistical observation per EMA survey) because the alcohol consumption or problem behavior outcomes focused on the period between the previous and the present survey and therefore the location of the corresponding events was not exactly known.

This review of selected articles published in *Health & Place* reveals that, of the published articles listed above, none relied on a GEMA protocol (i.e., collected data with both GPS receivers and EMA) *and* implemented a momentary analysis of these data.

Momentary vs. individual-level design to analyze GEMA or multisensor data

From a data collection perspective, we need studies collecting data from an increasing number of channels, including through passive tracking and momentary surveys. Passive tracking [including through wearable cameras combined with GPS receivers as published in the journal (Chambers et al., 2018)] provides more objective and accurate data than self-report on particular dimensions and makes it possible to fully dedicate survey time to dimensions that intrinsically need self-report. From a data processing perspective, studies will continue to develop and apply algorithms allowing us to predict from the raw sensor data relevant momentary behavioral and contextual variables (sleep, travel behavior, body posture and

physical activity, environmental exposures). Such data collections permit to encode real-life exposures and circumstances into a set of variables with an unprecedented level of accuracy.

From an analytical perspective, a major interest of continuous monitoring studies is to confront at a momentary level (at the level of relevant time segments) environmental, behavioral, perceptual, and health indicators, and to investigate time sequences and chains of phenomena among them. Thus, except particular analytical circumstances, aggregating the repeated data for a participant into individual variables might represent a missed opportunity, assuming that the research potential of these data lies in their disaggregation across space and time (Chaix, 2018).

An issue is that when the repeated information collected over several days is aggregated at the individual level, there are risks of aggregation fallacy (the well-known ecological fallacy is a comparable inferential error). Consider a study correlating exposure to fast-food restaurants aggregated in the overall 7-day daily path area with junk food consumption over the same period. An association between higher exposure and junk food consumption would not imply that this unhealthy food consumption occurs after exposure to, and as the result of being exposed to, fast-food restaurants. Thus a design aggregating data that could be analyzed at a finer resolution is more vulnerable to confounding.

As another benefit, disaggregated data permit to investigate synergistic effects of environmental and situational factors on behavior and health (Chaix, 2018). They permit to investigate whether environmental factors are magnified in particular situations and under specific circumstances. These investigations of momentary effects pave the way for the development of just-in-time adaptive interventions, e.g., environmental interventions, or

behavioral interventions delivered through smartphone applications, that aim to provide the right amount of support to the right person in the right place at the right time (Nahum-Shani et al., 2016).

With GPS receivers and personal environmental sensors, we are pretty good at disaggregating environmental exposures over space and time, to determine local (space) momentary (time) exposures. However, studies still lag behind to correspondingly disaggregating behavioral and health outcomes. One reason why such a large fraction of GPS studies in public health have focused on physical activity is that accelerometers provide readily usable momentary outcome data. Smartphone-based EMA in GEMA and other sensor studies is key to collect momentary information on other behavioral and mental well-being outcomes but also on a large range of environmental or situational factors, be they explanatory variables, confounders, or modifiers.

Studies of momentary health outcomes (e.g., heart rate variability, blood pressure, lung function, mental well-being, etc.) based on short-term monitoring are important as they allow researchers to investigate mechanisms, which repeated a large number of times, lead to the development of chronic conditions. However, for the latter to be confirmed, these short-term follow-up designs need to be extended to incorporate a longer-term perspective, e.g., with repeated sensor-based assessments months or years apart.

Overall, articles published in *Health & Place* illustrate that a range of measurement devices, data collection designs, and analytical tools are being developed to dig into the infinite richness of transient combinations of environments and situations that influence health states and behaviors. To go further in this direction in order to efficiently inform momentary environmental interventions, *Health & Place* would warmly welcome sound momentary

analyses of place effects on health relying on GPS tracking, ecological momentary assessment, and monitoring with other passive sensors.

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