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Context-sensitive ecological momentary assessments; integrating real-time exposure measurements, data-analytics and health assessment using a smartphone application

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ABSTRACT

Introduction: Modern sensor technology makes it possible to collect vast amounts of environmental, behavioural and health data. These data are often linked to contextual information on for example exposure sources which is separately collected with considerable lag time, leading to complications in assessing transient and/or highly spatially variable environmental exposures. Context-Sensitive Ecological Momentary Assessments[1] (CS-EMAs) could be used to address this. We present a case study using radiofrequency-electromagnetic fields (RF-EMF) exposure as an example for implementing CS-EMA in environmental research.
Methods: Participants were asked to install a custom application on their own smartphone and to wear an RF-EMF exposimeter for 48 h. Questionnaires were triggered by the application based on a continuous data stream from the exposimeter. Triggers were divided into four categories: relative and absolute exposure levels, phone calls, and control condition. After the two days of use participants filled in an evaluation questionnaire.
Results: 74% of all CS-EMAs were completed, with an average time of 31 s to complete a questionnaire once it was opened. Participants reported minimal influence on daily activities. There were no significant differences found between well-being and type of RF-EMF exposure.
Conclusions: We show that a CS-EMA based method could be used in environmental research. Using several examples involving environmental stressors, we discuss both current and future applications of this methodology in studying potential health effects of environmental factors.

1. Introduction

Advances in sensor technology make it possible to log continuous (personal) measurements of various environmental, behavioural and health parameters. Data from these sensors is often stored electronically, allowing it to be viewed and processed later. Such data can subsequently be statistically analysed and linked to contextual information on exposure sources and/or health effects collected via separate electronic means, via questionnaires such as daily diaries, or linkage to registry-based disease or geospatial databases. The downside of this approach is that the separate collection of data hampers full data-integration, which in turn can lead to a considerable lag time between an exposure event and the moment the questionnaire or diary is filled in. This is particularly problematic for assessments of parameters with a transient or variable nature. Examples include environmental exposures that display a high spatial or spatio-temporal variability, or variable or transient health outcomes such as heart-rate variability which could change quickly within a short time frame.

Ecological momentary assessment (EMA) encompasses a range of data collection methodologies used in, amongst others, clinical psychology. Key aspects of EMA are the repeated collection of data under real-world environment conditions, close in time to an event, and at strategically selected moments (Stone and Shiffman, 1994; Shiffman et al., 2008). Depending on the event of interest, triggers for assessments can take place at set intervals, at random moments of the day, at predefined events or following some other sampling scheme. More recently, context-sensitive ecological momentary assessments (CS-EMAs) have been introduced. CS-EMA is an extension of the classic EMA methodology in which a data stream is used to determine the

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[1] CS-EMA: Context-Sensitive Ecological Momentary Assessment.

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moment of assessment (Intille, 2007). For example Dunton et al. (2016) used the smartphone's internal motion sensor to trigger momentary assessments when a predefined amount of physical activity had been detected. The advantages of (CS-)EMA include a better recall due to the short time period between the event of interest and the assessment, and the ability to collect data in the natural, real-life environment of a subject.

The ability to continuously collect and process large amounts of data on environmental parameters, in combination with CS-EMA approaches could be used to identify exposure sources and to explore potential health effects related to environmental factors. We carried out a case study in which we developed a smartphone application capable of processing incoming data in real-time, using exposure levels to trigger momentary assessments. We used exposure to radiofrequency electromagnetic fields (RF-EMFs) as a test case. RF-EMF is highly spatially variable and there have been reports of individuals ascribing a variety of health problems to exposure to RF-EMF (also called electromagnetic hypersensitivity). Frequently reported symptoms include concentration problems, headache, nervousness and fatigue, often occurring within minutes of exposure (Röösli et al., 2004). Previous studies have investigated such effects in controlled laboratory studies. However, these studies have been criticized because usually just one exposure was applied, whereas real-life exposures would represent a mix of different types of frequencies and signal types. Therefore, the use of an EMA design, where the real-life environment is a key aspect, could provide an informative way to study this association. A similar concept has been tried by Bogers et al. (2013), who performed a study where continuous collection of radiofrequency electromagnetic field (RF-EMF) data was combined with a random trigger EMA design. In this study design, the RF-EMF exposure levels did however not trigger the assessments, making it difficult to collect sufficient assessments on less common events.

The aim of the presented study is to test the technical feasibility of CS-EMA by real-time processing of environmental sensor data, the adherence to assessments whose triggers are based on sensor data, and the influence on daily activities of participants using RF-EMF exposure as a test case.

2. Methods

2.1. Study population and protocol

Participants were recruited from the city of Utrecht (the Netherlands) and its surrounding area between May and October 2015. Eligibility criteria included being at least 18 years of age, using a smartphone running the Android operating system, and being able to understand the Dutch language. Participants were recruited via an online portal (www.proefbunny.nl) and obtained a small monetary compensation for their efforts. Two appointments, 48 h apart, were made with each participant. During the first appointment the custom smartphone application (ExpoMDiary) was installed on the participants own smartphone, and the RF-EMF exposimeter was handed out. Participants were instructed to wear the RF-EMF exposimeter between the two appointments and to answer the triggered questionnaires when possible. Each participant was provided with a small bag to carry the RF-EMF exposimeter at the hip level as previously described by Martens et al. (2016). Equipment and data was retrieved during the second appointment and the participant was asked to fill out a short evaluation questionnaire. The evaluation questionnaire consisted of questions regarding the amount of time the devices were carried, the perceived influence on daily activities, and whether the participant had ever linked health problems to RF-EMF exposure. The medical ethical committee of the University Medical Center Utrecht (UMCU) reviewed the study protocol and concluded that further ethical approval was not required.

2.2. RF-EMF exposimeter

An ExpoM - RF exposimeter (Fields at Work GmbH, Switzerland) was used to monitor RF-EMF exposure. The device is capable of simultaneously monitoring 16 different frequency bands, covering the most relevant RF-EMF sources with a high sensitivity (Fields at Work, 2016). Detailed specifications are provided as Supplementary material. Samples were taken once every 8 s and subsequently transmitted to the smartphone application via Bluetooth. Data transmission took less than 100 ms, was performed between the measurement intervals and thus did not interfere with measurements taken. Smartphone and exposimeter had to be within three to four metres of each other to transfer data, depending on the environmental conditions (i.e.: line of sight, smartphone cover).

2.3. ExpoMDiary application

The ExpoMDiary application was written for smartphones running on version 4.0 or later of the Android operating system. If Bluetooth connection to the exposimeter was lost for more than 1 min, the participant received a message asking to check whether the exposimeter was still turned on and within range. If the application was inadvertently turned off, e.g. by turning the smartphone off and back on, it restarts automatically and resumes its functionality. When running, the application would process incoming data and trigger assessments (questionnaires) following the predefined trigger conditions. Relative and absolute exposure events were triggered based on exposimeter data, while phone call events were triggered on call information provided by the participants' smartphone. The condition(s) for triggering the questionnaire, current exposure levels, time to respond and complete the questionnaire, and whether it was completed or not were all recorded.

2.4. Questionnaire trigger conditions

A questionnaire assessment was triggered when one of the primary and all of the secondary conditions were met. Four events were specified as primary conditions: 1) a sudden relative increase in exposure, 2) exposure exceeding an absolute threshold, 3) an incoming or outgoing phone call, or 4) no questionnaires triggered for the past 1.5 h (control event). Sudden relative increase was defined as a tenfold increase in power density (mW/m^2) compared to the moving average of the past half hour. The threshold for the absolute exposure level was set at 10 mW/m^2 (1.94 V/m). This is roughly a quarter of the maximum power density observed by Joseph et al. (40.4 mW/m^2 (3.9 V/m)) during in-situ measurement in the Netherlands, Belgium and Sweden (Joseph et al., 2012). Phone calls are particular events of interest as the phone is typically held close to the head during these events, causing higher exposure levels to the brain. The questionnaire would appear after the phone call was finished.

Secondary conditions were specified as not to overburden the participants. To allow undisturbed sleep, no questionnaires were triggered between 10 pm and 8 am. Minimum wash-out period between answered questionnaires was 45 min. Lastly, no more than 10 questionnaires were triggered on a particular day. Ignored or missed questionnaires did not count towards this total of 10 questionnaires per day. Triggers followed a first come, first serve hierarchy where the first valid trigger would be used, regardless of the previous type or number of triggers during the day.

2.5. Questionnaires

Once triggered, the questionnaire would pop-up on the main screen of the smartphone while simultaneously triggering an audio and vibrate alert. When unanswered, a reminder would pop-up after 5 min. After 10 min the questionnaire would disappear altogether and counted as unanswered.