



Letter

Design of a smartphone application to monitor stress, asthma symptoms, and asthma inhaler use

Advances in the treatment and prevention of asthma have curtailed deaths, hospitalizations, and increases in prevalence rates during the past 30 years.¹ Nevertheless, the effectiveness of long-term asthma management is mediated by behavioral factors, such as adherence to medication and psychosocial stress. In a study using ecological momentary assessment (EMA) to monitor asthma inhaler use, half of all nonadherence cases occurred while participants were with their peers.² However, the study relied on subjective reports of adherence. Associations between stress and asthma symptoms have been observed, but these associations have relied on retrospective self-report, potentially introducing recall bias. Laboratory studies have found causal associations between stress and biological markers of immune responses related to asthma.^{3,4} However, these settings may not represent real-world situations. Furthermore, both laboratory and longitudinal studies to date have not captured the effect of daily variations in adherence, stress, and symptoms.

Advancements in technology have led to commercial availability of low-cost personal computing devices (smartphones) capable of executing advanced health-related applications (apps) and communicating with external sensors via short-wave radio signals (Bluetooth).⁵ EMA using smartphones is a method of capturing real-time data that maintain ecological validity, reduce recall bias, preserve within-day changes, and capture objective data from external devices to reduce social desirability bias.⁶ This letter describes the design of a smartphone app that integrates EMA- and Bluetooth-enabled sensors for asthma inhalers. This technology can measure real-time asthma symptoms, social and physical context, behavior, stress, and inhaler use.

Development of the application was a collaborative effort from a multidisciplinary team of researchers and computer scientists. The app was installed on Samsung Galaxy Y (model S5460) smartphones running the latest available version of Google's Android operating system and loaned to participants. Study personnel conducted iterative development (α) testing before initiating pilot (β) testing using a small ($N=20$) English-speaking convenience sample of Hispanic middle and high school students (mean [SD] age, 14.6 [1.7] years; age range, 12–17 years) enrolled in a mobile asthma management clinic for low-income families.⁷ Written parental consent and child assent were obtained at enrollment; the study was approved by the institutional review board at the University of Southern California. Physicians assisted at enrollment to

inform participants that the app was not a replacement for treatment. The app uses signal-contingent (ie, randomly timed) and event-contingent (ie, context sensitive) EMA sampling triggered by asthma inhaler use. Inhaler use is detected when the phone receives a signal from a Bluetooth sensor on the participant's quick-relief and controller medications.

The signal-contingent EMA component of the software prompts the user with an electronic survey at a random time within each of 7 designated time windows: 7 to 9 AM, 9 to 11 AM, 11 AM to 1 PM, 1 to 3 PM, 3 to 5 PM, 5 to 7 PM, and 7 to 9 PM. No surveys are deployed before 3 PM on weekdays (during school time). After receiving a prompt (eFig 1), the participants are presented with a set of questions querying current levels of positive and negative affect, stress, energy, and fatigue, the type of activity currently being performed, and information about social and physical contexts (eTable 1). In addition, participants are asked to recall stressful events, asthma symptoms, and asthma coping-related behaviors occurring since the last survey (or in the past 4 hours if the last survey was completed >4 hours earlier) (eTable 1).^{8–10}

The event-contingent (ie, context-sensitive) EMA component of the app runs a background service that monitors all incoming Bluetooth connections. Participants are provided with 2 small, buttonlike devices that attach to the tops of quick relief (ie, rescue) and controller metered-dose inhalers (Propeller sensor, provided at no cost by Propeller Health, Madison, Wisconsin) designed to transmit a Bluetooth signal to the phone when the inhaler is actuated. Approximately 5 minutes after the background service captures a Bluetooth sensor signal, the app initiates a real-time self-report survey. The first question in this survey asks whether the participant used a rescue inhaler, control inhaler, or neither (ie, inhaler actuated unintentionally). If a participant reports any inhaler use, the survey subsequently queries the severity of asthma symptoms experienced, the type of activity performed, and social and physical contexts encountered just before the inhaler use. Questions also ask about stressful events experienced since the last survey (or in the past 4 hours if the last survey was completed >4 hours earlier) (eTable 1).

To reduce burden on participants, EMA surveys contain logical question branching for question subsets. With the exception of questions related to performed activity type, a randomized selection algorithm was used for signal-contingent question subsets such that each subset had a 60% chance of appearing on any given survey. Data from all surveys are uploaded to a secure file transfer protocol server at the end of the day. At the completion of testing, the phones were retrieved from participants and the phone features restored to factory settings.

During pilot testing, participants received a daily mean (SD) of 3.2 (0.9) (range, 1–4.57) signal-contingent and 2.1 (2.6) (range,

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Table 1
Sample demographic characteristics and use satisfaction in pilot testing

Variable	No. (%) of study participants (N = 20)
Sex	
Male	11 (55)
Female	9 (45)
Ethnicity	
Hispanic	20 (100)
Overall, how satisfied are you with the mobile phone surveys?	
Very satisfied	10 (50)
Satisfied	10 (50)
Dissatisfied	0
Very dissatisfied	0
Overall, how easy/difficult was it to use the mobile phone surveys?	
Very easy	19 (95)
Somewhat easy	1 (5)
Somewhat difficult	0
Very difficult	0
Overall, how easy/difficult was it to answer the mobile phone surveys after an asthma attack?	
Very easy	6 (30)
Somewhat easy	3 (15)
Somewhat difficult	1 (5)
Very difficult	1 (5)
Did not answer any after an asthma attack	9 (45)
Overall, the mobile phone surveys interrupted my daily activities.	
Strongly agree	1 (5)
Agree	1 (5)
Disagree	13 (65)
Strongly disagree	5 (25)
Overall, answering the mobile phone surveys required too much of my time.	
Strongly agree	0
Agree	1 (5)
Disagree	10 (50)
Strongly disagree	9 (45)
Overall, how easy/difficult was it to answer the mobile phone surveys in the middle of the night?	
Very easy	5 (25)
Somewhat easy	6 (30)
Somewhat difficult	2 (10)
Very difficult	0
Did not answer any in the middle of the night	7 (35)

0.1–7.8) event-contingent prompts across all 7 days. The EMA prompt adherence rates ranged from 20% to 100% (mean [SD], 51.4% [21.8%]). Users reported general satisfaction and ease of use, whereas some reported difficulty with answering surveys that interrupted them in the middle of the night (Table 1).

Once rigorously tested, the EMA portion of the app (source code) will be made publicly available (at no cost) to researchers. Open-source Android applications allow for localization to languages other than English and installation on participant-owned devices or loaned phones, thereby reducing cost. Furthermore, the application

also allows for monitoring using other sensors (eg, built-in motion and location sensors and external personal ozone monitors). Future studies should seek to improve adherence rates, generalize the findings to non-Hispanic subpopulations, and assess adolescent health literacy. This application has the potential to assist researchers and clinicians to better understand real-time experiences of adolescent patients with asthma, increase adherence to asthma treatment regimens, tailor treatments to their specific needs, and enhance patient-physician communication.

Supplementary Data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.anai.2014.12.017>.

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In the past four hours, has anything stressful happened to you?

- ☐ No stressful things have happened
- ☐ A few stressful things have happened
- ☐ Many stressful things have happened

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eFigure 1. Screenshot of a standard survey question.

eTable 1

Ecological momentary assessment items presented to participants at survey prompts

Root question (item ^{a1})	Response options	Contingency
How were you feeling (1)? (HAPPY, JOYFUL, MAD OR ANGRY, NERVOUS OR ANXIOUS, SAD, STRESSED)	Not at all A little Quite a bit Extremely	Signal
How certain did you feel that you can cope with all the things that you have to do (1)?		Signal
How confident did you feel about your ability to handle your personal problems (1)?		Signal
How ENERGETIC or FULL OF PEP were you feeling (1)?		Signal
How FATIGUED or TIRED were you feeling (1)?		Signal
Did you use a CONTROL or RESCUE inhaler?	Control inhaler, rescue inhaler, I didn't use it	Event
(If NEITHER is Selected) Why was the INHALER pressed?	I pressed it by accident, someone else pressed it, it was bumped or something hit it, other	Event
(If OTHER is Selected) Why was the inhaler pressed?	Please type your answer or type "I don't know."	Branch
What were you DOING (1)(2)?	Reading/homework, using technology, active play/sports/exercising, eating/drinking, going somewhere, sleeping, something else	Signal/event
(If SOMETHING ELSE) Please specify what you were DOING [1][2]:	Please type your answer.	Branch
(If Using technology) While using technology (TV, phone), were you:	Playing video games, talking, texting, using the internet, watching shows/movies, other	Branch
(If GOING SOMEWHERE) While going somewhere, were you:	Walking, biking, riding a bus, riding the metro/train, riding in a car/taxi, other (skateboarding, etc)	Branch
WHERE were you (1)(2)?	Home (indoors), school (indoors), outdoors, restaurant, store/mall, someone else's house (indoors), in a car, other	Signal/event
(If OUTDOORS) Where were you OUTDOORS ?	Home (front/back yard), school, park/trail, sidewalk, road, parking lot, other	Branch
Were you (1)(2): Choose all that apply.	Alone, with your mom/dad, with your sister(s) or brother(s), with your friend(s)	Signal/event
Has anything stressful happened to you (3)(4)?	No stressful things have happened, a few stressful things have happened, many stressful things have happened	Signal/event
Has anyone teased you (3)(4)?	Yes, and caused very much stress	Signal/event
Have you argued with anyone (3)(4)?	Yes, and caused some stress	Signal/event
Have you had a misunderstanding or disagreement with your parents (3)(4)?	Yes, and caused a little stress	Signal/event
Have you had too many things to do (3)(4)?	Yes, but not at all stressful	Signal/event
Have you experienced ____ (2)(3)(4)?	No	Signal/event
(COUGHING , WHEEZING , CHEST TIGHTNESS , SHORTNESS OF BREATH)	Not at all	Signal
Have you avoided strenuous activities because of your asthma (3)(4)?	A little	
Have you avoided situations that could bring on an asthma attack (3)(4)?	Quite a bit	Signal
Have your worried about having an asthma attack (3)(4)?	Very much so	Signal

^{a1} Indicates just before the phone went off; 2, just before you used your inhaler; 3, since the last survey you answered; and 4, in the past 4 hours.