Experimental Design & Machine Learning Opportunities in Mobile Health

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advancing methods, improving health

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The Dream!

"Continually Learning Mobile Health Intervention"

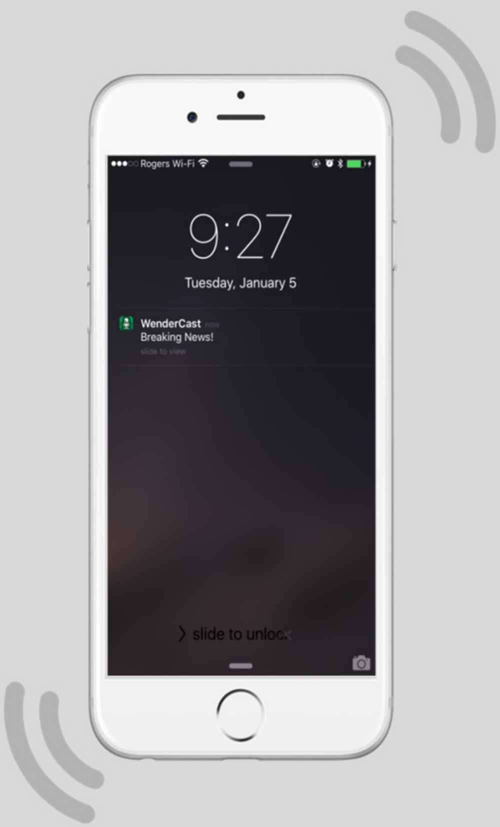
- Help you achieve, and maintain, your desired long term healthy behaviors
  - Provide sufficient short term reinforcement to enhance your ability to achieve your long term goal
- The ideal mobile health intervention
  - will engage you when you need it and will not intrude when you don't need it.
  - will adjust to unanticipated life events

Setting

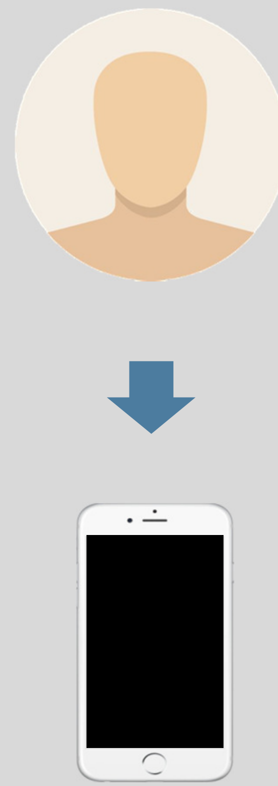
- Mobile health science studies involving clinical populations
- Machine learning/reinforcement learning tied closely to scientific inquiry in behavioral science
  - Experimental Design in ML/RL
  - Causal Inference in ML/RL
  - Interpretable ML/RL

Mobile Intervention Types

PUSH



PULL



Goal

Determine when and in which setting

- whether the mobile device/wearable should deliver a treatment push &
- which type of push to deliver.

Sequential decision making

- Inform behavior change science
- Development of treatment policy

Conceptual Data

- On each individual: $O_1, A_1, Y_2, \dots, O_t, A_t, Y_{t+1}, \dots$

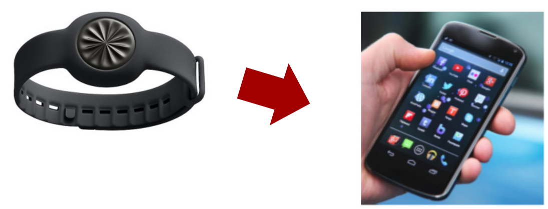
- t: Decision point
- O_t: Observations at t^{th} decision point (high dimensional)
- A_t: Treatment at t^{th} decision point (pushes)
- Y_{t+1}: Proximal response (e.g., reward, utility)

Heartsteps

V1 study; 42 days

Observations

- Commercial wearable wrist band (data each minute); Smartphone sensor data(6 times per day); Daily self-report



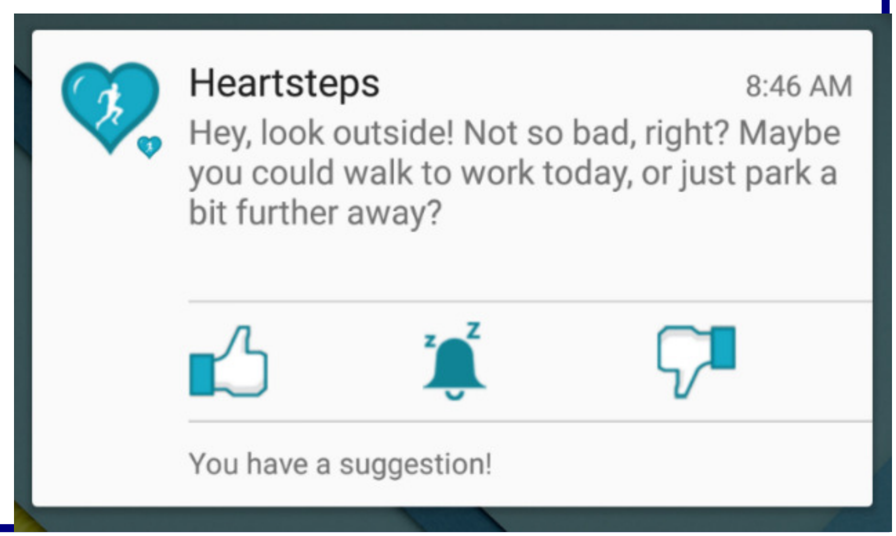
Pushes

- Activity planning for following day (each evening)
- In the moment tailored activity suggestions (5 pre-specified times per day)

Heartsteps

Pushes

1) Types of treatments that can be provided at a decision point, *t*
2) Whether to provide a treatment



Heartsteps

V2 study; 90 days

Observations

- Commercial wearable wrist band (data each minute); Smartphone sensor data(6 times per day); Daily self-report

Pushes

- 2x2 Factorial for morning greeting (each morning)
- Anti-sedentary message (at 5 min. intervals during day & only if sedentary over prior 30 minutes)
- Activity suggestions (5 pre-specified times per day)
- Evening greeting (each evening)

Sense^2 STOP

10 days

Observations

- Investigational wearable wrist and chest bands (data output< 1 second intervals); Self-report (6 times/day)

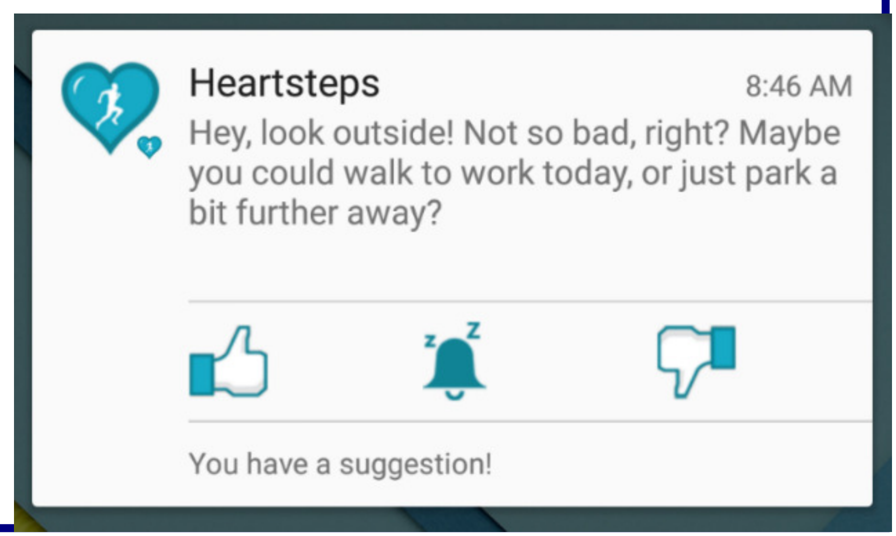
Pushes

- Reminder to utilize app directed stress-management exercises (every minute of 10 hour day & only if a stress classification is possible)

Availability

Treatments can only be delivered at a time t if an individual is *available*.

Treatment effects at a decision point are conditional on availability.



Goal

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Micro-Randomized Trial

On each participant and at each decision point, t, randomize between treatment actions, a

Pre-specified algorithm for the randomization probability:

$$P[A_t=a|\ H_t,\ I_t=1]$$

- $I_t=1$ if available, $I_t=0$ if not
- H_t denotes data on participant through t

Some Challenges

- Experimental design → the formula for the randomization probabilities, $P[A_t=1 | H_t, I_t=1]$
  - All tuning parameters, entire trial protocol must be pre-specified prior to study
- The choice of proximal response, aka "reward."
- Non-stationarity
- Need for multiple, interacting, treatment policies

Randomization

Heartsteps V1 activity suggestion

- Team decides to provide an average of 3 tailored activity suggestions per day (5 opportunities per day)
- Binary $a=0,1$

$$P[A_t=1 \mid H_t, I_t=1]=.6$$

Randomization

Heartsteps V2 anti-sedentary message

- Randomize only if user has been sedentary for ≥ 30 min. Team decides approximately 1.5 messages per day.
- Using Heartsteps V1 data, built algorithm to predict, at each time point, the mean and variance of the number of remaining available, sedentary, decision times in day.
- Randomization probabilities use these predictions.

Randomization

Sense^{2}Stop reminder

- Team decides approximately 1.5 reminders per day when currently stressed & 1.5 reminders per day when currently not-stressed.
- Using data from another smoking study (with no intervention), built algorithm based on a simple Markovian model to predict, at each time point, number of remaining available stressed and non-stressed episodes in day.
- Randomization probabilities use this prediction.

Randomization

Heartsteps V2 tailored activity suggestion

- Use a "Thompson Sampling Contextual Bandit" algorithm to randomize at each of 5 decision times per day.
- Thompson Sampling prior is based on Heartsteps V1 data.

Assess feasibility of algorithm

Randomization

Enhance Feasibility of Contextual Bandit Algorithm:

- Randomization probabilities from Thompson Sampling are clipped between .10 and .80
- How to select the proximal response (reward)—not just stepcount….

Proximal Response (Reward)

<u>For analyses conducted after study ends:</u>

Each type of push designed to operate on a different time scale

- Heartsteps activity suggestion
  – Stepcount over 30 min. following randomization
- Heartsteps V2 anti-sedentary message
  – Stepcount or heartrate over next 5 (?) min. following randomization

Proximal Response (Reward)

In different settings push is expected to operate on different time scales

- Sense^{2}Stop reminder
  - % time stressed over subsequent hour if currently stressed
  - % time stressed over subsequent 4 hours if currently not stressed

Non-stationarity: Heartsteps V1

On each of *n=37* participants:

- Tailored activity suggestion
  - **Provide a suggestion with probability .6**
  - **Do nothing with probability=.4**

- 5 times per day * 42 days= 210 randomizations per participant

Non-stationarity; Heartsteps V1

The data indicates that there is a causal effect of the activity suggestion vs no activity suggestion on step count in the succeeding 30 minutes.

- This effect deteriorates with time
- The walking activity suggestion initially increases step count over succeeding 30 minutes by $\approx$ 171 steps but by day 21 this increase is only $\approx$ 35 steps.

Non-stationarity; Heartsteps V1

The deteriorating effect of the walking activity suggestion on the subsequent 30 min. stepcount may be due to

- Habituation
- Burden

(e.g. unobserved/poorly observed variables)

Multiple Treatment Policies

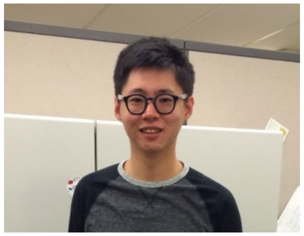
Multiple causal pathways → need to learn multiple interacting treatment policies

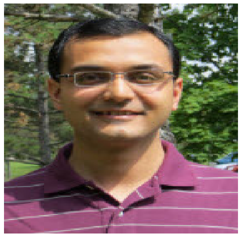
- Treatment pushes and responses at weekly, daily, hourly, minute level time scales
- Engagement pushes

Last Comments

- Reinforcement learning involves learning causal inferences
- Randomization enables causal inferences based on minimal structural assumptions
- Theory for tracking in reinforcement learning

Collaborators!





Conceptual Models

$$Y_{t+1} \text{ “}\sim\text{” } \alpha_0 + \alpha_1 Z_t + \beta_0 A_t$$

$$Y_{t+1} \text{ “}\sim\text{” } \alpha_0 + \alpha_1 Z_t + \alpha_2 d_t + \beta_0 A_t + \beta_1 A_t d_t$$

- $t=1,\ldots T=210$
- Y_{t+1} = log-transformed step count in the 30 minutes *after* the t^{th} decision point,
- $A_t = 1$ if an activity suggestion is delivered at the t^{th} decision point; $A_t = 0$, otherwise,
- Z_t = log-transformed step count in the 30 minutes *prior* to the t^{th} decision point,
- d_t =days in study; takes values in (0,1,….,41)

Pilot Study Analysis

$$Y_{t+1} \text{ “}{\sim}\text{” } \alpha_0 + \alpha_1 Z_t + \beta_0 A_t \text{, and}$$

$$Y_{t+1} \text{ “}{\sim}\text{” } \alpha_0 + \alpha_1 Z_t + \alpha_2 d_t + \beta_0 A_t + \beta_1 A_t d_t$$

Causal Effect Term	**Estimate**	**95% CI**	**p-value**
$\beta_0 A_t$ *(effect of an activity suggestion)*	$\hat{\beta}_0$=.13	(-0.01, 0.27)	.06
$\beta_0 A_t + \beta_1 A_t d_t$ *(time trend in effect of an activity suggestion)*	$\hat{\beta}_0$ = .51 $\hat{\beta}_1$ = -.02	(.20, .81) (-.03, -.01)	<.01 <.01

Heartsteps

Goal: Develop an mobile activity coach for individuals who have coronary artery disease

Three iterative studies:

- 42 day micro-randomized pilot study with sedentary individuals,
- 90 day micro-randomized & personalized study,
- 365 day personalized study

Continually Learning Mobile Health Intervention

1) Trial Designs: Are there effects of the actions on the proximal response? *experimental design*

2) Data Analytics for use with trial data: Do effects vary by the user's internal/external context,? Are there delayed effects of the actions? causal inference

3) Learning Algorithms for use with trial data: Construct a "warm-start" treatment policy. *batch Reinforcement Learning*

4) Online Algorithms that personalize and continually update the mHealth Intervention. *online Reinforcement Learning*