Explanatory and Predictive Models for mHealth

Peter Pirolli
Why Model?
Why model?

• Understanding and insight

• Develop new analytic tools and methods

• Predict impact of new technology, interventions, interaction techniques

• Develop new design principles

• Predict the effects of specific interventions for specific people
Motivating Example
Problem: Lifestyle Change (Behavior Change)
Solutions exist, but do not scale.
Example: Kaiser Permanente Hawaii

- Very successful weight loss programs (81% lose weight)
- Long-term maintenance problem
- Bottleneck in servicing members
- Geography
Multi-Part Dashboard

**PARC NutriWalking**

Week 7

*You*  
ASC Dev

---

**fittleBot posted:**

New this week (Week 7):
Almost there! In addition to having another healthy meal or snack in your daily eating, this week start to write down what you eat for breakfast. You’ll be adding a few body weight exercises to your walking: 45 minutes, five times this week.

2 hours ago

---

**fittleBot posted:**

Tip of the Day (Week 6, Day 7):
Changing your relationship with foods does not mean that you put certain foods off limits. If you’re like many people, you likely have a few foods that you avoid for fear of cannibalism. Try replacing the mental block on these foods with a new positive relationship.

---

**Walk with exercises 45 minutes**

Incorporate body weight exercises into your walk. (See info cards for details.)

- **Nope**
- **Almost**
- **Did it**

Report how your goal "Walk with exercises 45 minutes" went today.

---

**Select different activity**

Incorporate body weight exercises into your walk.

- **Walk with exercises 45 minutes**
- **Stretch 10 minutes**

---

**fittleBot posted:**

New this week (Week 7):
Bodyweight exercises are a simple, effective way to improve balance, flexibility, and strength without machinery or extra equipment. Turn this card over for more details.

Rating: ★★★★★

How to get started:

Lie face up on the ground and place your hands behind your head, lightly supporting it with your fingers.

Bring the knees in to the chest and lift the shoulder blades off the floor without pulling on the neck.

Rotate to the left, bringing the right elbow towards the left knee as you straighten the
Experiment: Fittle Supporting Groups Engaged in Behavior Change Challenges

- 8 weeks
- Two professionally designed challenges
- \( N = 19 \) participants
- Ages 23-77 (mean = 43)
- Diverse ethnicity and jobs (researchers, managers, engineers, admin staff...)

Results Summary

- Fittle effect sizes \( d = 1.0 \) means a 1 standard deviation improvement
  - Reduced stress: \( d = 0.61 \)
  - Healthy eating: \( d = 0.85 \)
  - Physical activity: \( d = 0.91 \)
  - 12/19 lost weight

- Comparable to superiority of mastery learning in educational research \( d = 0.66 \)

- Differences among teams accounted for 41% of the variance
Bigger Effects?

- Fittle effect sizes \[d = 1.0\] means a 1 standard deviation improvement
  - Reduced stress: \[d = 0.61\]
  - Healthy eating: \[d = 0.85\]
  - Physical activity: \[d = 0.91\]
  - 12/19 lost weight

- Comparable to superiority of \textit{mastery learning} in educational research \([d = 0.66]\)

- Differences among teams accounted for 41% of the variance

**Hypothesis:**
\textit{Even bigger impact if we can create automated intelligent coaching!}
Type of Models
Types

- Predictive vs Explanatory

- Static vs Dynamical

- Stochastic vs non-Stochastic

- Techniques
  - Linear models, Bayesian Machine Learning, neural networks, Support Vector Machines, Deep Learning….
  - Dynamical Control Theory, agent-based models, cognitive models…
# Levels of Explanation

<table>
<thead>
<tr>
<th>Scale</th>
<th>Time Unit</th>
<th>Band</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^7$ s</td>
<td>Months</td>
<td>Social</td>
</tr>
<tr>
<td>$10^6$ s</td>
<td>Weeks</td>
<td></td>
</tr>
<tr>
<td>$10^5$ s</td>
<td>Days</td>
<td></td>
</tr>
<tr>
<td>$10^4$ s</td>
<td>Hours</td>
<td>Rational</td>
</tr>
<tr>
<td>$10^3$ s</td>
<td>10 min</td>
<td></td>
</tr>
<tr>
<td>$10^2$ s</td>
<td>Minutes</td>
<td></td>
</tr>
<tr>
<td>$10^1$ s</td>
<td>10 seconds</td>
<td></td>
</tr>
<tr>
<td>$10^0$ s</td>
<td>Seconds</td>
<td>Psychological</td>
</tr>
<tr>
<td>$10^{-1}$ s</td>
<td>100 msec</td>
<td>Biological</td>
</tr>
<tr>
<td>$10^{-2}$ s</td>
<td>10 msec</td>
<td></td>
</tr>
</tbody>
</table>

Source: Allen Newell (1990) *Unified Theories of Cognition*
Levels of Prediction (Self-Efficacy Model)

Physical Modeling and Coaching
Physical Model: Banister Impulse-Response Model

- Purpose:
  - Predict training effects
  - Maximize Training schedules

- “Impulses” of training have both positive and negative effects on “response” (performance)

Mathematical equations:

\[ p_t = p_0 + k_a \sum_{s=0}^{t-1} e^{-(t-s)/\tau_a}w_s - k_f \sum_{s=0}^{t-1} e^{-(t-s)/\tau_f}w_s \]

- Positive > Negative Gain

Diagram:

- Performance
- Starting Performance
- Positive Gain
- Decay
- “Stress”
- Endurance Training
- FATIQUE
- Fitness
- Fatigue
- Performance
Model-based Predictions & Personal Training

Source: iTRIMP

NutriWalking Overview

Dashboard

Goal Reporting

Question Answering

Daily goals

Weekly goal progress

Team feed

How many days a week do you play vigorous sports? How much time do you usually play in a day?

How many days a week do you usually do aerobic fitness activity? What is the typical time you spend doing an aerobic activity in a day?

How many days a week do you usually do flexibility activities? What is the typical time you spend doing a flexibility activity in a day?

How many days a week do you usually walk? What is the typical time you spend walking in a day?

Pick a walking goal for the first week:
- 25 minutes, 3 times a week
- 20 minutes, 3 times a week
- 15 minutes, 3 times a week

Fit a uniform step trajectory to long-term goal

Determine long-term goal: AHA

Estimate pre-intervention activity level

Daily Reporting & Rescheduling

I see that you didn’t do your walk today. Did you remember to do it?
How hard the activity was for you?
How difficult was it for you to fit it in your schedule?

Pick activities for a 7 day horizon
Reschedule & pick activities for 7 day horizon

Model Revision: regress

Observe behavior
Access user’s reasons (too hard)
Determine ‘regress’ trajectory.

Model Revision: progress

Observe behavior
Access user’s reasons (too easy)
Determine ‘progress’ trajectory.

Psychological Modeling and Coaching
Self-efficacy

• Belief in capacity to execute behaviors

• Interventions
  - Guided Enactive Mastery
  - Selective Self-monitoring
  - Vicarious Experience
  - .....
Dynamical Systems Model of Self-efficacy
(Martin, Rivera, Riley, Hekler, Buman, Adams, & King, 2014)

• Control systems model based on a fluid analogy
  - One has an “inventory” of self-efficacy that can increase or decrease in ways that depend on various inputs (e.g., social support; performing the target behavior)

• Built to address self-efficacy in relation to physical activity

There is an “inventory” of self-efficacy that can change over time.
Self-efficacy affects behavior

Increases in behavior can increase self-efficacy.
Perceived social support can be an input...
...that increases or decreases self-efficacy
Perceived barriers or obstacles can be another input....

...that increases/decreases self-efficacy
Computational Neurocognitive Theory (ACT-R)

Social Cognitive Theory

Self-Efficacy → Intention → Behavior

Redefine a “macro” theory of behavior change...

ACT-R

Redefine a “macro” theory of behavior change...

...into a finer-grained computational simulation
• A theory of the structure of the brain and the functioning of the mind

• A software simulation environment

• How brain modules (goal, memory, perception,...) operate dynamically over time in producing behavior
\[ E = PG - C \]

**Expected Gain Equation**

\[ A_i = B_i + \sum_j W_j S_{ji} \]

**Activation Equation**

\[ B_i = \ln \sum_{j=1}^{n} t_j^{-d} \]

**Base-Level Learning Equation**

\[ S_{ji} = \ln \frac{a \cdot R_{ji} + F(C_j) \cdot E_{ji}}{a + F(C_j)} \]

**Posterior Strength Equation**

\[ P = \frac{1}{1 + e^{\frac{M_{ip} - \tau}{\sigma}}} \]

**Retrieval Probability Equation**

\[ T_{ip} = F e^{-f M_{ip}} \]

**Retrieval Time Equation**

\[ P(i) = \frac{e^{M_{ip}/t}}{\sum_j e^{M_{jp}/t}} \]

**Chunk Choice Equation**

\[ M_{ip} = A_i - MP \cdot \sum_{conditions} (1 - Sim(v, d)) \]

**Match Equation**

\[ V = \min \sum_i P_i (1 - Sim(V, V_i))^2 \]

**Memory Blending**

**ACT-R**

- Declarative
  - Goal
  - Retrieval
- Production
  - Vocal
  - Imaginal
  - Manual
  - Aural
  - Visual
  - Visual Location
- Behavior
“System 1/System 2”

Mastering your inner elephant

System 2
Explicit

System 1
Implicit

ACT-R

Subsymbolic Dynamics

Expected Gain Equation

 Activation Equation

Base-Level Learning Equation

Posterior Strength Equation

Retrieval Probability Equation

Retrieval Time Equation

Chunk Choice Equation

Memory Blending

\[ E = PG - C \]
\[ A_i = B_i + \sum_j W_{ij} S_j \]
\[ B_i = \ln \sum_j e^{a_i} \]
\[ S_{ji} = \ln \left( \frac{a - B_i^j + F(C_j) \cdot E_{ji}}{a + F(C_j)} \right) \]

\[ P = \frac{1}{1 + e^{-x}} \]

\[ T_{retrieval} = Fe^{-\frac{1}{M_{ret}}} \]

\[ P(i) = \frac{\sum_{j} e^{M_{.par}(i,j)}}{\sum_{j} e^{M_{ret}(i,j)}} \]

\[ M_{ret} = A_i - MP \cdot \sum_{conditions} (1 - Sim(c, d)) \]

\[ V = \min \sum P_i (1 - Sim(V, V_i))^2 \]
Testing the Model in a Study of DStress: Stress Reduction through Exercise & Meditation

Hello, John.
Here are today's activities:

- Kneeling Plank
- Cruncbes
- Static Lunge With Wall

Program Overview

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Completion</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-Mar</td>
<td>Kneeling Plank</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Crunches</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Static Lunge</td>
<td>Did not do it</td>
<td>Gym</td>
</tr>
<tr>
<td>18-Mar</td>
<td>Meditation</td>
<td>Started</td>
<td>Anywhere</td>
</tr>
</tbody>
</table>
DStress: Stress Reduction through Exercise & Meditation

46 Exercises

Upper body, lower body, circuit
DStress: Stress Reduction through Exercise & Meditation

Hello, John.
Here are today's activities:

- Kneeling Plank
- Crunches
- Static Lunge With Wall

Program Overview

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Completion</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-Mar</td>
<td>Kneeling Plank</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Crunches</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>18-Mar</td>
<td>Meditation</td>
<td>Started</td>
<td>Anywhere</td>
</tr>
</tbody>
</table>
DStress: Stress Reduction through Exercise & Meditation

Hello, John.
Here are today's activities:

- Kneeling Plank
- Crunches
- Static Lunge With Wall

Program Overview

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Completion</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-Mar</td>
<td>Kneeling Plank</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Crunches</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Static Lunge</td>
<td>Did not do</td>
<td>Gym</td>
</tr>
<tr>
<td>18-Mar</td>
<td>Meditation</td>
<td>Started</td>
<td>Anywhere</td>
</tr>
</tbody>
</table>
DStress:
Stress Reduction through Exercise & Meditation

Hello, John.
Here are today's activities:

- Kneeling Plank
- Crunches
- Static Lunge With Wall

Program Overview

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity</th>
<th>Completion</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>19-Mar</td>
<td>Kneeling Plank</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Crunches</td>
<td>Did it</td>
<td>Gym</td>
</tr>
<tr>
<td>19-Mar</td>
<td>Static Lunge</td>
<td>Did not do</td>
<td>Gym</td>
</tr>
<tr>
<td>18-Mar</td>
<td>Meditation</td>
<td>Started</td>
<td>Anywhere</td>
</tr>
</tbody>
</table>

Activity Report

Hello, Artie1.
You may report your activities for 09-02-2013 here. Thanks!

It's best that these exercises are done at the gym.

Did you get to the gym today?
- Yes
- No

Crunches
- I completed 2 sets of this exercise
- I started but didn't finish
- I didn't start the 2 sets
DStress Study

\[ N = 65 \text{ (42 Female)} \\
\text{Aged 19-59 (} M = 31 \text{)} \]

Difficult - Fixed Schedule

Adaptive Schedule

Easy - Fixed Schedule

The DStress Study

Activity Pool

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>name</td>
<td>type</td>
<td>difficulty</td>
</tr>
<tr>
<td>2</td>
<td>Pushups-off-wall</td>
<td>upper-body</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Kneeling-Plank</td>
<td>upper-body</td>
<td>2.25</td>
</tr>
<tr>
<td>4</td>
<td>Dumbbell-Kneeling-Row</td>
<td>upper-body</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>Push-ups-on-Smith-machine-bar</td>
<td>upper-body</td>
<td>2.625</td>
</tr>
<tr>
<td>6</td>
<td>Half-Kneeling-Row-with-Resistance-Band</td>
<td>upper-body</td>
<td>3.25</td>
</tr>
<tr>
<td>7</td>
<td>Standing-Band-Chest-Press</td>
<td>upper-body</td>
<td>3.5</td>
</tr>
<tr>
<td>8</td>
<td>High-plank</td>
<td>upper-body</td>
<td>4.875</td>
</tr>
<tr>
<td>9</td>
<td>Dumbbell-Vertical-Chest-Press</td>
<td>upper-body</td>
<td>5.25</td>
</tr>
<tr>
<td>10</td>
<td>Dumbbell-chest-supported-row</td>
<td>upper-body</td>
<td>5.5</td>
</tr>
<tr>
<td>12</td>
<td>Jumping-jack-pushup-legs-widen-only</td>
<td>upper-body</td>
<td>7.5</td>
</tr>
<tr>
<td>13</td>
<td>Renegade-row-with-weights</td>
<td>upper-body</td>
<td>7.5</td>
</tr>
<tr>
<td>14</td>
<td>crunches</td>
<td>Circuit</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>March-in-place</td>
<td>Circuit</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Participants assigned to different exercise schedules

- **Easy** - fixed schedule
- **Difficult** - fixed schedule
- **BabySteps** - adaptive schedule
Rasch Measurement Model

\[
Pr(X_{ij} = 1) = \frac{\exp(\theta_i - \delta_j)}{1 + \exp(\theta_i - \delta_j)}
\]
Estimated Exercise Difficulties & Person Abilities

Average Expert Rating of Difficulty

Estimated Difficulty

Ability $\theta$

Difficulty $\delta$

$\text{r} = 0.72$
Adjustable (Personalized) Schedules of Behavioral Goals Achieve Higher Compliance
Intuitions Behind a Self-Efficacy/Motivation Model

- I’m considering the **goal** to do a set of activities $A$ that I believe have some difficulty $\delta_g$

- Call upon **memory**: What have I done that is **similar to** $A$ & what was the maximum difficulty $\delta_E$ of those past experiences?

- **Perceived self-efficacy**: Based on the difficulty $\delta_E$ of my successful past experiences, I believe my ability is $\theta_E$

- I **predict my goal success** to be based on the relation between my perceived self-efficacy and the difficulty of the activity
Goals and Memory Chunks in ACT-R

**Goal**

GOAL-35
ISA BEHAVIOR-GOAL
BEHAVIOR STATIC_LUNGE_WITH_WALL
DIFFICULTY -0.5437191
ABILITY NIL
MOTIVATION NIL
UTILITY 1

**Memory**

BEHAVIOR-EXPERIENCE100-0
ISA BEHAVIOR-EXPERIENCE
BEHAVIOR MARCHING_IN_PLACE
DIFFICULTY -0.013206851
ABILITY 0.025988732
MOTIVATION 0.242358
UTILITY 1.0
OUTCOME SUCCESS

BEHAVIOR-EXPERIENCE5-0
ISA BEHAVIOR-EXPERIENCE
BEHAVIOR PUSHUPS_OFF_WALL
DIFFICULTY -1.037143
ABILITY -1.0252459
MOTIVATION 0.23818936
UTILITY 1
OUTCOME SUCCESS
If Self-efficacy is a Memory Phenomenon: What Might we Predict?

- Positive experiences are “impulses” of positive benefits. Impulses decay with time.

  - Frequency effects
    - I’ve gone to the gym every day for 20 years, I’m confident I can do it today.

  - Recency (lag) effects
    - I can’t remember the last time I lifted weights, I’m not confident I can do it today.

- “Stress” (or “stretch”) effects.
  - I remember I surfed a 20 ft wave (3x my normal!). I’m confident I can do more than I usually do.
Signature Phenomena
DStress Data Exhibit Signature Phenomena

![Graphs showing data exhibit signature phenomena](image)

- **Frequency (days)** vs. **Success**: The graph shows a positive linear relationship between frequency and success, with success increasing as frequency increases.
- **Lag (days)** vs. **Success**: This graph displays a negative linear relationship, indicating that success decreases as the lag increases.
- **Last Stress (logits)** vs. **Success**: Here, the relationship appears to be positive, with success increasing as the last stress (in logits) increases.

These graphs illustrate the trends observed in the DStress data exhibit, highlighting the signature phenomena across different variables.
Fit of ACT-R-Based Model to 28-day DStress mHealth
Concluding Thoughts

• (Echoing Donna): Emerging technologies provide rich, granular data to transform vague, static theories into precise dynamical models that can serve as a foundation for precise (individualized) behavioral interventions

• Integration. Integrated models can provide unified accounts of how all the relevant psychological and physical factors work together to predict behavior

• Decomposition. Long-term behavior change over weeks and years can be decomposed into events occupying briefer units of time and experience. Models can bridge predictions over those different levels.

• Adaptive Intervention. Short- and long-term outcomes/effects predicted by models can be used to optimize specific interventions for specific individuals in specific contexts at specific times

• Generativity. Models lead to new theories that lead to innovative interventions
Thanks

- Shane Ahern
- Victoria Bellotti
- Nicole Crenshaw
- Hong Du
- Jacqui LeBlanc
- Pai Liu
- Artie Konrad
- Les Nelson
- Shiwali Mohan
- Ashwin Ram
- Jonathan Rubin
- Frank Rolek
- Michael Silva
- Simon Tucker
- Anusha Venkatakrishnan
- Jesse Vig
- Steve Whittaker
- Rong Yang
- Michael Youngblood