

InterventionViz: Visual Analysis of Behavior-Change Intervention Dynamics

Category: Research

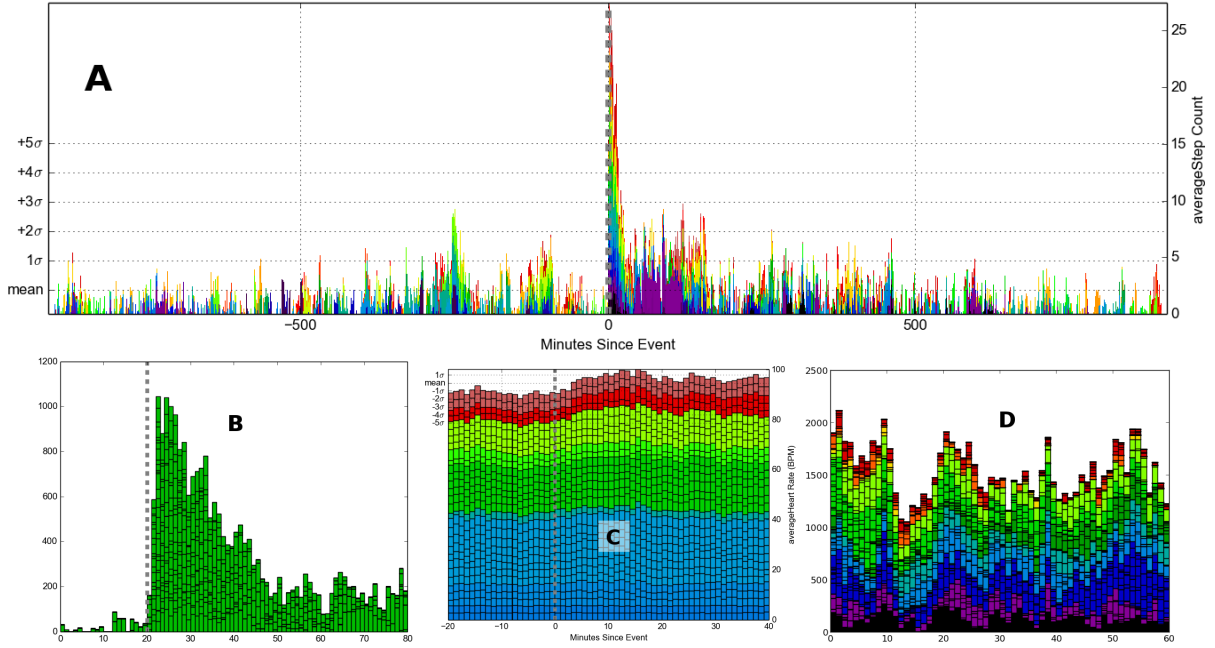


Fig. 1. TODO: label subfigs A,B,C,D. A) Aggregated step counts surrounding an intervention event shows event response dynamics and individual variations across events. TODO: color by events and make shorter B) Aggregation of step counts showing dramatic response to the the control intervention. C) Heart rate data aggregated across KnowMe participants shows a mild response to an SMS intervention. D) Aggregated step counts of subjects briefly exposed to an active mAvatar shows little trend. TODO: reference B,C,D from text

Abstract— With the advent of research-grade wearable sensor suites and increasingly ubiquitous human-computer interface comes the opportunity for a new generation of behavioral theory and behavior change methodologies. Just-in-time interventions (JITIs) designed to optimize a subjects behavior based on their momentary context are under exploration as a potentially powerful ally for practitioners and commercial behavior health applications. Analysis of the effect an intervention has on a target behavior, however, is a complex task not well handled by current methods.

In this work we explore the application of aggregated time-series visualization techniques to aid analysis of intervention event effects with emphasis on the dynamics of participant response to intervention. To highlight the strengths and caveats of the techniques employed, data from two trial studies of physical activity interventions ($n=11$, $n=10$) and one empirical control dataset ($n=1$) are utilized. The insights presented in this work offer a foundation for future visualization research addressing this problem and as a guide for behavioral scientists in need of more novel methods of analysis.

Index Terms—Visualization in Social and Information Sciences, Hypothesis Testing, Visual Evidence, Time Series Data, Qualitative Evaluation, Biomedical and Medical Visualization

1 INTRODUCTION

1.1 Motivation

1.1.1 Why Health Interventions?

Despite significant advances in the theory and practice of behavioral science, humans continue make poor behavioral choices on a daily basis, and the reasons for those choices remain, to some extent, uncharted. The consequences of these daily choices are often insignificant in the moment but over time build up to larger individual and societal problems. In fact, many of today's greatest health challenges can be mapped back to individual behavioral choices. A habitual lack of physical activity, poor diet, and smoking is likely to lead to a variety of health problems (e.g., obesity, diabetes, heart disease, cancer, chronic pain, depression), lower quality of life and shortened lifespans [13, 9, 44, 33]. Smoking and lack of exercise are behaviors that clearly affect health and longevity (by increasing the chance of getting cancer, or decreasing the chance of obesity and diabetes), but the general populace seems to lack power over their own habits. Similar challenges exist outside the realm of personal health. Academic success is a function of attending class and completing assigned tasks, among other daily behaviors[6]. In personal finance, poor day-to-day purchasing decisions can add up to large financial debts[26].

Behavior change is the art and science of facilitating adoption of new behaviors or abandoning of old behaviors. Behavior change interventions are particularly important to modern health care systems in developed countries, where preventative behavioral treatment receives little attention from health care practitioners.

1.1.2 Why Do Intervention Dynamics Matter?

The confluence of pervasive sensing, machine learning, network access, and computation facilitates new approaches to guiding behavioral choices. These systems can detect behaviors and psychological states such as stress[3, 24], physical activity[23, 11], social interaction[43], and smoking[34], automatically and, in some cases, in real-time. These data provide new opportunities for the human-computer interaction (HCI), behavioral science, and other related communities to develop user interfaces for mobile behavioral interventions that help users make better in the moment behavioral choices related to health[22, 25], productivity[20, 35, 21], personal finance[14], and environmental stewardship.[10] New methods for evaluating these behavioral interventions remain underexplored and conventional methods of analysis do not offer the level of detail needed to explore the implicit dynamics of just-in-time, interactive, or adaptive interventions.

1.1.3 Contributions

In addition to metrics of success of an intervention, behavioral theorists need tools to help understand the dynamics of behavioral responses to a stimulus. Due to the lack of a dynamical treatment of behavior within theories, existing models behavior appear inadequate to inform state-of-the-art intervention development [32]. Applicable methods of intervention analysis [?] and data visualization have been slow to reach behavioral researchers, dramatically limiting their ability to develop of state-of-the-art behavioral theories to address these shortcomings.

In order to help bridge the gap between state-of-the-art data analysis and behavioral research, in this paper we present methods for exploring the dynamical responses of behavior-change intervention events built on a foundation of user-driven design principles. Through a survey of 11 behavioral scientists and countless consultations with domain experts on the cutting edge of behavioral intervention design, we have identified and attempted to address a set of goals and key tasks which are of special interest to researchers in this area.

In this paper we present:

1. a set of design considerations to guide visualization and tool design in this domain
2. introduction to intervention response dynamics in relation to developing theories

3. visualization methods which address some key tasks addressing the goals identified in the design considerations section

This work breaks new ground in the application domain, but also provides guidelines for future work bridging the data visualization and behavioral science communities.

2 PREVIOUS WORK

2.1 Related Event-based Time Series Visualization

"Lifelines" [31] allow for the exploration of events in a series for one individual, and new research in event sequence analysis [42], including analysis of event patterns [41, 12, 39] and the relation of multiple symptoms [40] helps researchers examine outcomes on a "macro-scale" across many subjects by aggregating records into a single view. Additionally, the problem of identifying patterns at multiple time scales has been partially addressed through clustering of time series [38], and methods for exploring the "paths" traversed by many individuals between many event types and statistical analyses to highlight relationships between events has recently been established [18].

To our knowledge, little existing work addresses the dynamics of a numerical variable's response to a behavioral intervention event. Statistical methods of intervention analysis [1], have been applied across various disciplines but thus far there has been little demand for these methods in behavioral science. Only recently has new wearable sensing technology made time-intensive, in-the-wild measurements feasible. Additionally, the prospect of ubiquitous intervention delivery via mobile devices and the concept of Just-in-Time-Adaptive-Interventions (JITAI) have introduced a new demand for a more detailed understanding of human behavior.

2.2 Current Intervention Methods

Recent advances in sensing and ubiquitous computing are enabling examination of and influence over behavior at small time scales (on the order of seconds) and in a wide range of daily life contexts. New wearable sensing technologies are changing the way we do experiments, and mobile phones are a powerful new medium for delivering behavioral interventions "just-in-time".

Recent works have explored "adaptive interventions" tailored based on "tailoring variables" which may include user preferences, context, and personality [4]. Methods for evaluating adaptive interventions are in many ways similar to "fixed" interventions [4], and the use of the multiphase optimization strategy (MOST) and sequential multiple assignment randomized trials (SMART) [5] maximize efficiency in applying these methods. These methods become more difficult to apply, however, when dealing with Just in Time Adaptive Interventions (JITAI).

Existing work on visual analysis of systems usability [19] may be applied to the evaluation of JITAI systems, however, these methods focus largely on a single record, rather than generalizations drawn from across many. Additionally, little theoretical guidance in terms of effect latency or delay exists to aid in the planning or analysis of experimental trials.

A theoretical basis which takes dynamical effects into consideration to enable improved behavioral intervention optimization has been proposed for interventions mediating gestational weight gain [8], smoking behavior [37], childhood anxiety [30], and fibromyalgia [7]. This new type of theoretical model is most effective on the timescale of multiple days, weeks, or months - partially because the confounds of contextual, within-day variations make analysis at this level difficult, but mostly because theories of behavior at this time scale are underdeveloped. Methods for analyzing the dynamics of intervention responses using existing data are needed in order to catalyze the development of theories to explain these signals.

3 DESIGN CONSIDERATIONS

Many of the research questions faced by JiTAI developers are similar to those of fixed interventions. Researchers primary concerns remain centered around assessment of an intervention's ability to effect the target behavior. Assessments are similarly judged by their reliability and validity, and good study design remains central to a good validation of intervention efficacy.

In addition to those existing, new challenges unique to JiTAI design and analysis must be addressed. As interventions grow in their abilities to adapt, the search space of the problem grows exponentially. Each additional "tailoring variable" or parameter added makes strictly empirical methods unfeasible. Furthermore, theoretical models of behavior at the small timescales applicable to JiTAIs are underdeveloped and largely unsupported by empirical data.

Though research questions remain the same, the additional challenges introduced in JiTAI design suggest that more detailed analysis and modeling methods may be appropriate. Predictive modeling of behavior would allow for JiTAIs to optimize interventions based on quantitative, personalized models. In order to enable development of these models, data visualization methods for exploring intervention effect over time and across participants are needed.

When asked about the biggest hurdle blocking simulation and modeling from breaking into behavioral science, a majority of responders cited the need for better tools and collaboration to improve their understanding of the techniques. In order to facilitate development of these tools, we present a set of design considerations that have been developed based on many iterations of user-driven discussions to identify 1) common goals of an intervention efficacy analysis, 2) the key analysis tasks which need to be enabled or improved, 3) typical characteristics of intervention datasets, and 4) weaknesses in current methodologies.

3.1 User Goals

In this section we define the primary goals of a behavior-change intervention researcher looking to apply JiTAIs. These goals have been developed through an extensive literature review, a survey of 11 behavioral scientists interested in applying modeling and simulation to their work, and close collaboration with domain experts.

3.1.1 Assess Intervention Effectiveness

First and foremost researchers are interested in showing that their intervention was effective. T-tests and p-values - despite their shortcomings [27] - have long dominated this domain, so researchers are looking for equally succinct indicators of success. The nature of highly-personalized, context-dependent, and rapidly-optimized JiTAIs makes these analyses difficult for specific interventions, and thus researchers have been limited to testing over larger time-scales - comparing intervention-on vs control days, for instance.

In addition to the gauged effectiveness of an intervention, behavioral researchers wish to understand the limits on intervention "dosage" for each participant before they drop out of the program or stop engaging with the intervention. This metric is often referred to as the "tolerability" of the intervention. In order to maximize the effectiveness of a behavioral intervention, researchers want to optimize the dose so that the intervention pushes the subject as much as possible, while still staying within a tolerable range for the subject. In order to meet the desire to explore tolerability analysis, methods fall somewhere between drug-dosage tolerability and analysis of user drop-out rate in a software system.

3.1.2 Characterize Intervention Response

Second only to measuring the efficacy of an intervention, the second goal of the behavioral researcher is to characterize how the intervention works. Multiple behavioral intervention reviews have shown that interventions explicitly based on psychological theory are more effective [15]. Though there is clear motive to use existing theory as a guide for intervention design, behavioral theories cannot answer many of the questions being raised by JiTAI designers [32].

Little research exists on the dynamics of intervention response, so it is not clear what amount of time must be measured after intervention

delivery in order to record the effect. For within-subject comparison, is one day of each condition long enough? - or perhaps the effect can last many days? Researchers need a more detailed understanding of the dynamics of intervention response in order to plan experiments to ensure that various experimental conditions do not overlap and confound each other in within-subject studies. Furthermore, the optimization of intervention delivery is a highly context-dependent problem which can greatly benefit from an increased understanding of user state over time.

3.1.3 Response and Effectiveness vs Subgroups

Another goal of the behavioral researcher is to characterize how differences among individuals, sub-groups, and contexts affect effectiveness and dynamics of response. Subgroup analysis allows for existing theories to grow in complexity through incorporation of new conditions.

3.1.4 hypothesis generation

It is out of the focused exploration of subgroupings from an experiment that researchers often identify new ideas for future experimentation. Similarly, through detailed analysis of subgroups based on intervention context come ideas for future interventions. Researchers desire the ability to explore these subgroups through focused inspection, but they also wish to leverage automated or guided analysis in order to aid in identification of new hypotheses worth testing.

3.2 Characteristics of Intervention Datasets

Behavioral scientists with data-overload are becoming increasingly common as wearable sensors increase in popularity. There no doubt exist many under-utilized datasets with novel contributions to theory waiting to be discovered.

Common features of contemporary behavioral research dataset include:

- Multiple time-scales - may types of data also means measurement at many different frequencies
- crossover designs - within-subject comparison is the preferred method for gauging efficacy of an intervention
- high-frequency numerical measures - Accelerometers, ECG, GPS, and much more
- numerical measures with low frequency - Ecological Momentary Assessment (EMA) constructs, blood-draws
- contextual, nominal data at various frequencies - activity classification, location classification, social contexts

4 EXAMPLE APPLICATION: PHYSICAL ACTIVITY

As an example application to demonstrate the strengths of the proposed visual analytics we analyze two empirical datasets with a minute-level metric of physical activity level and intervention events delivered throughout a period of 28 days. In both studies interventions were delivered with the intent of increasing subjects physical activity, and responses to interventions varied between participants and delivery contexts. In addition to this data, a control dataset with known intervention responses is included for comparison.

These datasets provide a good test bed for application of the visualization methods presented here. Measurement of physical activity (PA) is a well-studied topic, and many interventions focus on increasing physical activity. At the same time, the cognitive processes surrounding physical activity are familiar to most researchers and numerical representation of PA is easily interpreted.

The differences in the chosen dataset also highlight the strengths and weaknesses of methodologies. The n-of-one control dataset with a strong intervention acts as a baseline with predetermined response characteristics. The mAvatar study data shows less prominent effects study wide, but has potentially interesting subgroups for exploration. Additionally the mAvatar data is unique in that it contains two interventions targeting the same theory, but influencing in opposing directions. Lastly, the KNOWME data represents a JiTAI with a clear study-wide effect.

The interventions in these datasets are all expected to primarily effect the level of the target behavior (see figure 2), but the dynamics of the response may differ greatly. The control intervention (by design) is expected to have minimal decay and a decay which starts 5m following the intervention. Thus we can expect the control intervention to closely resemble figure 3 (bottom). We have found no existing work to guide our expectations for the dynamics of the mAvatar and KNOWME datasets, but each targets very different psychological concepts which might be expected to have unique dynamic signatures.

4.1 mAvatar Study

An alternating treatment design is used to examine subject behavior over a period of 8+ days in order to test the effect size of an avatar-based live wallpaper deployed on Android phones. Subjects (n=11) aged 11-14 were exposed to a simple, animated cartoon avatar on their mobile device showing alternating levels of physical activity. Each day the avatar would either be active (playing basketball, running, bicycling) or sedentary (watching TV, on a computer, or playing video games). Fitbit One electronic pedometers were used to estimate subject levels of physical activity via step count.

4.2 KnowMe Study

In this study ten teenagers were asked to carry a smartphone and wear an accelerometer and a heart rate monitor (PAdevice??) for 3 days. Physical activity was measured continuously and was monitored in real time. When a subject had been continuously sedentary for two hours, a personalized SMS text message was sent to their phone. Each text message is manually crafted to prompt the subject to be more physically active.

MORE DETAILS NEEDED

4.3 Control Dataset

The control dataset is the result of manual recording of one subject undergoing an imaginary, very potent intervention. Whenever the subject was at his desk a random timer was set for an interval ranging from 10 to 120 minutes. When the timer went off, the time was logged and the subject intentionally increased his level of physical activity for a period of no less than 5 minutes. Step counts were recorded throughout the duration of the two-week study period using a fitbit one electronic pedometer.

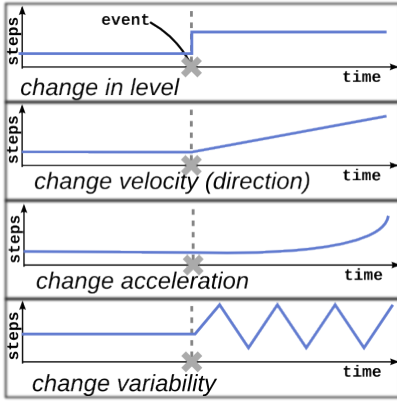


Fig. 2. Theoretical responses to an intervention (adapted from [16]).

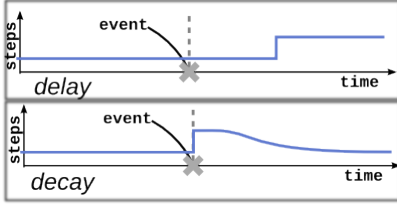


Fig. 3. Level-change responses with delay and decay (adapted from [16]).

5 TASKS

Existing macro-scale methods can determine if an intervention has a significant influence over our target behavior, but it does not give much insight into how the event has an effect over time. The dynamic response to the intervention has only recently become available for study thanks to increasingly ubiquitous wearable sensor technology, and so conventional methods have dealt with low-frequency outcome measures with clever study design. Now that we can measure outcomes at much higher frequencies, methods which leverage this additional information should be adopted.

The dynamic response of the targeted behavior leading up to and following the event tells us much more about how this effect begins and fades over time. A deeper look into the shape of the signal following our event may even reveal a significant effect overlooked by our previous analysis, and much more quantitative behavioral models become possible.

From the goals outlined in the design guidelines section, we have identified several key tasks which a researcher might undertake and present visuals to address these tasks.

5.1 Highlighting Event Dynamics

The dynamics surrounding a particular event are most commonly shown using a time series. The instance or span of the event is marked on the time-axis and the value of the behavioral measure (physical activity in this case) is encoded in the height at each point in time. We can describe several idealized intervention types based on behavioral theory using this common visualization paradigm.

Figure 2 shows the case where an event instantaneously causes permanent change in the target behavior, but in the many cases the intervention will have a temporary effect on the target behavior and will have some delay before setting in.

These intervention response dynamics as shown in figure 3 are critically important for just-in-time adaptive intervention developers, but are largely unaddressed in current theory.

5.2 Event-time Alignment

Figures 2 and 3 give us sense of what an intervention should look like, but in reality individual variations in context completely mask

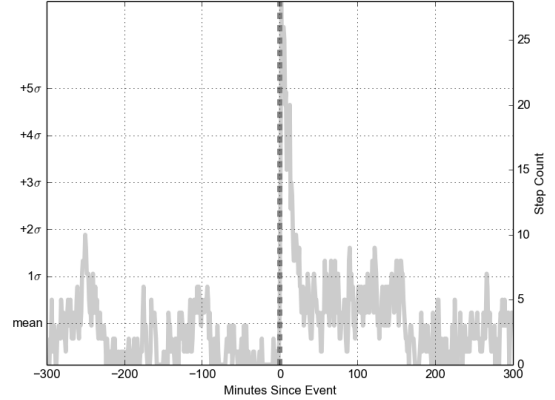
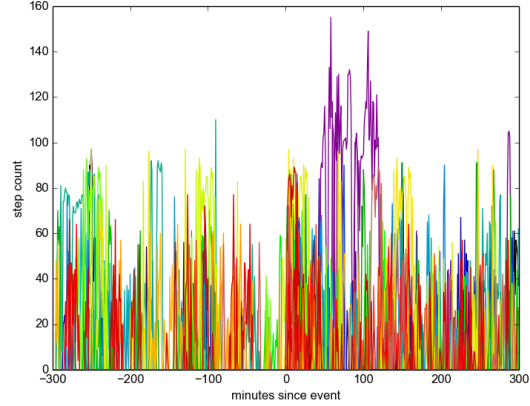


Fig. 4. Comparison of all event responses (top) to average response (bottom) surrounding the control dataset intervention.

the often small effect of an intervention (see Figure 4 (top)). This is a familiar problem with a familiar solution. By time-shifting our data view so that each intervention event falls at $t=0$ in a time-series, we can average the series together in order to identify effects which are common between all events. Aggregated measurements surrounding each event begin to give a better picture of the latency and delay of the response.

This approach can be taken for all events in one subject's time series to characterize that subject, or can be applied across subjects to characterize a more generalized response to the intervention.

Figure 4 makes clear the value of this method for drawing general conclusions from a set of seemingly random data. When looking at all events individually (figure 4 top), it is difficult to spot any pattern in the series. One notable event seems to stand above the rest from 20-60min following the intervention, and a cursory glance at this visual might lead one to believe that this intervention was only effective in that one instance. When averaging across all event responses, however, a clear, significant response is evident (figure 4 bottom).

As expected, figure 4 shows the control intervention to be quite effective at increasing the step count. The additional y-axis showing the mean and standard deviation of the series is included to give an increased sense of the significance of this effect relative to data which may be out of frame. In addition to the nearly immediate response, a longer-lasting effect reaching out to approximately 180m after the event seems to be boosting step count, though the all-events view in figure 4 as well as the stacked-events display in Figure 1 reveal that there are two events which may be the cause. Though the average line-graph makes spotting effects easy, we must be wary of outlying events or participants which can skew the average. This danger can be sometimes mitigated through use of median in place of mean, but since step-count does not obey a normal distribution (0 values are almost always modal), that approach does not work well in this case.

5.3 Stacking

To address the shortcomings of the aforementioned average-line shown in figure 4, individual events can be shown on the graph and stacked. This yields the same shape, and the y-axis can be easily normalized to match our average series by dividing by the number of events. While still averaging out random contextual influences, this visual also provides indication that the average result is not due to one outlier event, enables easy spotting of missing data or faulty sensors, and gives some indication of the number of events considered. For an n-of-one dataset such as the control dataset, events can be graphed with a unique color. In figure 1, event colors are chosen based on the order in which they were observed. Color mapping of events can also be used to visually group events based on time of day, location of the event, or participant.

Figure 5 shows the difference between a plot of various average response lines and the stacked area plot. The thin lines in figure 5 (top) represent the response of each participant to the event averaged across all events for that participant. The thick line shows the average across all participants average series.

The stacked bars in figure 5 (bottom) are colored by participant ID, and each represent one unique event - stacked in order of event incidence. This allows researchers to search for both participant outliers within the set as well as event outliers within each participant.

The linegraph allows for identification of unique individuals (such as red, light blue TODO: mark these and reference by marker not color), but the stackplot better highlights the overall effect and also shows the number of events considered. Another key difference between these two approaches is the proportionate weighting of subjects into the global effect display. The line-graph approach considers each subject equally regardless of the number of events recorded of that subject, whereas the stackplot considers the events equally and thus each subject's contribution is weighted by the number of events recorded.

$$\bar{y}(t) = \frac{1}{N} \sum_{i=1}^N y_i(t) \quad (1)$$

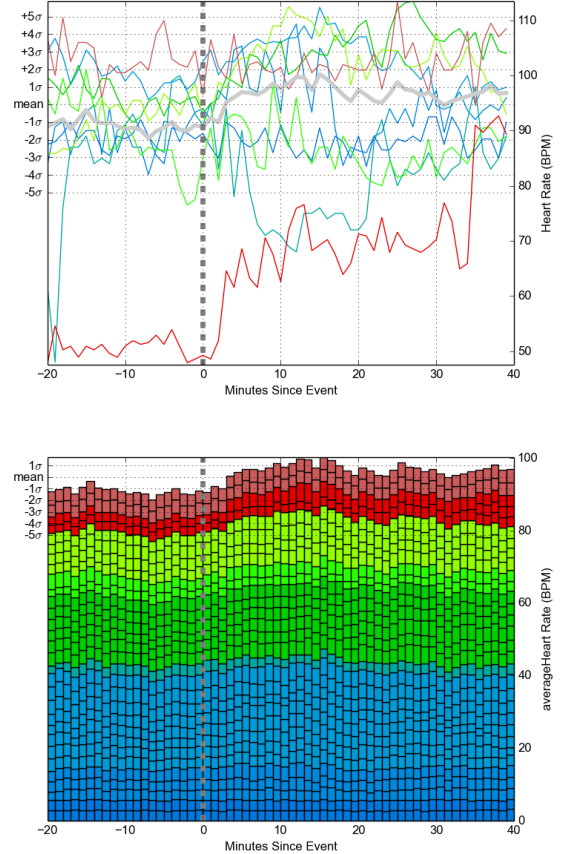


Fig. 5. Comparison of knowMe average lines and stacked bars.

$$\bar{y}(t) = \frac{1}{P} \sum_{p=1}^P \frac{1}{n_p} \sum_i i = 1^n y_{i,p}(t) \quad (2)$$

Equations (1) and (2) shows the difference in aggregation methods for line vs stacked views where N is the total number of events across all participants, P is the number of participants, n_p represents the number of events for subject p , y_i represents the time series for event i , and $y_{i,p}$ represents the time series for subject p 's event i . Aggregating data via method (2) does a better job to ensure that one participant does not skew results, but can give too much weight to data from a participant with few events.

Figure 5 shows an increase in heart rate (TODO: use a different measure. which one?) following the delivery of a physical-activity-suggesting sms message. Though the behavioral measure differs greatly from that used in the control dataset and 4, a comparison of the y-values in terms of standard deviation also reveals that this effect is less extreme than what we observe in the control intervention.

The deviation from the mean as measured relative to the standard deviation gives a sense of how unlikely the signal is to be a random artifact, but methods for evaluating the statistical likelihood of observing a particular shape are not covered here.

5.4 Controlling for Intervention Delivery Context

In some cases introducing a control event against which to compare the experimental event can help isolate the intervention from the context in which it is delivered. For instance, an intervention delivered on a mobile device is always delivered within the context of phone interaction. That is, the user is always using the phone when the intervention is delivered. It is possible that "using the phone" has it's own unique effect on the behavioral measure. Thus, using "phone use" events as a baseline against which to compare "phone use and intervention delivery" strengthens the chance that the observed effect is a result of the intervention itself and not the result of frequently concurrent contextual forces.

Using the control dataset as an example, random points in time when the subject was at his desk can serve as the control event against which to compare the experimental "intervention" event.

To represent a difference between two intervention effect time series visually we return to the use of line averages due to the confounding nature of negatively-valued bars in stacked graphs.

TODO: fig line graph of controlData avg(intervention)-avg(control)

5.5 Comparing Event Types

Aforementioned methods used to provide a contextual baseline of comparison for events can also be applied to allow for a comparison between two event types. By treating one event as the baseline, differences between the events can be visualized. Using this paradigm, nearly equivalent event responses will have a near-zero difference. Positively-valued areas of the resulting chart indicate times when the "experimental event" had a greater positive effect on the target measure, or, conversely, that the "control event" had a greater negative effect on the target measure.

The mAvatar dataset contains two types of intervention which may be interesting to compare: 1) active-avatar viewing, 2) sedentary-avatar viewing. In this case, the two event types are theoretically opposite in effect, meaning that the sedentary-avatar effect should resemble a mirrored version of the active-avatar effect. Thus, the difference should accentuate the intervention's effect signature and better isolate the behavioral response from noisy data.

Even with two oppositely-polarized events figure 6 fails to show the dramatic effect a researcher might hope for on average. The lack of observed effect indicates that the intervention had no effect on average. In this case, researchers attribute the apparent lack of effect to an ambiguity in study design which led to two opposing conditions: 1) subjects respond positively to physically-active avatars via the Proteus Effect [?] 2) subjects respond negatively to physically-active avatars via falsely perceived biofeedback.

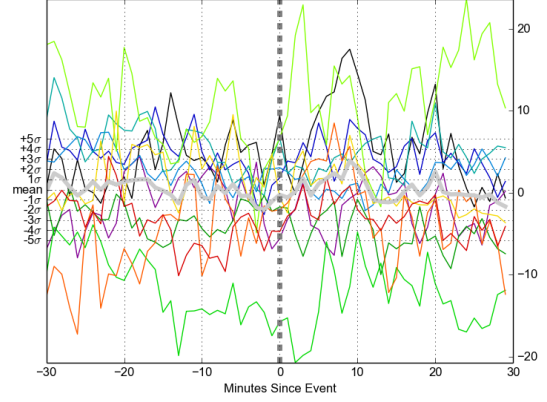


Fig. 6. Active-event series average minus sedentary-event series average. (average shown as bold)

Figure 6 suggests this subgrouping within the data in the individual participant series.

TODO: talk more about the subgroups (+ response vs -response), label the series.

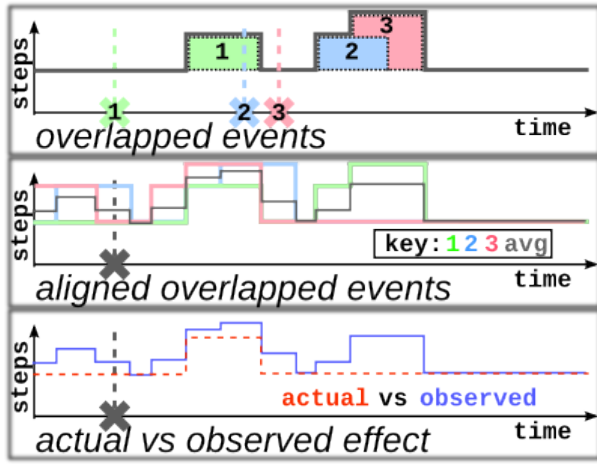


Fig. 7. Overlapping analysis windows confounds observed effect after time-alignment.

6 DISCUSSION AND FUTURE WORK

6.1 Dealing With Overlapped Data Frames

When looking at data surrounding an event, we must be cognizant of how instances of the same event at another time may effect our data. For instance, if our analysis targets the 30min following an event, and the event frequently occurs at 10m intervals, the overlapping signals will create unwanted artifacts.

Figure 7 illustrates this point by showing how events falling within each other's windows of analysis confound the data and ultimately yields a signal quite unlike the actual effect response. In real data, this is further complicated by the non-linear way in which effects are expected to combine. Study designs utilizing methods outlined in this paper should design studies to minimize overlapping analysis windows.

Event overlap becomes somewhat inevitable, however, for large event window sizes.

TODO: figure: comparison of events selected with/without overlap from mAvatar dataset to demonstrate difference (especially at high time intervals like no-overlap for 3hrs around event)

Figure ?? shows a comparison between data retrieved using the two methods of analysis: no overlap vs overlap ignored. Allowing no overlap between events helps ensure that multiple interventions effects do not skew the data, but ignoring these data can drastically reduce data sample if large times following the event are used because very few events are so isolated.

6.2 Alternative Stacked-Area Representation

Use of the "themeRiver/streamgraph" [?, 2] paradigm for plotting stacked area charts may offer an improved view of the contribution of individual time series to the aggregated result, further easing the identification of outlier participants or events.

6.3 Modeling Observed Effects

Ever since [], behavioral scientists have sought theories to explain, influence and change human behavior. Theories are built on constructs that explain or act as prerequisites for performance (or lack of performance) of a behavior. For example, constructs such as location, social networks, and time of day (external context) influence behavior as much or more so than a person's internal traits and states, such as personality, emotional state, and mental health. With the right theory in hand, behavioral scientists can develop interventions that target these constructs to effectively drive behavior change (ref to Figure of simple cause and effect model).

However, such theory-driven approaches to behavioral interventions have shown limited success. There are likely many reasons for this, but one clear reason is that the underlying behavioral theories driving such interventions is wrong.

TODO? Some example models of the aforementioned effects for control and/or knowMe data.

transfer function modeling? fitting of a fluid-flow analogy using a priori constructs? other?

6.4 Characterizing Psychological Influence of Events via Response Signature

Different psychological mechanisms act on different time-scales and, likewise, with different dynamics. The delay of effect onset and decay of the effect observed in data can be used to suggest what psychological mechanisms are at work. In this way, interventions could be characterized in terms of applicable theory via the the dynamics observed.

6.5 Statistical Analysis of Features

Much existing work on the statistical testing of between-phase differences in traditional AB study designs [29] is applied in the evaluation of the efficacy of a one-time or repeatedly applied intervention, and methods for evaluating the likelihood of features in a time-series are also well documented [17, 36]. Through combination of existing intervention analysis techniques [1], goodness-of-fit evaluations of model formulations [28] in comparison to surrogate time series, and the presented visualization methods, researchers can begin to build dynamic models of human behaviors to enable clever JiTAIs.

7 CONCLUSION

There are many reasons why behavior change is hard: people build up habits over time, behaviors may be tied to addictive substances or activities, behavior is tied to normal daily human experience and context (i.e. smoking more often when with a certain group of individuals or in a particular location). The full potential of behavioral interventions - particularly JiTAIs - will continue unrealized until mechanistic methods of behavior modeling are adopted by the behavior science community.

The presented visualization methods allow for more detailed analysis of how a subjects behavior responds to a stimuli over time. These methods, when combined with a computational modeling approach to understanding human behavior may enable behavioral scientists to formulate more accurate and more application-ready theories, leading to more effective behavioral interventions.

REFERENCES

- [1] G. E. Box and G. C. Tiao. Intervention analysis with applications to economic and environmental problems. *Journal of the American Statistical association*, 70(349):70–79, 1975.
- [2] L. Byron and M. Wattenberg. Stacked graphs—geometry & aesthetics. *Visualization and Computer Graphics, IEEE Transactions on*, 14(6):1245–1252, 2008.
- [3] K.-h. Chang, D. Fisher, J. Canny, and B. Hartmann. How's my mood and stress?: an efficient speech analysis library for unobtrusive monitoring on mobile phones. In *Proceedings of the 6th International Conference on Body Area Networks*, pages 71–77. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2011.
- [4] L. M. Collins, S. A. Murphy, and K. L. Bierman. A conceptual framework for adaptive preventive interventions. *Prevention science*, 5(3):185–196, 2004.
- [5] L. M. Collins, S. A. Murphy, and V. Strecher. The multiphase optimization strategy (most) and the sequential multiple assignment randomized trial (smart): new methods for more potent ehealth interventions. *American journal of preventive medicine*, 32(5):S112–S118, 2007.
- [6] H. Cooper, J. C. Robinson, and E. A. Patall. Does homework improve academic achievement? a synthesis of research, 1987–2003. *Review of educational research*, 76(1):1–62, 2006.
- [7] S. Deshpande, D. E. Rivera, J. W. Younger, and N. N. Nandola. A control systems engineering approach for adaptive behavioral interventions: illustration with a fibromyalgia intervention. *Translational behavioral medicine*, 4(3):275–289, 2014.
- [8] Y. Dong, D. E. Rivera, D. S. Downs, J. S. Savage, D. M. Thomas, and L. M. Collins. Hybrid model predictive control for optimizing gestational

- weight gain behavioral interventions. In *American Control Conference (ACC)*, 2013, pages 1970–1975. IEEE, 2013.
- [9] A. L. Dunn, M. H. Trivedi, and H. A. O’Neal. Physical activity dose–response effects on outcomes of depression and anxiety. *Medicine & Science in Sports & Exercise*, 2001.
- [10] J. J. Elliott. Development of an energy-information feedback system for a smartphone application. 2012.
- [11] B. A. Emken, M. Li, G. Thatte, S. Lee, M. Annavaram, U. Mitra, S. Narayanan, and D. Spruijt-Metz. Recognition of physical activities in overweight hispanic youth using knowme networks. *Journal of physical activity & health*, 9(3):432, 2012.
- [12] J. A. Fails, A. Karlson, L. Shahamat, and B. Shneiderman. A visual interface for multivariate temporal data: Finding patterns of events across multiple histories. In *Visual Analytics Science And Technology, 2006 IEEE Symposium On*, pages 167–174. IEEE, 2006.
- [13] O. H. Franco, C. de Laet, A. Peeters, J. Jonker, J. Mackenbach, and W. Nusselder. Effects of physical activity on life expectancy with cardiovascular disease. *Archives of internal medicine*, 165(20):2355–2360, 2005.
- [14] D. Gallego Vico, G. Huecas, and J. Salvachúa Rodríguez. Generating context-aware recommendations using banking data in a mobile recommender system. In *ICDS 2012, The Sixth International Conference on Digital Society*, pages 73–78, 2012.
- [15] K. Glanz and D. B. Bishop. The role of behavioral science theory in development and implementation of public health interventions. *Annual review of public health*, 31:399–418, 2010.
- [16] G. V. Glass, V. L. Willson, and J. M. Gottman. *Design and analysis of time-series experiments*, volume 197. Colorado Associated University Press Boulder, 1975.
- [17] B. S. Gorman and D. B. Allison. Statistical alternatives for single-case designs. 1996.
- [18] D. Gotz and H. Stavropoulos. Decisionflow: Visual analytics for high-dimensional temporal event sequence data. 2014.
- [19] B. L. Harrison, R. Owen, and R. M. Baecker. Timelines: an interactive system for the collection and visualization of temporal data. In *Graphics Interface*, pages 141–141. Citeseer, 1994.
- [20] J. Ho and S. S. Intille. Using context-aware computing to reduce the perceived burden of interruptions from mobile devices. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 909–918. ACM, 2005.
- [21] S. Jewell. Productivity via mobile phones: Using smartphones in smart ways. *Journal of Electronic Resources in Medical Libraries*, 8(1):81–86, 2011.
- [22] P. Klasnja and W. Pratt. Healthcare in the pocket: Mapping the space of mobile-phone health interventions. *Journal of biomedical informatics*, 45(1):184–198, 2012.
- [23] M. Li, V. Rozgic, G. Thatte, S. Lee, B. Emken, M. Annavaram, U. Mitra, D. Spruijt-Metz, and S. Narayanan. Multimodal physical activity recognition by fusing temporal and cepstral information. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 18(4):369–380, 2010.
- [24] H. Lu, D. Frauendorfer, M. Rabbi, M. S. Mast, G. T. Chittaranjan, A. T. Campbell, D. Gatica-Perez, and T. Choudhury. Stresssense: Detecting stress in unconstrained acoustic environments using smartphones. In *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, pages 351–360. ACM, 2012.
- [25] I. Nahum-Shani, M. Qian, D. Almirall, W. E. Pelham, B. Gnagy, G. A. Fabiano, J. G. Waxmonsky, J. Yu, and S. A. Murphy. Q-learning: A data analysis method for constructing adaptive interventions. *Psychological methods*, 17(4):478, 2012.
- [26] J. M. Norvilitis, P. B. Szablicki, and S. D. Wilson. Factors influencing levels of credit-card debt in college students1. *Journal of Applied Social Psychology*, 33(5):935–947, 2003.
- [27] R. Nuzzo. Statistical errors. *Nature*, 506(13):150–152, 2014.
- [28] A. Pankratz. *Forecasting with dynamic regression models*, volume 935. John Wiley & Sons, 2012.
- [29] R. I. Parker and D. F. Brossart. Evaluating single-case research data: A comparison of seven statistical methods. *Behavior Therapy*, 34(2):189–211, 2003.
- [30] A. A. Pina, L. E. Holly, A. A. Zerr, and D. E. Rivera. A personalized and control systems engineering conceptual approach to target childhood anxiety in the contexts of cultural diversity. *Journal of Clinical Child & Adolescent Psychology*, 43(3):442–453, 2014.
- [31] C. Plaisant, B. Milash, A. Rose, S. Widoff, and B. Shneiderman. Lifelines: visualizing personal histories. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 221–227. ACM, 1996.
- [32] W. T. Riley, D. E. Rivera, A. A. Atienza, W. Nilsen, S. M. Allison, and R. Mermelstein. Health behavior models in the age of mobile interventions: are our theories up to the task? *Translational behavioral medicine*, 1(1):53–71, 2011.
- [33] R. Ross, D. Dagnone, P. J. Jones, H. Smith, A. Paddags, R. Hudson, and I. Janssen. Reduction in obesity and related comorbid conditions after diet-induced weight loss or exercise-induced weight loss in men: randomized, controlled trial. *Annals of internal medicine*, 133(2):92–103, 2000.
- [34] E. Sazonov, K. Metcalfe, P. Lopez-Meyer, and S. Tiffany. Rf hand gesture sensor for monitoring of cigarette smoking. In *Sensing Technology (ICST), 2011 Fifth International Conference on*, pages 426–430. IEEE, 2011.
- [35] T. Sohn, K. A. Li, G. Lee, I. Smith, J. Scott, and W. G. Griswold. *Place-its: A study of location-based reminders on mobile phones*. Springer, 2005.
- [36] H. K. Suen and D. Ary. *Analyzing quantitative behavioral observation data*. Psychology Press, 1989.
- [37] K. P. Timms, D. E. Rivera, M. E. Piper, and L. M. Collins. A hybrid model predictive control strategy for optimizing a smoking cessation intervention. In *American Control Conference (ACC)*, 2014, pages 2389–2394. IEEE, 2014.
- [38] J. J. Van Wijk and E. R. Van Selow. Cluster and calendar based visualization of time series data. In *Information Visualization, 1999.(Info Vis’99) Proceedings. 1999 IEEE Symposium on*, pages 4–9. IEEE, 1999.
- [39] K. Vrotsou, K. Ellegard, and M. Cooper. Everyday life discoveries: Mining and visualizing activity patterns in social science diary data. In *Information Visualization, 2007. IV’07. 11th International Conference*, pages 130–138. IEEE, 2007.
- [40] K. Wongsuphasawat and D. Gotz. Outflow: Visualizing patient flow by symptoms and outcome. In *IEEE VisWeek Workshop on Visual Analytics in Healthcare, Providence, Rhode Island, USA*, 2011.
- [41] K. Wongsuphasawat and D. Gotz. Exploring flow, factors, and outcomes of temporal event sequences with the outflow visualization. *Visualization and Computer Graphics, IEEE Transactions on*, 18(12):2659–2668, 2012.
- [42] K. Wongsuphasawat, J. A. Guerra Gómez, C. Plaisant, T. D. Wang, M. Taieb-Maimon, and B. Shneiderman. Lifeflow: visualizing an overview of event sequences. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1747–1756. ACM, 2011.
- [43] D. Wyatt, T. Choudhury, J. Bilmes, and J. A. Kitts. Inferring colocation and conversation networks from privacy-sensitive audio with implications for computational social science. *ACM Transactions on Intelligent Systems and Technology (TIST)*, 2(1):7, 2011.
- [44] D. G. Yanbaeva, M. A. Dentener, E. C. Creutzberg, G. Wesseling, and E. F. Wouters. Systemic effects of smoking. *Chest Journal*, 131(5):1557–1566, 2007.