

# Dynamical Systems Modeling using EMA Data: An Illustration from Smoking Cessation

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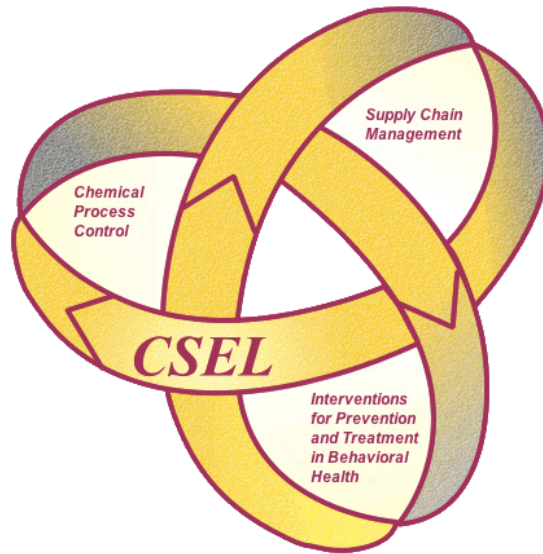


## Outline



- What is dynamical systems modeling?
- UW-CTRI Ed Sr. data description.
- Approaches:
  - Modeling craving dynamics as a result of quitting.
  - Dynamical mediation (with craving as a mediator, and cigarettes smoked as outcome).
  - Smoking as a feedback system involving craving self-regulation.
- Summary and conclusions.

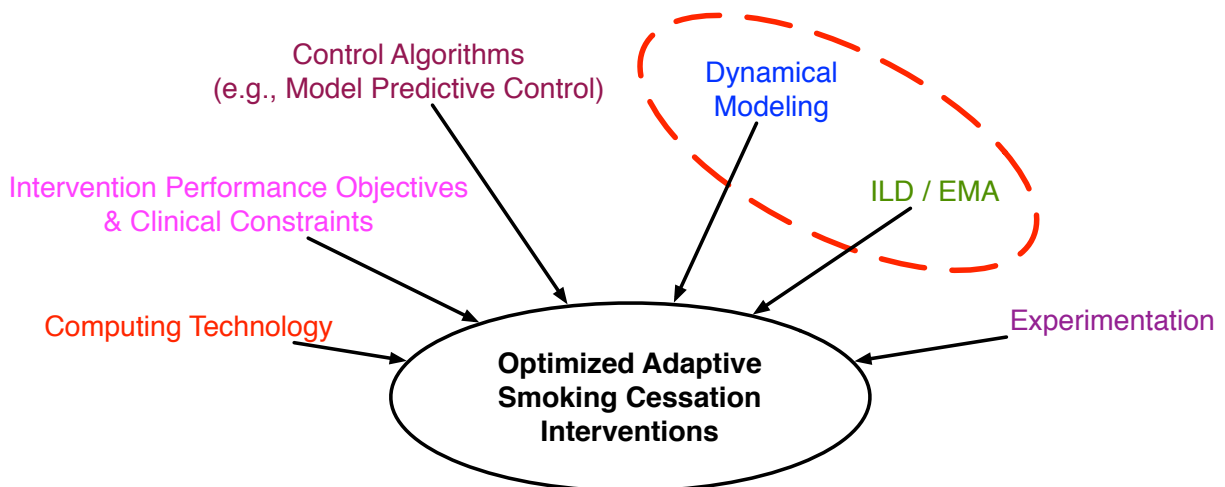
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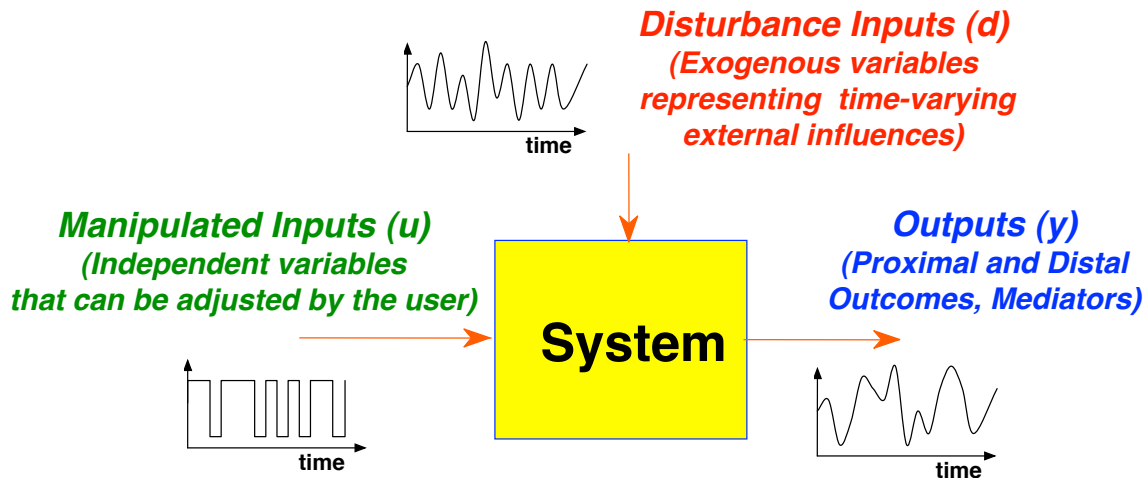
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### The End Goal: Optimized Interventions



Our end goal is to apply principles from *control systems engineering* towards optimizing smoking cessation interventions; our focus for today is on the important subproblem of *dynamical systems modeling* from intensive longitudinal data obtained via EMA (or related means).

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- Dynamical systems thinking considers how to characterize the transient response resulting from changes in manipulated inputs (e.g., intervention component dosages) and disturbance inputs (e.g., external influences) on outputs (e.g., proximal or distal outcomes, mediators).
- The above is a block diagram “signals and systems” representation (not to be confused with path diagrams).

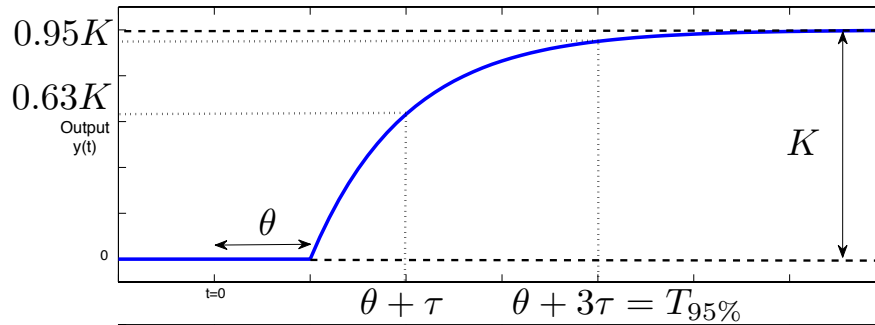
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- Serves to better understand the concepts of *change* and *effect* in interventions; this includes:
  - what to measure, and how often
  - within and between participant variability
- Allows more efficient use of intensive longitudinal data
- Enables the application of *control engineering principles* for achieving time-varying adaptation of intervention components based on participant response.

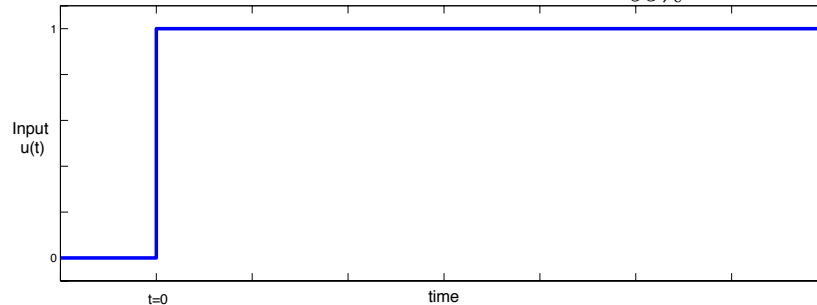
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$$\tau \frac{dy}{dt} + y(t) = Ku(t - \theta)$$

**Output  $y(t)$**   
(e.g., Craving,  
Cigarettes  
Smoked)



**Input  $u(t)$**   
(e.g., Quitting,  
Dosage Change,  
Stress)

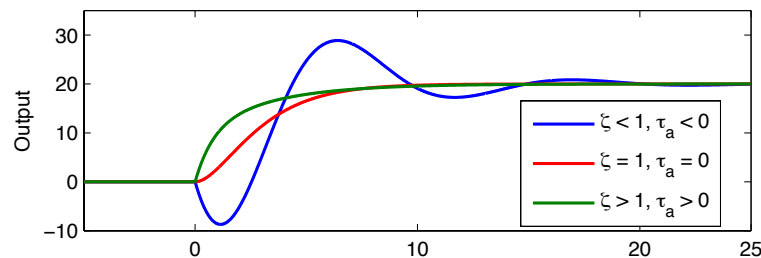


Gain ( $K$ ), time constant ( $\tau$ ), delay ( $\theta$ ), and settling time ( $T_{95\%}$ ) are all part of the “lingo” of dynamical systems...

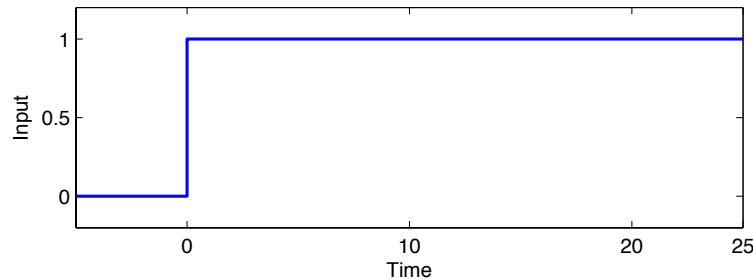
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$$\tau^2 \frac{d^2y}{dt^2} + 2\zeta\tau \frac{dy}{dt} + y(t) = K_p \left( u(t) + \tau_a \frac{du}{dt} \right)$$

**Output  $y(t)$**   
(e.g., Craving,  
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**Input  $u(t)$**   
(e.g., Quitting,  
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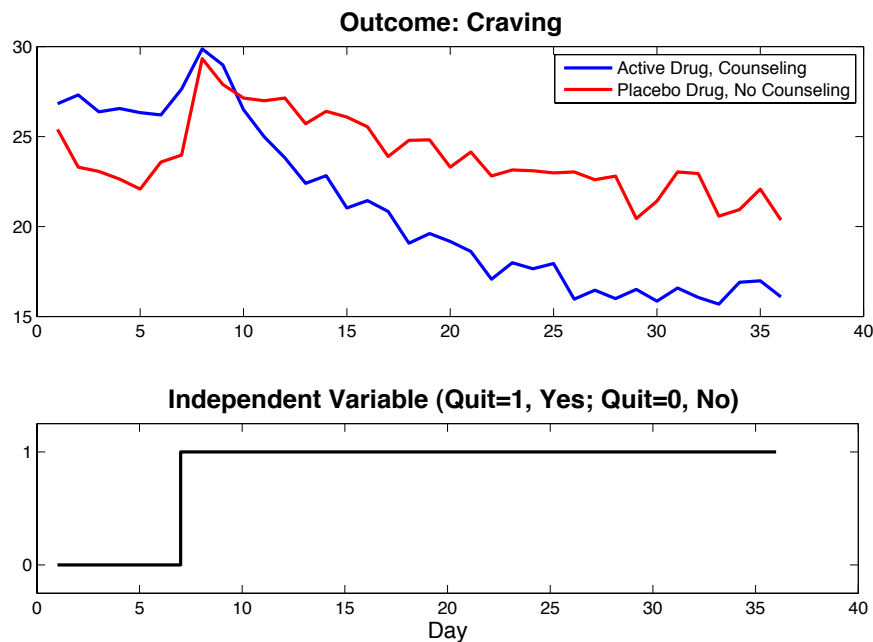


- Rise time, settling time, overshoot, oscillation, and inverse response are important characteristics of this model response.

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- Data from study described in McCarthy *et al.*, *Addiction*, Vol. 103, pgs. 1521-1533, 2008. Active drug is bupropion SR.
- 11 week study; randomization ( $n = 463$ )
  - Drug: Drug, Placebo
  - Counseling: Yes, No
- Treatment Conditions:
  - Active Drug with Counseling (AC;  $n=101$ )
  - Active Drug, No Counseling (ANc;  $n = 101$ )
  - Placebo with Counseling (PC;  $n = 100$ )
  - Placebo, No Counseling (PNc ;  $n = 101$ )
- $T = 42$  daily observations for each participant

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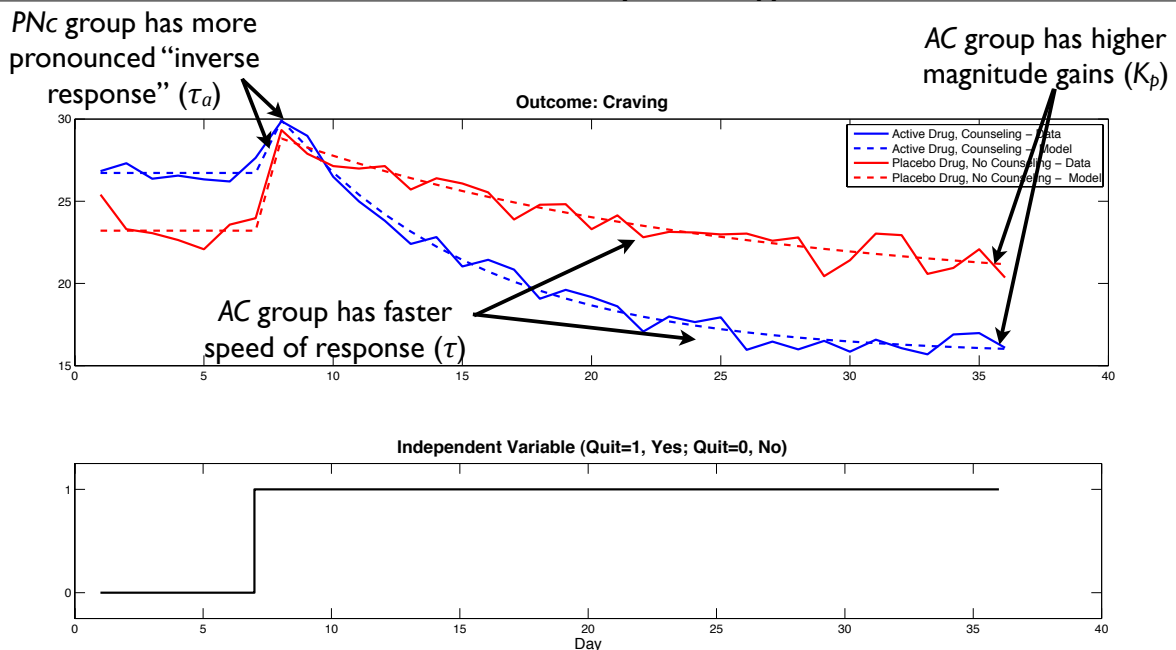


- Comparison of craving scores versus quit for two treatment groups (active drug with counseling (AC, blue) vs. placebo-no counseling (PNc, red)).

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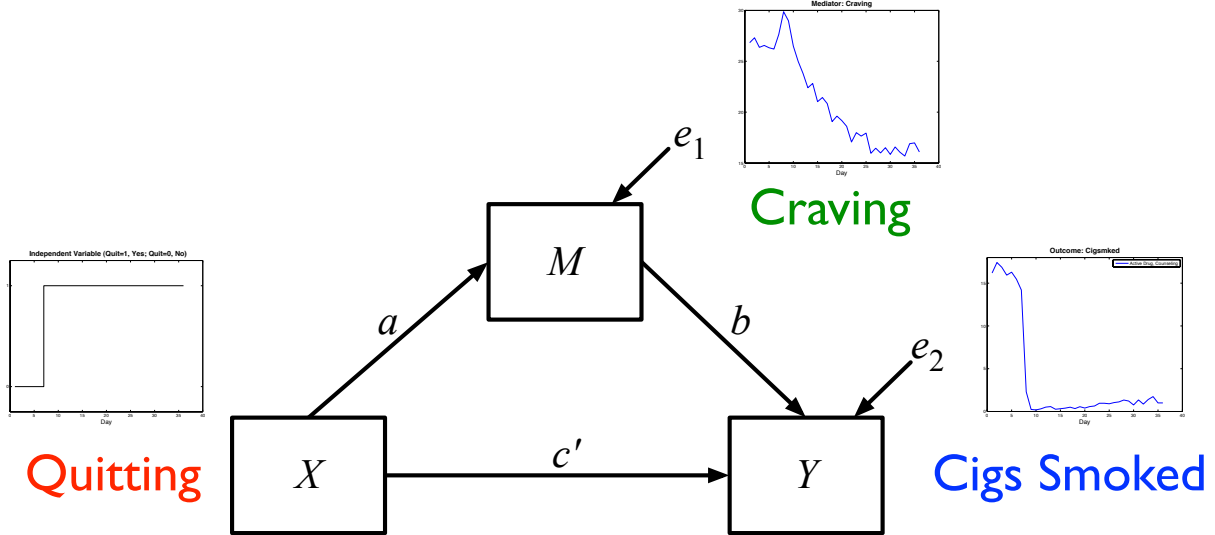
- Parameter estimation performed using the **Process Models** feature in Matlab's System Identification Toolbox (one-step ahead prediction-error minimization for continuous differential equation structures).
- *Functional data analysis* (FDA) is well-suited as a parameter estimation scheme for this model (Trail *et al.*, 2012); estimating time-varying coefficients is a natural extension of this work.
- *Model parsimony* is an appealing aspect of differential equation modeling, given the diversity of responses that can be obtained from a relatively small number of parameters.
- The proper choice of *sampling interval* is a very important consideration in this type of analysis.

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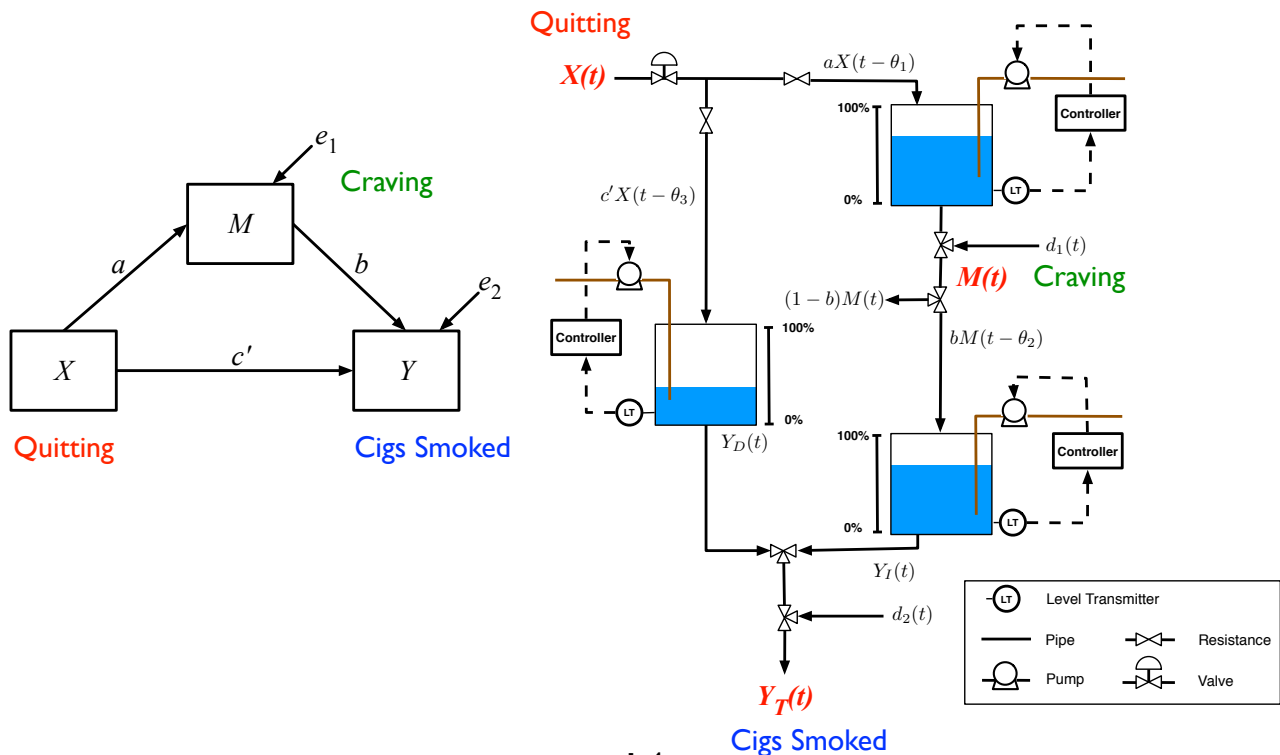
- Second-order models fit 63.8 and 86.1% of the variance for the PNc (red) and AC (blue) treatment groups, respectively.

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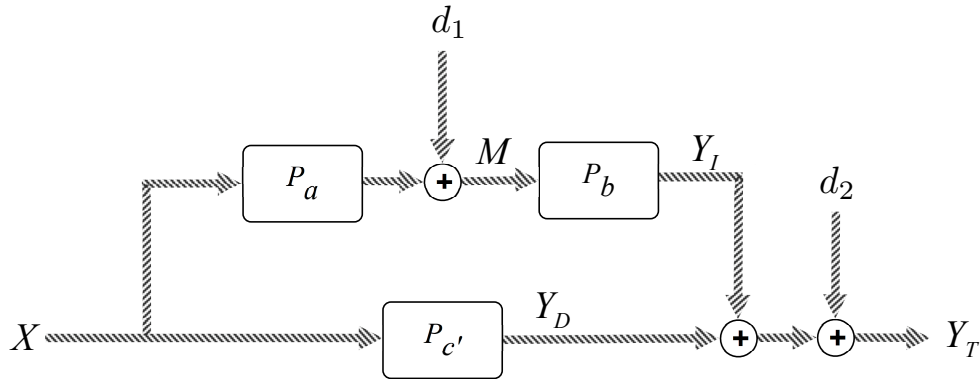


All variables observed;  $M$  and  $Y$  continuous;  $X$  can be categorical

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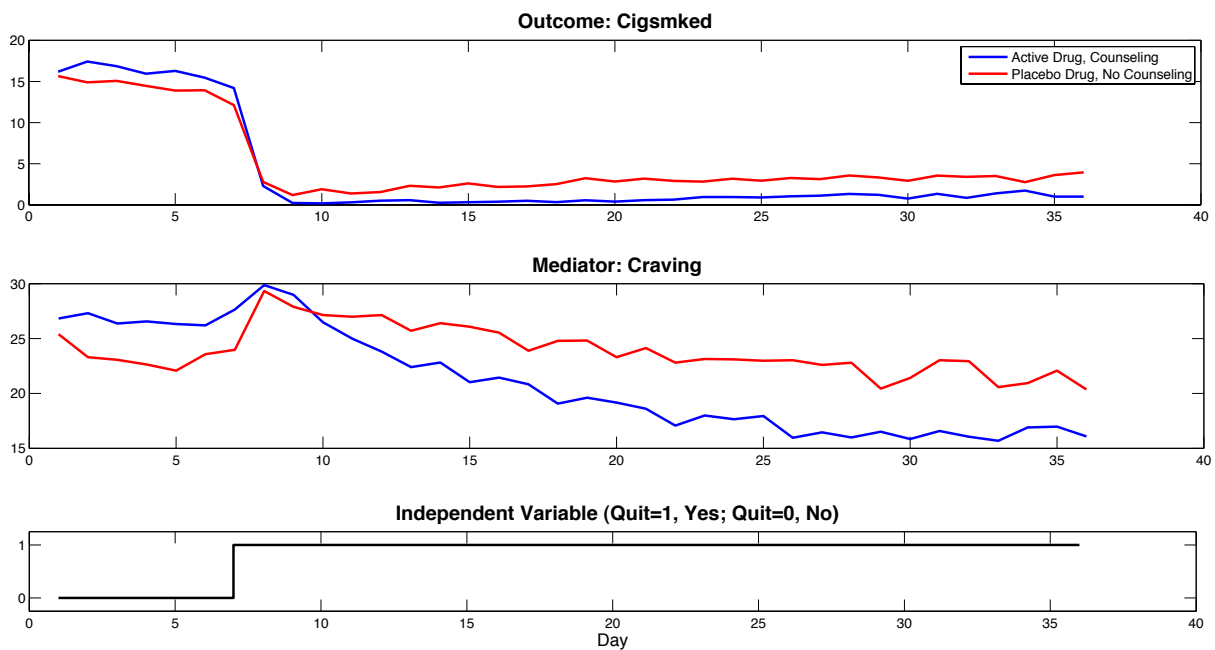


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- A signals and systems block diagram, not a path diagram.
- $P_a$ ,  $P_b$ , and  $P_c'$  represent *transfer functions*; these are compact representations of differential equation models
- Arrangement allows for a generalization of dynamic mediation analysis beyond fluid analogies.

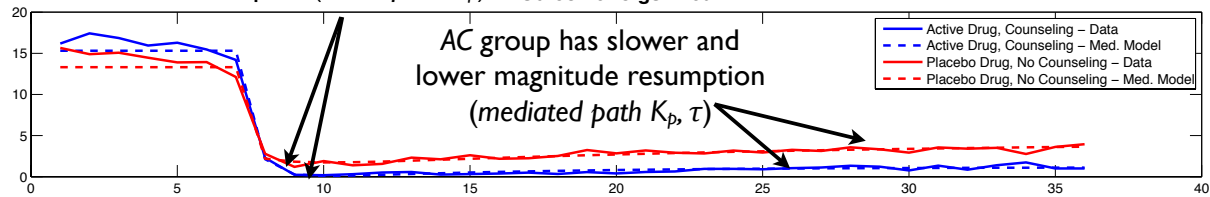
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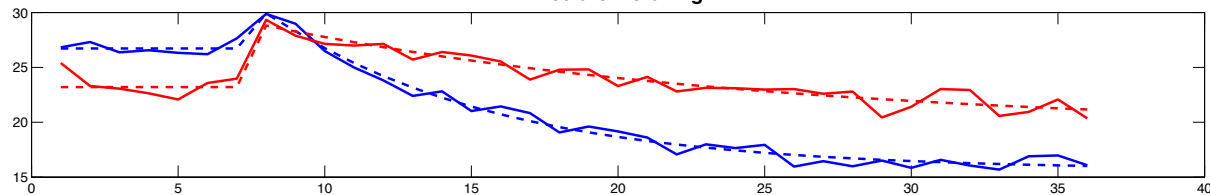
Comparison of average cigarettes smoked and craving scores for two treatment groups (active drug with counseling (AC, blue) vs. placebo-no counseling (PNC, red)).

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AC group displays more substantial  
initial "quit" (direct path  $K_p$ ) Outcome: Cigsmked



Mediator: Craving



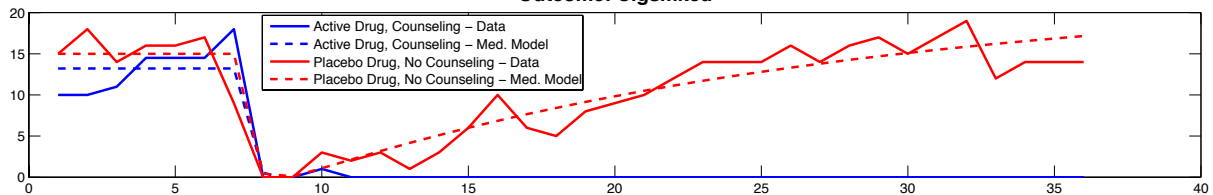
Independent Variable (Quit=1, Yes; Quit=0, No)



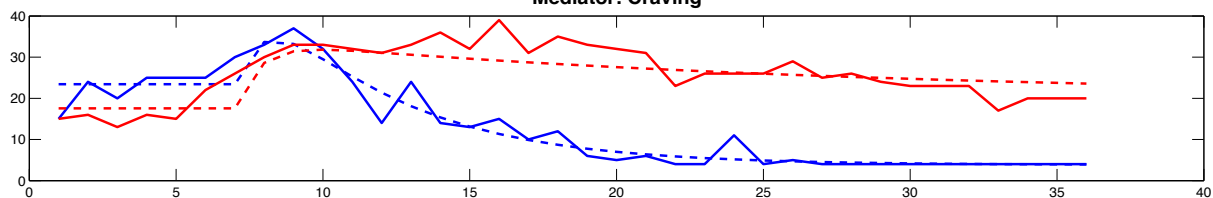
The mediated pathway contributes more to the net outcome in the **PNC** group as compared to the **AC** group.

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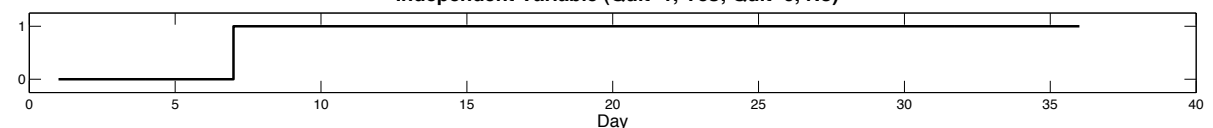
Outcome: Cigsmked



Mediator: Craving

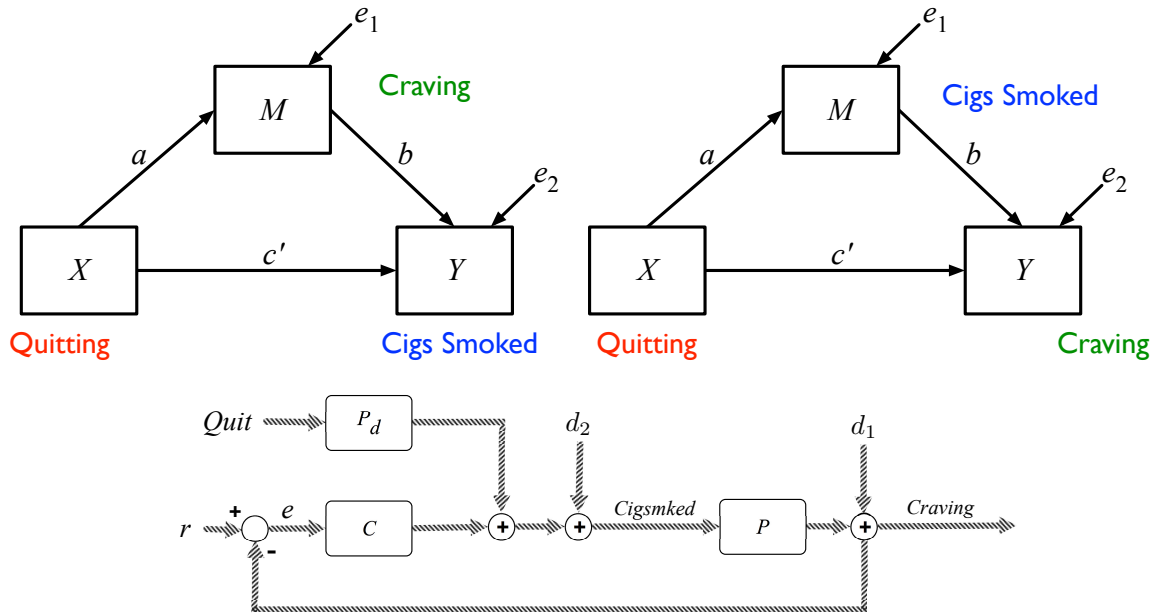


Independent Variable (Quit=1, Yes; Quit=0, No)

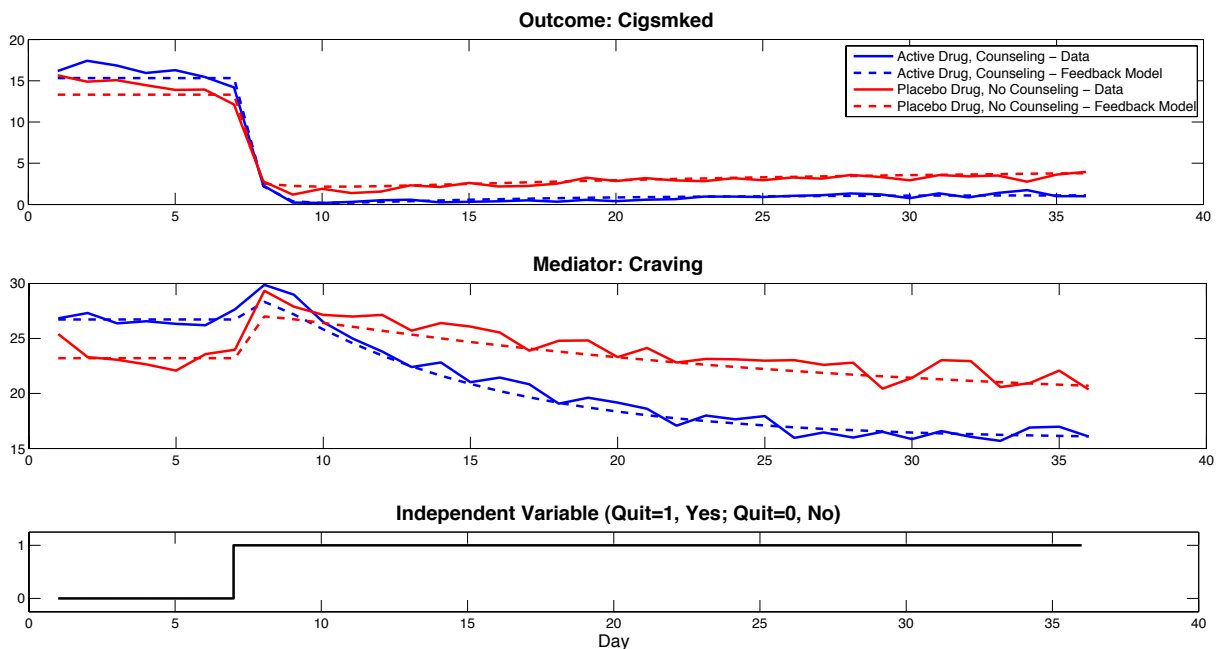


Idiographic results for a representative participant from the **PNC** and **AC** groups.

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Dynamical systems analysis (Timms *et al.*, 2012b, in press) suggests that a feedback model involving the self-regulation of craving through smoking describes the smoking process more comprehensively than traditional mediation analysis. This concept is consistent with nicotine regulation theories and extensions as discussed by Walls and Rivera (2009 Society for Prevention Research).



The feedback/craving self-regulation model (Timms *et al.* 2012b) displays similar fits to the mediation model structures; however, only one model structure is needed to comprehensively capture the dynamical relationship between variables.

- Dynamical systems modeling of ILD/EMA data from the Ed Sr. smoking cessation intervention has been examined.
- The differential equations associated with dynamical systems modeling can be readily estimated using algorithms from system identification (engineering) or functional data analysis (statistics).
- Dynamical models offer a parsimonious, effective means for describing change over time that makes them useful in optimized smoking cessation interventions relying on control engineering approaches.
- Dynamic mediation model structures related to smoking cessation were examined; these can be generalized through a feedback model structure based on craving self-regulation that is inspired by nicotine regulation theories.

- How can *behavioral theories* be reconciled (and better integrated) with the physical (fluid) analogies and generalized dynamical system structures that have been presented?
- *Experimental design* in support of dynamic modeling represents an interesting topic for future research.
- Research towards generalized approaches for dynamical systems modeling of smoking cessation interventions that incorporates mediation, moderation, confounding, latent variables, and gene-environment interactions.
- Use of these models in optimized adaptive behavioral interventions using model predictive control (Nandola and Rivera, 2012).

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