

Dynamic Structural Equation Modeling of Intensive Longitudinal Data Using Multilevel Time Series Analysis in Mplus Version 8 (Blocks 2 and 3)

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Workshop in Utrecht and Zurich, July 13 and 17, 2017

We thank Noah Hastings for excellent assistance

Mplus Version 8:

Methods for Analyzing Intensive Longitudinal Data

- Time series analysis ($N = 1$)
- Two-level time series analysis ($N > 1$)
 - Random effects varying across subjects (subject is level 2, so many more random effects than usual)
- Cross-classified time series analysis
 - Random effects varying across subjects and time
- Dynamic Structural Equation Modeling (DSEM)
 - General latent variable modeling
 - Bayesian estimation
 - Statistical background:
 - Asparouhov, Hamaker & Muthén (2017). Dynamic structural equation models. Technical Report, www.statmodel.com
 - Asparouhov, Hamaker & Muthén (2017). Dynamic latent class analysis. Structural Equation Modeling, 24, 257-269

The Version 8 Mplus User's Guide adds $N=1$ examples 6.23 - 6.28 and $N > 1$ examples 9.30 - 9.40, many with two parts (basic and advanced).

- **Introduction to Bayesian analysis**
- Introduction to longitudinal analysis
- $N=1$ time series analysis
- Two-level time series analysis
- Cross-classified time series analysis
- Latent variable time series analysis

- Bayesian advantages over ML
- An example: Estimating a mean
- Convergence of Bayes iterations
- Trace and autocorrelation plots
- Speed of Bayes in Mplus
- Bayes references

- Six key advantages of Bayesian analysis over frequentist analysis using maximum likelihood estimation:
 - 1 More can be learned about parameter estimates and model fit
 - 2 Small-sample performance is better and large-sample theory is not needed
 - 3 Parameter priors can better reflect results of previous studies
 - 4 Analyses are in some cases less computationally demanding, for example, when maximum-likelihood requires high-dimensional numerical integration
 - 5 In cases where maximum-likelihood computations are prohibitive, Bayes with non-informative priors can be viewed as a computing algorithm that would give essentially the same results as maximum-likelihood if maximum-likelihood estimation were computationally feasible
 - 6 New types of models can be analyzed where the maximum-likelihood approach is not practical (e.g. DSEM)

Why Are Bayesian Computations Possible Where ML Computations Are Not?

The general modeling features of DSEM make ML almost impossible, creating the need for Bayesian estimation.

An intuitive description of the computational difference between ML and Bayes (with non-informative priors):

- ML works with the joint distribution of all variables to find the parameter values that give the logL maximum
- Bayes works with a series of conditional distributions for the parameters to get (posterior) parameter distributions
- The joint distribution can be difficult to describe whereas the conditional distributions can be easier
- Bayes is sometimes the only feasible alternative when the joint distribution is hard to formulate

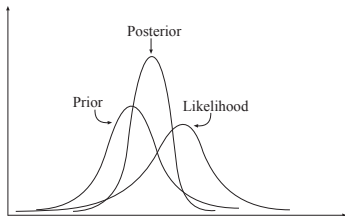


Figure: Informative prior

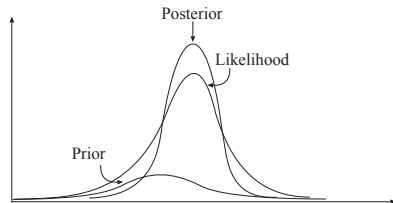


Figure: Non-informative prior

● Priors:

- Non-informative priors (diffuse priors): Large variance (default in Mplus)
 - A large variance reflects large uncertainty in the parameter value. As the prior variance increases, the Bayesian estimate gets closer to the maximum-likelihood estimate
- Weakly informative priors: Used for technical assistance
- Informative priors:
 - Informative priors reflect prior beliefs in likely parameter values
 - These beliefs may come from substantive theory combined with previous studies of similar populations

- Frequentists sometimes object to Bayes using informative priors
 - But they already do use such priors in many cases in unrealistic ways (e.g. factor loadings fixed exactly at zero)
- Bayes can let informative priors reflect prior studies
- Bayes can let informative priors identify models that are unidentified by ML which is useful for model modification (BSEM)
- The credibility interval for the posterior distribution is narrower with informative priors

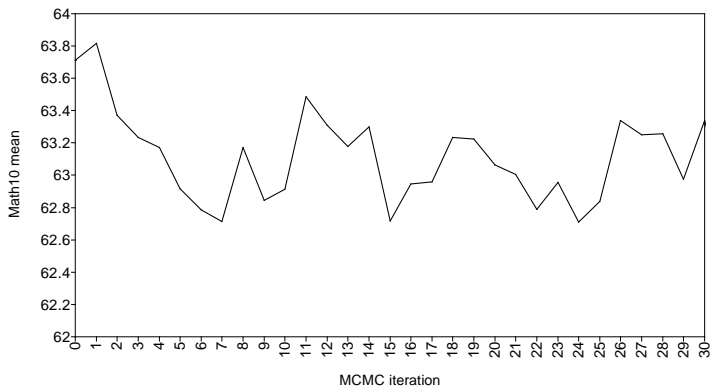
An MCMC Example: LSAY Math with Missing Data

	math7	math10
n_1		
n_2		missing

- Three sets of unknowns assuming bivariate normality:
 - 2 means, 2 variances, and 1 covariance
 - n_2 missing values on math10

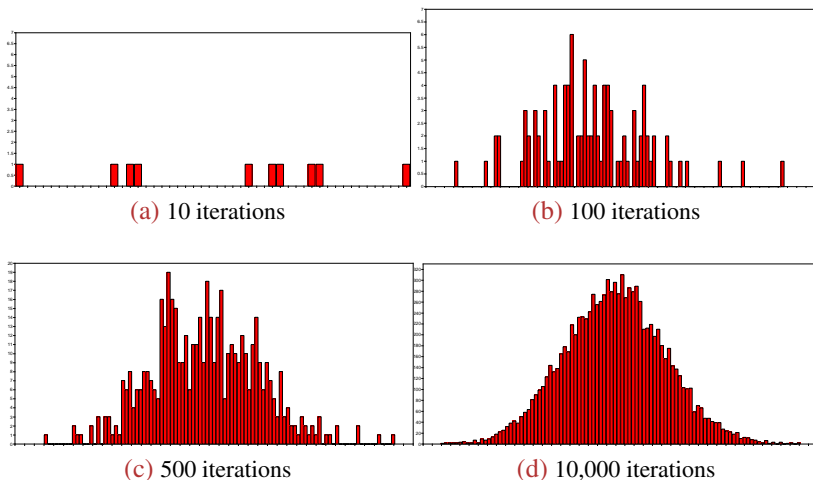
- 1 Draw values for the two means from the conditional distribution of the means conditioned on the variance-covariance parameters, the observed and missing data, and the priors.
- 2 Draw values for the n_2 missing values on math10 from the conditional distribution of missing values conditioned on the mean parameters, the observed data, and the priors.
- 3 Draw values for the two variance and covariance parameters from the conditional distribution of the variance-covariance parameters conditioned on the mean parameters, the observed and missing data, and the priors.

20 MCMC Iterations for the LSAY Math10 Mean

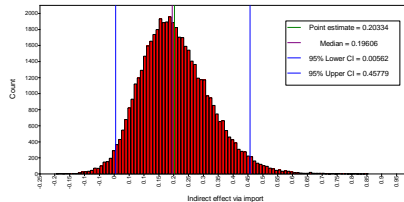
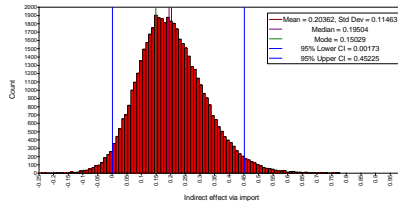


- Starting value for the mean is the listwise estimate of 63.7

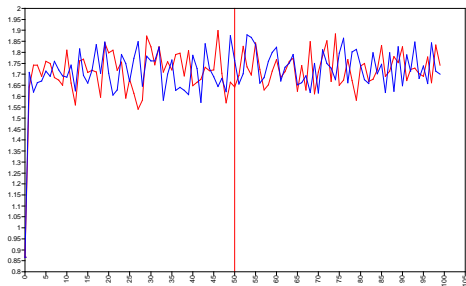
Posterior Distributions of the LSAY Math10 Mean Using Different Number of MCMC Iterations



Bayes Posterior Distribution Similar to ML Bootstrap Distribution: Credibility versus Confidence Intervals



Convergence: Trace Plot for Two MCMC Chains. PSR



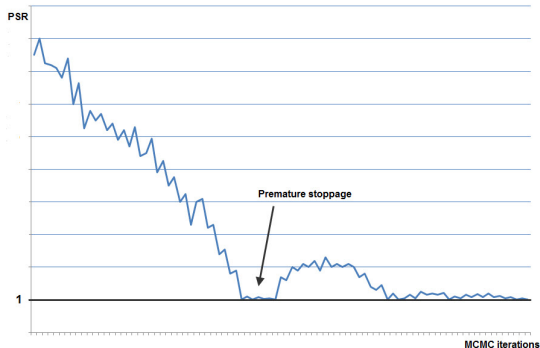
Potential scale reduction criterion (Gelman & Rubin, 1992):

$$PSR = \sqrt{\frac{W + B}{W}}, \quad (1)$$

where W represents the within-chain variation of a parameter and B represents the between-chain variation of a parameter. A PSR value close to 1 means that the between-chain variation is small relative to the within-chain variation and is considered evidence of convergence.

Convergence of the Bayes Markov Chain Monte Carlo (MCMC) Algorithm

Figure: Premature stoppage of Bayes MCMC iterations using the Potential Scale Reduction (PSR) criterion



TECH8 Screen Printing of Bayes MCMC Iterations

Mplus - [3-19 Brea 21 AR on residuals]

File Edit View Mplus Plot Diagram Window Help

between = female age;
with: C:\Windows\system32\cmd.exe

```
!
lag;
miss;
tinte;
useob;
ar
ar
ar
ar
ar
ar
idva;
Define:
female
age =
cente
Analysis:
type
estim
proc
biter
Model:
%With%
resid;
phi | resid on resid;
urge@0.01;
logv | resid;
syx | resid on negaff;
negaff;

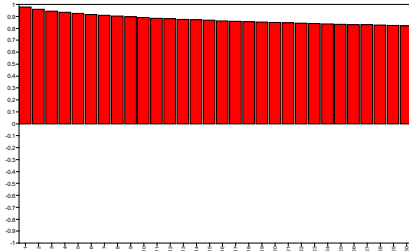
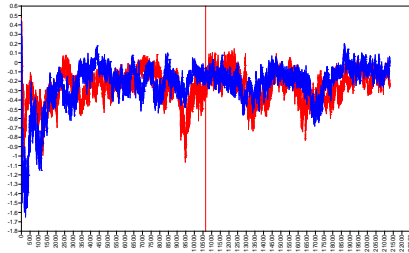
%Between%
urge phi logv syx on female age;
urge phi logv syx with urge phi logv syx;
```

TECHNICAL 8 OUTPUT FOR BAYES ESTIMATION

ITERATION	POTENTIAL SCALE REDUCTION	PARAMETER WITH HIGHEST PSR	TIME	TOTAL TIME
100	1.080	12	16.83	16.8
200	1.072	20	17.27	34.1
300	1.057	19	16.78	50.9
400	1.085	3	16.71	67.6
500	1.076	16	17.07	84.7
600	1.082	21	16.77	101.4
700	1.098	23	16.99	118.4
800	1.112	20	16.80	135.2
900	1.072	23	16.79	152.0
1000	1.063	8	16.97	169.0
1100	1.106	8	16.90	185.9
1200	1.149	8	16.97	202.9
1300	1.179	8	17.04	219.9
1400	1.182	8	17.23	237.1
1500	1.210	8	16.87	254.0
1600	1.214	8	18.05	272.1
1700	1.206	8	17.40	289.5
1800	1.178	8	17.40	306.9
1900	1.158	8	17.28	324.1
2000	1.144	8	17.09	341.2
2100	1.131	8	16.80	358.0

to finish its execution....
-C in the MS-DOS window

Trace and Autocorrelation Plots Indicating Poor Mixing



Wang & Preacher (2014). Moderated mediation analysis using Bayesian methods. *Structural Equation Modeling*.

- Comparison of ML (with bootstrap) and Bayes: Similar statistical performance
- Comparison of Bayes using BUGS versus Mplus: Mplus is 15 times faster
- Reason for Bayes being faster in Mplus:
 - Mplus uses Fortran (fastest computational environment)
 - Mplus uses parallel computing so each chain is computed separately
 - Mplus uses the largest updating blocks possible - complicated to program but gives the best mixing quality
 - Mplus uses sufficient statistics when possible
- Mplus Bayes considerably easier to use

Nevertheless - It's Going To Be Slower Than Usual: Timings For The Runs In This Talk

Using smoking data with $N = 230$, $T \approx 150$

- N=1 analysis of subject 227: 0 seconds
- First two-level analysis: 3:13
- Cross-classified analysis spotting a trend: 1:11
- Two-level trend analysis: 4:02
- Cross-classified trend analysis: 34 minutes
- Cross-classified ordinal factor analysis: 54 minutes (dichotomous 34 mins, continuous 16 mins)

Bengts PC as of June 2012: Dell XPS 8500, i7-3770 with 8 processors, CPU of 3.40 GHz, 12 GB RAM, 64-bit.

- Gelman et al. (2014). *Bayesian Data Analysis*, 3rd edition
- Lynch (2010). *Introduction to Applied Bayesian Statistics and Estimation for Social Scientists*
- Bayes technical reports on the Mplus website: See www.statmodel.com under Papers, Bayesian Analysis
- Muthén (2010). Bayesian analysis in Mplus: A brief introduction. Technical Report. www.statmodel.com
- Chapter 9 of Muthén, Muthén & Asparouhov (2016). *Regression and Mediation Analysis using Mplus*

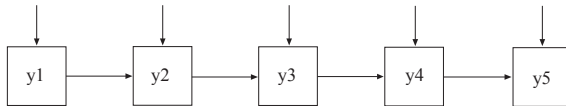
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- Non-intensive longitudinal data:
 - T small (2 - 10) and N large
 - Modeling: Auto-regressive (cross-lagged) and growth modeling
- Intensive longitudinal data:
 - T large (30-200) and N smallish (even $N = 1$) but can be 1,000. Often $T > N$
 - Modeling: We shall see

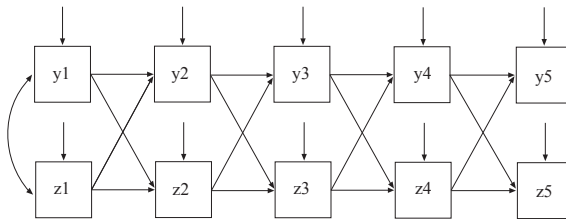
Common Methods for Non-Intensive Longitudinal Data

N large and T small (2 - 10):

(1) Auto-Regressive Modeling



Cross-lagged modeling (e.g. y = urge, z = negative affect):

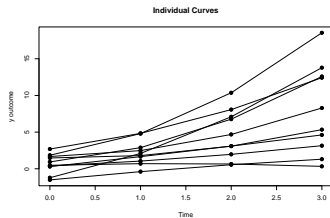
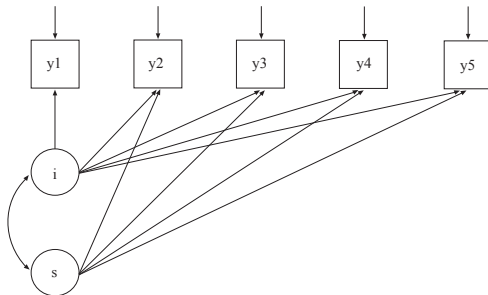


Extensions of the classic cross-lagged panel model:

- Hamaker et al., *Psych Methods* 2015: The random intercepts cross-lagged panel model
- Curran et al., *J of Consulting & Clinical Psych* 2014: The separation of between-person and within-person components
- Berry and Willoughby, *Child Development* 2016: Rethinking the cross-lagged panel model (growth model added)
 - Both models are fitted in Mplus

Common Methods for Non-Intensive Longitudinal Data:

(2) Growth Modeling

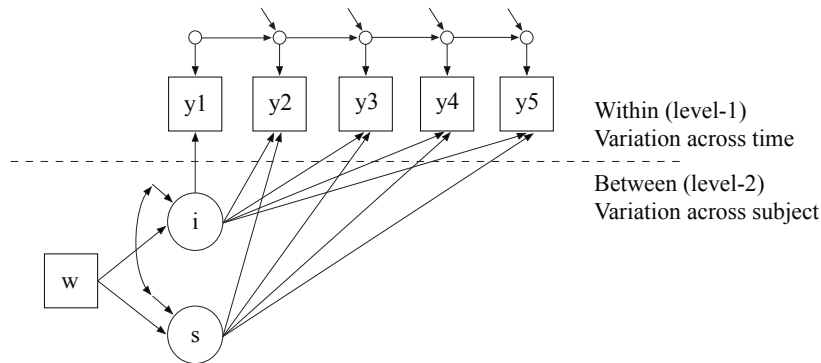


Why Is Regular Growth Modeling Not Sufficient For ILD?

There are 2 problems:

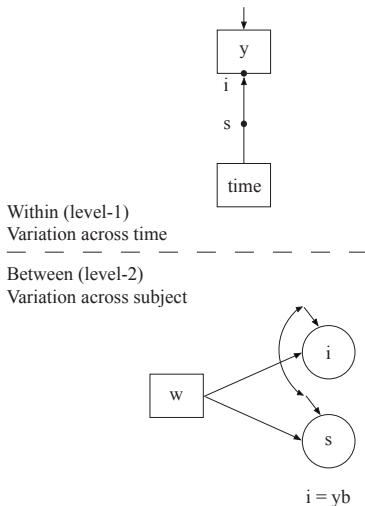
- 1 Correlation between time points not fully explained by growth factors alone due to closely spaced measurements - autocorrelation needs to be added
- 2 Time series are too long due to slow computations

Solving Problem 1. Add Residual (Auto) Correlation: Growth Modeling In Single-Level, Wide Format Version y as 5 columns in the data

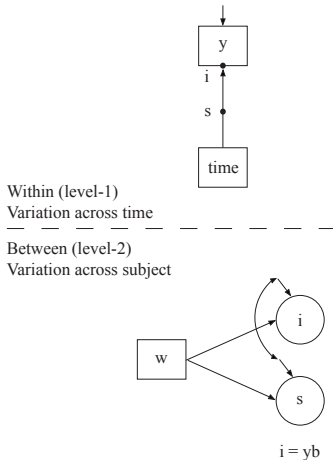


Mplus User's Guide ex6.17 - but cumbersome with large T.

Solving Problem 2. Switch From Single-Level to Two-Level, Long Format Version: y as 1 column in the data



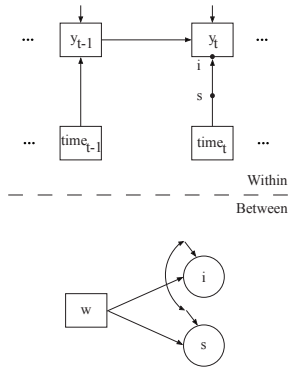
Growth Modeling In Two-Level, Long Format



```
VARIABLE: CLUSTER = subject;  
          WITHIN = time;  
          BETWEEN = w;  
  
ANALYSIS: TYPE = TWOLEVEL RANDOM;  
  
MODEL:   %WITHIN%  
         s | y ON time;  
         %BETWEEN%  
         y s ON w; ! y is the same as i  
         y WITH s;
```

But where is the autocorrelation? And how can it be made random?

Solution: Two-Level Time Series Analysis With A Trend Allowing Autocorrelation and Many Time points



Autoregression for the residuals instead?

Hamaker (2005). Conditions for the equivalence of the autoregressive latent trajectory model and a latent growth curve model with autoregressive disturbances. *Sociological Methods & Research*.

Example: Smoking Cessation (EMA)

Overview of Analyses

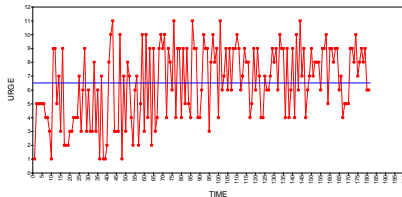
- $N = 1$ time series analysis
- Two-level time series analysis
- Cross-classified time series analysis - looking for trends over time and finding trend functions
- Adding trend to two-level time series analysis
- Cross-classified time series analysis with a trend
- Time-varying effect modeling (TVEM) using cross-classified time series analysis

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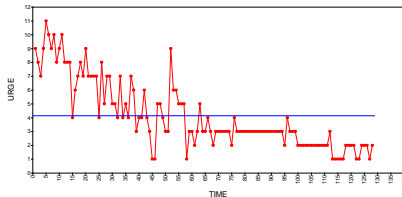
- Shiffman smoking cessation data
- $N = 230$, $T \approx 150$: Random prompts from Personal Digital Assistant (hand held PC) approx. 5 times per day for a month
- Variables: Smoking urge (0-10 scale), negative affect (unhappy, irritable, miserable, tense, discontent, frustrated-angry, sad), gender, age, quit/relapse
- Shiyko et al. (2012). Using the time-varying effect model (TVEM) to examine dynamic associations between negative affect and self confidence on smoking urges. *Prevention Science*, 13, 288-299

N = 1 Time Series Analysis Of Subjects 227 And 5

Smoking urge plotted against time for subject 227 (didn't quit)



Smoking urge plotted against time for subject 5 (did quit)



N = 1 Time Series Analysis Of Subjects 227 And 5

	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I.		Significance
				Lower 2.5%	Upper 2.5%	
urge ON						
urge&l	0.112	0.068	0.060	-0.027	0.240	
negaff	1.196	0.178	0.000	0.810	1.542	*
Intercepts						
urge	4.882	0.494	0.000	3.899	5.865	*
Residual Variances						
urge	5.719	0.635	0.000	4.646	7.070	*

	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I.		Significance
				Lower 2.5%	Upper 2.5%	
urge ON						
urge&l	0.822	0.050	0.000	0.723	0.918	*
negaff	-0.257	0.408	0.272	-1.087	0.516	
Intercepts						
urge	0.517	0.377	0.074	-0.247	1.230	
Residual Variances						
urge	2.007	0.272	0.000	1.566	2.617	*

- Used to create a new time variable and insert missing data records when data are misaligned with respect to time:
 - due to missed measurement occasions that are not assigned a missing value flag
 - due to random measurement occasions

For more details, technical discussion and simulations, see Asparouhov, Hamaker, Muthén (2017) at www.statmodel.com.

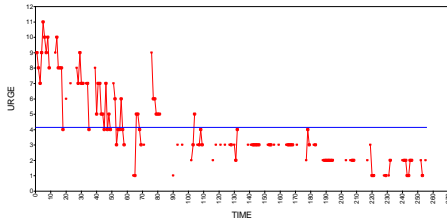
A Tinterval Example for One Subject

- Observed time given in fractions of a day - the 7 time points of the first day for one subject are shown in the table below
- An interval of 0.08 is used corresponding approximately to 2 hours ($2/24 = 0.0833$), that is, bin size = 0.08
- The lowest observed time is 0.32 (0.32×24 is 7:41 am); this is the mid point of the first bin, with the new time value 1 used in the analysis

Observed time	Bins	New time	Outcome
0.32	0.28 - 0.36	1	observed
0.39	0.36 - 0.44	2	observed
0.51	0.44 - 0.52	3	observed
0.59	0.52 - 0.60	4	observed
0.62	0.60 - 0.68	5	observed
	0.68 - 0.76	6	missing
0.77	0.76 - 0.84	7	observed
	0.84 - 0.92	8	missing
0.93	0.92 - 1.00	9	observed

N = 1 Time Series Analysis Using Tinterval=timeqd(0.08)

Subject 5 (did quit): Tinterval results in missing data records inserted to resolve different time distances between measurements



	Estimate	Posterior S.D.	One-Tailed P-Value	95% C.I.		Significance
				Lower 2.5%	Upper 2.5%	
Subject 5 without Tinterval						
urge ON						
urge&l	0.822	0.050	0.000	0.723	0.918	*
negaff	-0.257	0.408	0.272	-1.087	0.516	
Subject 5 with Tinterval (0.08)						
urge ON						
urge&l	0.844	0.037	0.000	0.772	0.917	*
negaff	-0.158	0.382	0.328	-0.930	0.577	

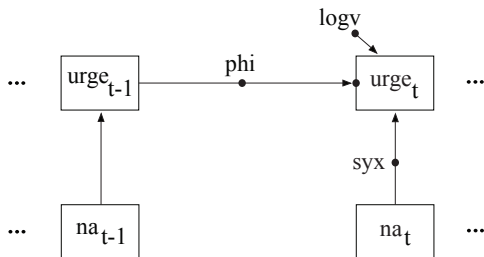
Mplus Input For Subject 5 Time Series Regression

TITLE: Shiffman smoking urge data N = 1 model for subject 5 (quit=1)
DATA: FILE = combined_relapsers_quitters_03-17-17.csv;
VARIABLE: NAMES = subject t day urge craving negaff arousal timeqd
 gender age quit;
 ! quit = 1 for quitters, 0 for relapsers
 USEVARIABLES = urge negaff;
 LAGGED = urge(1);
 MISSING = ALL(999);
 TINTERVAL = timeqd(0.08);
 USEOBSERVATIONS = subject EQ 5;
 IDVARIABLE = _recnum;
ANALYSIS: **ESTIMATOR = BAYES;**
 PROCESSORS = 2;
 BITERATIONS = (1000);
MODEL: **urge ON urge&1 negaff;**
 negaff;
OUTPUT: TECH1 TECH8 STANDARDIZED TECH4 RESIDUAL;
PLOT: TYPE = PLOT3;

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- Analysis of all $N = 230$ smoking data subjects
 - Allowing for parameter variation across subjects using random effects

Two-Level Time Series Analysis: Regression of Smoking Urge on Negative Affect (na) Using 4 Random Effects



Within

Mplus Input for Two-Level Regression Analysis

VARIABLE: NAMES = subject t day urge craving negaff arousal timeqd
gender age quit;
!quit = 1 for quitters, 0 for relapsers
USEVARIABLES = urge negaff age female;
CLUSTER = subject;
BETWEEN = female age;
WITHIN = negaff;
LAGGED = urge(1) negaff(1);
MISSING = ALL(999);
TINTERVAL = timeqd(0.08);

DEFINE: female = gender - 1;
age = (age-44.3)/10.1;
CENTER negaff(GROUPMEAN);

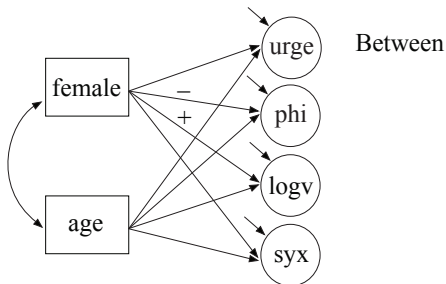
ANALYSIS: **TYPE = TWOLEVEL RANDOM;**
ESTIMATOR = BAYES;
PROCESSORS = 2;
BITERATIONS = (1000);

Mplus Input for Two-Level Regression Analysis, Cont'd

MODEL:	%WITHIN% phi urge ON urge&1; logv urge; syx urge ON negaff; negaff ON negaff&1; %BETWEEN% urge phi logv syx ON female age; urge phi logv syx WITH urge phi logv syx;
OUTPUT:	TECH1 TECH8 FSCOMPARISON STANDARDIZED TECH4 RESIDUAL;
PLOT:	TYPE = PLOT3; FACTORS = ALL;

Run time: 3:13

Between-Level Results



- phi ON female not significant unless both logv and syx are allowed to be random

New Output Warnings

*** WARNING

One or more individual-level variables have no variation within a cluster for the following clusters.

Variable Cluster IDs with no within-cluster variation

URGE 160 12 60 192 186 49

WARNING: PROBLEMS OCCURRED IN SEVERAL ITERATIONS IN THE COMPUTATION OF THE STANDARDIZED ESTIMATES FOR SEVERAL CLUSTERS. THIS IS MOST LIKELY DUE TO AR COEFFICIENTS GREATER THAN 1 OR PARAMETERS GIVING NON-STATIONARY MODELS. SUCH POSTERIOR DRAWS ARE REMOVED. THE FOLLOWING CLUSTERS HAD SUCH PROBLEMS:

160 115 205

BETWEEN-LEVEL FACTOR SCORE COMPARISONS

Results for Factor PHI

Ranking	Cluster	Factor Score	Ranking	Cluster	Factor Score	Ranking	Cluster	Factor Score
1	115	0.941	2	11	0.936	3	205	0.912
4	113	0.907	5	138	0.906	6	4	0.901

Checking the Time Interval Value

- The choice of 0.08 gives a warning:
THE VALUE SPECIFIED IN THE TINTERVAL OPTION MAY BE TOO BIG. THE MAXIMUM DISCREPANCY BETWEEN THE ACTUAL TIME AND THE TIME RECODED BY THE TINTERVAL OPTION IS 9.517 IN CLUSTER 33.
- 0.08 corresponds to 2 hours: $2/24 = 0.08$
- Because in this run 0.08 is represented as one time unit in the analysis, 9.517 corresponds to $9.517 * 2 = 19$ hours displacement
- Given the large displacement, the data for cluster (subject) 33 should be inspected: first 30 observations made in less than 2-day span!? (aim: 5/day)
- 0.08 should perhaps be changed to say 0.04

Checking Sensitivity to Tinterval Choices

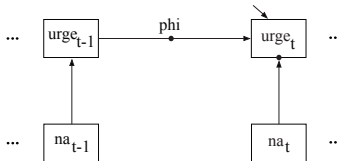
Univariate analysis of urge ON urge&1 with non-random ϕ and only the mean random

Tinterval	ϕ	Coverage	Time (secs)
0.08	0.325	0.41	22
0.06	0.344	0.31	25
0.04	0.373	0.20	40

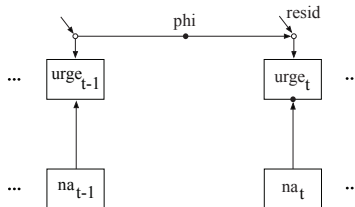
- If an AR(1) model holds, ϕ with interval t (say 0.04), results in ϕ^2 for interval $2t$ (0.08)
- Because 0.373^2 is not equal to 0.325, a pure AR(1) model does not hold (for instance, urge ON urge&2 is significant)
- Smaller time interval gives more missing data, i.e. lower coverage
 - 10 - 15 % coverage is good
 - Coverage as low as 5% is ok
- Smaller time interval gives longer run time

Technical Interlude: Ampersand Versus Hat

Where Should The Autocorrelation Be Applied?



Within



Within

Comparing Regular vs Residual Auto-Correlation

- AR for the residual language (version 8.1):

urge ON negaff;
phi | urge^ ON urge^1;

Model	DIC	pD
AR for the whole outcome	45,3727	69623
AR for the residual	45,6347	70440

- DIC: Deviance information criterion
 - Bayesian counterpart to BIC (lower is better)
- pD: Effective number of parameters
 - Also includes latent variables and missing data
- Requires a large number of iterations (20K used here); only for continuous outcomes

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- Latent variable time series analysis

Cross-Classified Time Series Analysis ($N > 1$)

- Two between-level cluster variables: subject crossed with time (one observation for a given subject at a given time point).
- Generalization of the two-level model providing more flexibility: random effects can vary across not only subject but also time

Consider the two-level model with a random intercept/mean:

$$y_{it} = \underbrace{\alpha + \alpha_i}_{\text{Between subject}} + \underbrace{\beta y_{w,it-1} + \varepsilon_{it}}_{\text{Within subject}}. \quad (2)$$

The corresponding cross-classified model is:

$$y_{it} = \underbrace{\alpha + \alpha_i}_{\text{Between subject}} + \underbrace{\alpha_t}_{\text{Between time}} + \underbrace{\beta y_{w,it-1} + \varepsilon_{it}}_{\text{Within subject}}. \quad (3)$$

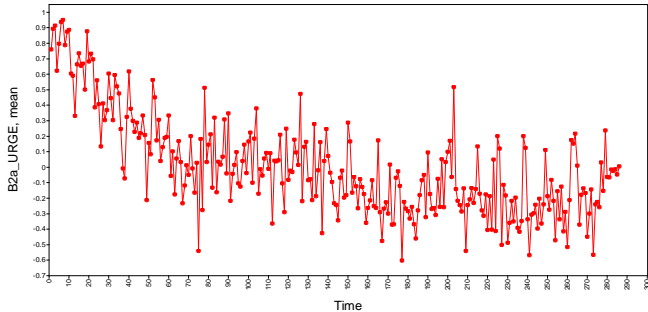
- The Bayes MCMC algorithm is more complex and considerably slower

Cross-Classified Analysis:

A Quick Way to Spot a Trend in a Variable

TITLE:	Shiffman smoking urge data, checking for trend in urge
DATA:	FILE = combined_relapsers_quitters_03-17-17.csv;
VARIABLE:	NAMES = subject t day urge craving negaff arousal timeqd gender age quit; !quit = 1 for quitters, 0 for relapsers USEVARIABLES = urge; CLUSTER = subject timeqd; LAGGED = urge(1); MISSING = ALL(999); TINTERVAL = timeqd(0.08);
ANALYSIS:	TYPE = CROSSCLASSIFIED RANDOM; ESTIMATOR = BAYES; PROCESSORS = 2; BITERATIONS = (1000);
MODEL:	% WITHIN % urge ON urge&1; % BETWEEN subject % urge; % BETWEEN timeqd % urge;
OUTPUT:	TECH1 TECH8;
PLOT:	TYPE = PLOT3; FACTORS = urge(50);

Cross-Classified Analysis of Trend: Time Series Plot of Urge Factor Scores



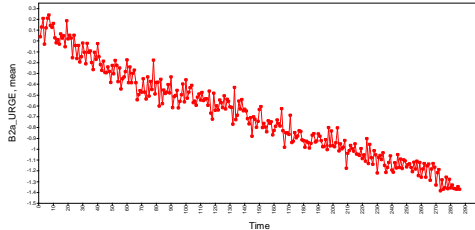
- Run time is only 1:11 with fixed AR(1)
- The trend can be modeled according to some functional form
 - In a cross-classified analysis
 - In a two-level analysis

Imposing Linear/Quadratic Trend in Cross-Classified

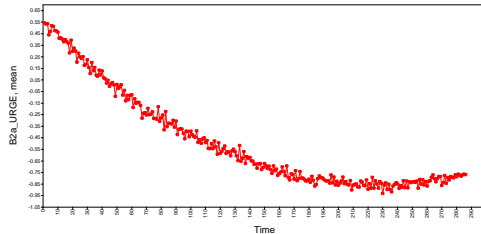
VARIABLE:	NAMES = subject t day urge craving negaff arousal timeqd gender age quit; !quit = 1 for quitters, 0 for relapsers USEVARIABLES = urge time time2; CLUSTER = subject timeqd; BETWEEN = (timeqd) time time2; LAGGED = urge(1); MISSING = ALL(999); TINTERVAL = timeqd(0.08);
DEFINE:	time = timeqd/100; time2 = time*time;
ANALYSIS:	TYPE = CROSSCLASSIFIED RANDOM; ESTIMATOR = BAYES; PROCESSORS = 2; BITERATIONS = (2000);
MODEL:	%WITHIN% urge ON urge&1; %BETWEEN subject% urge; %BETWEEN timeqd% urge; urge ON time time2;
OUTPUT:	TECH1 TECH8;
PLOT:	TYPE = PLOT3; FACTORS = urge(50);

Imposing Linear/Quadratic Trend in Cross-Classified

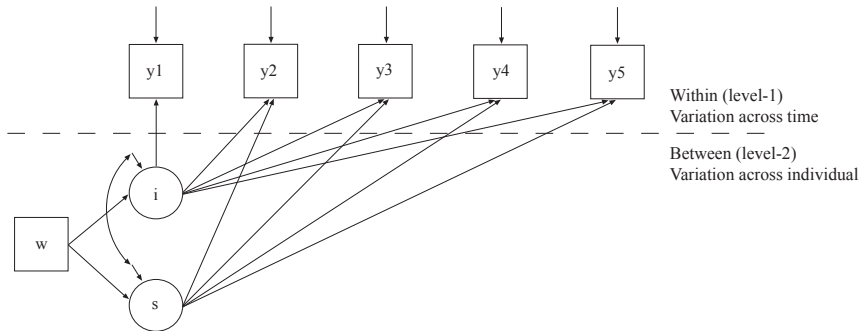
Linear:



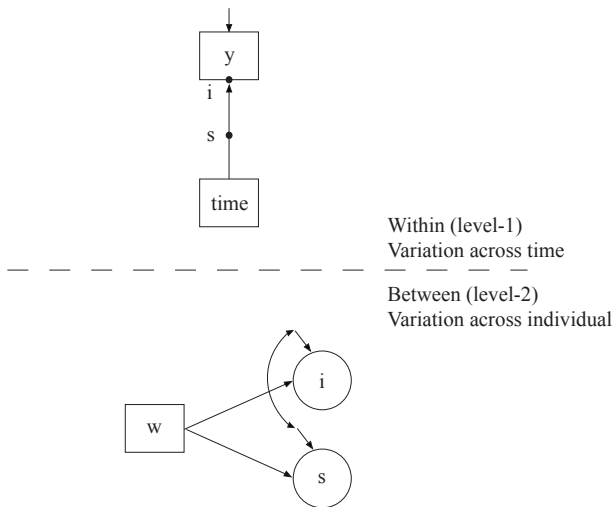
Quadratic:



Modeling the Trend: Recall How Growth Modeling Can Be Transformed From Wide To Long



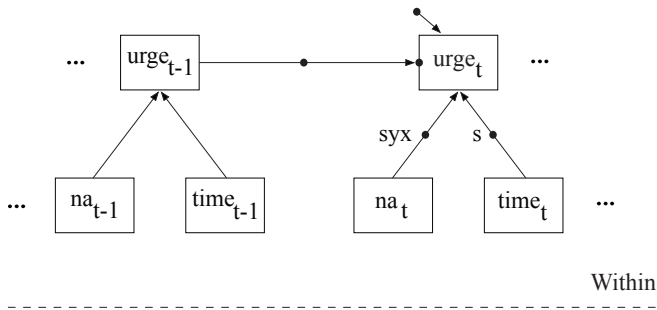
Growth Modeling: Two-Level, Long Format Version



Two-Level Time Series Analysis of Smoking Urge data

Adding a Trend for Urge.

- Growth Analysis with a Time-Varying Covariate



- Interpretation of s not the usual one; direct effect at each time
- An alternative formulation places the autoregression on the residuals (Hamaker, 2005; *SM&R*), resulting in the usual s interpretation

Mplus Input For Two-Level Trend Analysis

VARIABLE: NAMES = subject t day urge craving negaff arousal timeqd
 gender age quit;
 USEVARIABLES = urge quit negaff age female time;
 CLUSTER = subject;
 BETWEEN = female age quit;
 CATEGORICAL = quit;
 WITHIN = time negaff;
 LAGGED = urge(1);
 MISSING = ALL(999);
 TINTERVAL = timeqd(0.08);

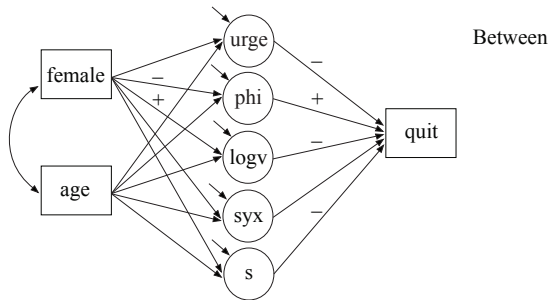
DEFINE: female = gender - 1;
 age = (age-44.3)/10.1;
 time = timeqd/100-1.305;
 CENTER negaff(GROUPMEAN);

ANALYSIS: TYPE = TWOLEVEL RANDOM;
 ESTIMATOR = BAYES;
 PROCESSORS = 2;
 BITERATIONS = (1000);

MODEL:	%WITHIN% phi urge ON urge&1; syx urge ON negaff; logv urge; s urge ON time; negaff; time; %BETWEEN% urge syx s phi logv ON female age; urge syx s phi logv WITH urge syx s phi logv; quit ON urge syx s phi logv female age;
OUTPUT:	TECH1 TECH8 FSCOMPARISON STANDARDIZED TECH4 RESIDUAL;
PLOT:	TYPE = PLOT3; FACTORS = ALL;

Run time: 4:02 (3:17 without FACTORS = ALL)

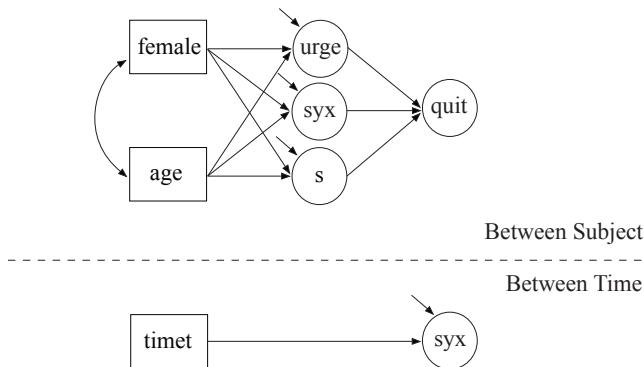
Results for Two-Level Regression Analysis of Smoking Urge Data: Adding a Trend for Urge. - Growth Analysis with a Time-Varying Covariate



Time-Varying Effect Modeling (TVEM) Using Cross-Classified Analysis

- Cross-classified modeling allows parameters to change over time
- An example is a regression slope
 - Does the influence of negative affect on smoking urge decline over time?

Cross-Classified Regression Analysis of Smoking Urge Data: Adding a Trend for Urge and the Negaff Regression Slope Cross-Classified Growth Analysis With a Time-Varying Covariate



Mplus Input for Cross-Classified Regression Analysis with an Urge Trend and a Negaff Slope Trend

VARIABLE: NAMES = subject t day urge craving negaff arousal timeqd
gender age quit;
! quit = 1 for quitters, 0 for relapsers
USEVARIABLES = urge quit negaff age female timew timet;
CLUSTER = subject timeqd;
BETWEEN = (subject) female age quit (timeqd) timet;
CATEGORICAL = quit;
WITHIN = negaff timew;
LAGGED = urge(1);
MISSING = ALL(999);
TINTERVAL = timeqd(0.08);

DEFINE: female = gender - 1;
age = (age-44.3)/10.1;
timew = timeqd/100-1.305;
timet = timew;
CENTER negaff(GROUPMEAN subject);

ANALYSIS: TYPE = CROSS RANDOM;
ESTIMATOR = BAYES;
PROCESSORS = 2;
BITERATIONS = (1000);

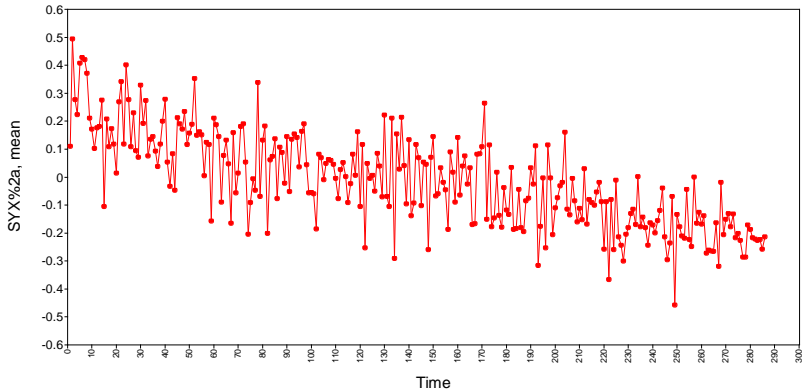
MODEL:	<pre>% WITHIN % urge ON urge&1; syx urge ON negaff; s urge ON timew; negaff; timew; % BETWEEN subject % urge syx s ON female age; urge syx s WITH urge syx s; quit ON urge syx s female age; % BETWEEN timeqd % syx ON timet; urge WITH syx; s@0;</pre>
OUTPUT:	<pre>TECH1 TECH8;</pre>
PLOT:	<pre>TYPE = PLOT3; FACTORS = ALL;</pre>

- Run time: 34 minutes

Trend in Slope for Urge Regressed on Negative Affect

%BETWEEN timeqd%

syx ON timet; ! the estimate is significant negative



- syx%2a is the factor score for the slope
- The effect of negative affect on smoking urge is reduced over time

- Introduction to Bayesian analysis
- Introduction to longitudinal analysis
- N=1 time series analysis
- Two-level time series analysis
- Cross-classified time series analysis
- **Latent variable time series analysis**

Time Series Analysis with Latent Variables:

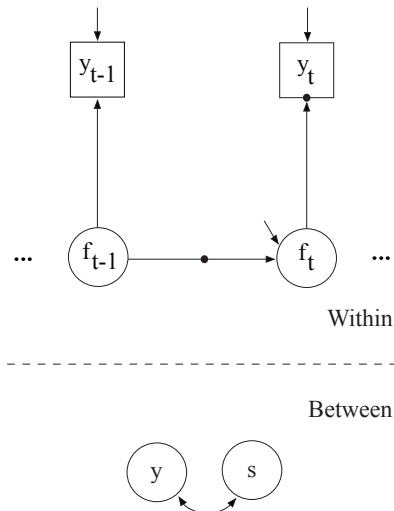
Latent Variables on the Within Level

- So far we have focused on latent variables on the between level in the form of random effects
 - Although on Within we have used the latent variable within-level decomposition of the outcome, centering by y_{bi} :

$$y_{wit} = y_{it} - y_{bi}$$

- Now we introduce within-level factors:
 - Factors defined by single indicators with measurement error
 - Residual factors in ARMA(1,1)
 - Factors defined by multiple indicators
 - Two-level and Cross-classified analysis
- Categorical latent variables (version 8.x, although an SEM article is already online; Asparouhov, Hamaker, Muthén, 2017):
 - Transition modeling (Hidden Markov, regime switching, time-series LTA) with latent class variables
 - Growth mixture modeling

Single-Indicator Measurement Error Model

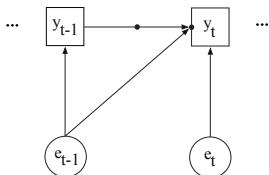


- Two types of errors:
 - Dynamic errors carry over from occasion to occasion (unobserved influences)
 - Measurement errors don't carry over (making errors answering; white noise)
- The model is identified unlike regular factor analysis due to auto-regressive feature (like panel data modeling a la Werts, Linn & Jöreskog, 1977)
- Schuurman et al. (2015) *Frontiers of Psych*; $N = 1$

Input for Measurement Error Model

TITLE:	this is an example of a two-level time series analysis with a first-order autoregressive AR(1) factor analysis model for a single continuous indicator and measurement error
DATA:	FILE = ex9.33.dat;
VARIABLE:	NAMES = y subject; CLUSTER = subject;
ANALYSIS:	TYPE = TWOLEVEL RANDOM; ESTIMATOR = BAYES; PROCESSORS = 2; BITERATIONS = (5000);
MODEL:	%WITHIN% f BY y@1(&1); s f ON f&1; %BETWEEN% y WITH s;
OUTPUT:	TECH1 TECH8;
PLOT:	TYPE = PLOT3;

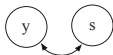
A Related Model: ARMA(1,1)



Within

MODEL: %WITHIN%
s | y ON y&1;
e BY y@1 (&1);
y@.01;
y ON e&1;

Between

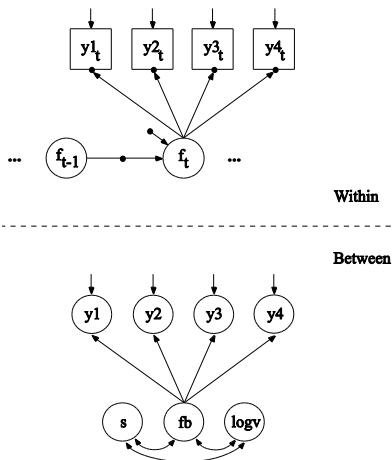


- AR stands for autoregressive and MA stands for moving average (Shumway & Stoffer, 2011)

Thoughts on Measurement Error versus ARMA(1,1)

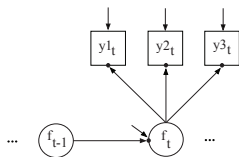
- Granger and Morris (1976) and Schuurman et al. (2015) show that for $N = 1$ time series analysis, ARMA (1, 1) is an alternative representation of the data used in the measurement error model; formulas show translation of parameters
 - In the Mplus implementation the measurement error formulation converges more smoothly than ARMA(1,1)
 - The $N = 1$ versions of these models require a large T , say $T > 100$
 - Preliminary simulations indicate that the $N > 1$ versions have good performance at $T = 50$, reasonable performance at $T = 25$, and maybe acceptable performance at $T = 14$: Suitable for daily diary designs
- AR models assume exponential decays in autocorrelation - the measurement error model allows a slower, more realistic decay (Asparouhov, 2017)
- A preliminary observation: it appears to be difficult to add random variance to the factor in the measurement error model
- Research questions: How does performance compare to having multiple indicators (e.g. 10 NA items)? Is random variance easier there?

Two-Level Factor Analysis: UG ex9.34



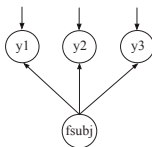
- Random intercepts become latent factor indicators on Between
- The figure shows a DAFS (direct autoregressive factor score) model on Within
- An alternative is the WNFS (white noise factor score) model which uses $y1$ - $y4$ ON $f\&1$ instead of f ON $f\&1$
- A combination model is also identified (may need large T)
- $N = 1$ factor analysis: Engle & Watson (1981) in JASA, Molenaar (1985) in Psychometrika

Cross-Classified Factor Analysis: UG ex9.40

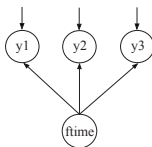


Within

Between
subject



Between
time



Measurement Non-Invariance Across Subjects

Using Two-Level Factor Analysis: Random Intercepts

- For a certain item measured for individual i at time t , two-level factor analysis (see, e.g., Muthén, 1994) considers

$$y_{it} = \underbrace{\nu + \lambda_b f_{bi} + \varepsilon_{bi}}_{\text{Between}} + \underbrace{\lambda_w f_{wit} + \varepsilon_{wit}}_{\text{Within}}. \quad (4)$$

- This can be re-expressed as

$$\text{Level 1: } y_{it} = \nu_i + \lambda_w f_{wit} + \varepsilon_{wit}, \quad (5)$$

$$\text{Level 2: } \nu_i = \nu + \lambda_b f_{bi} + \varepsilon_{bi}, \quad (6)$$

which is a random intercept model, that is, there is measurement non-invariance across subjects wrt the intercepts (Jak et al., 2013, 2014; Muthén & Asparouhov, 2017). IRT typically uses $\lambda_w = \lambda_b$, $\varepsilon_{bi} = 0$,

$$\text{Level 1: } y_{it} = \nu + \lambda f_{it} + \varepsilon_{wit}, \quad (7)$$

$$\text{Level 2: } f_{it} = f_{bi} + f_{wit}, \quad (8)$$

- that is, no non-invariance and one single factor dimension

Measurement Non-Invariance of Intercepts and Loadings Across Subjects and Time

- Two-level analysis:
 - Random intercepts varying across subjects
 - Random loadings varying across subjects: $s1 - s10 \mid f BY y1 - y10$
 - Asparouhov & Muthén (2015), Fox (2010)
- Cross-classified analysis:
 - Random intercepts varying across subjects and **time**
 - Random loadings varying across subjects
 - Version 7.4 had cross-classified analysis with random intercepts and loadings but not auto-correlation needed for ILD
 - For an example of random loadings varying across subjects, see the Mplus Version 8 User's Guide ex9.40 part2

- The two-level and cross-classified factor analysis models imply
 - Measurement intercept and loadings possibly varying across subject and time
 - Factor variances and residual variances varying across subject and time
- This implies that reliabilities of test scores (based on a set of items) vary across subject and time
 - Hu, Nesselroade et al. (2016). Test reliability at the individual level. *Structural Equation Modeling*.
- But why not instead look at the precision with which the factor scores can be estimated?
 - Mplus Version 8 Monte Carlo simulations give correlations between true scores and estimated scores

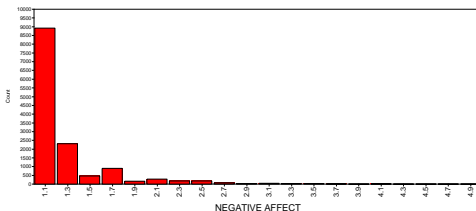
Example: Item Factor Analysis (IRT)

Using 10 Negative Affect Items

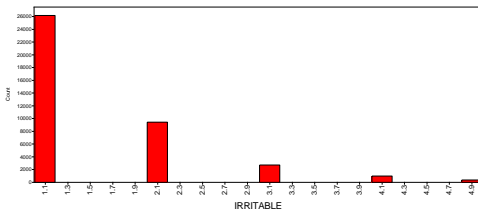
- Data from the older cohort of the Notre Dame Study of Health & Well-being (Bergeman): $N = 270$, $T = 56$ (daily measures on consecutive days)
- Wang, Hamaker, Bergeman (2012). Investigating inter-individual differences in short-term intra-individual variability. *Psychological Methods*
- Predictors and distal outcomes of negative affect development over the 56 days
- 10 NA items (5-cat scale): afraid, ashamed, guilty, hostile, scared, upset, irritable, jittery, nervous, distressed (average score used in article). Wide format would have 56×10 variables
- Question format: Today I felt... (1 = Not at all, ..., 5 = Extremely)
- 1-factor DAFS model

Negative Affect Distributions of NA in Bergeman Data

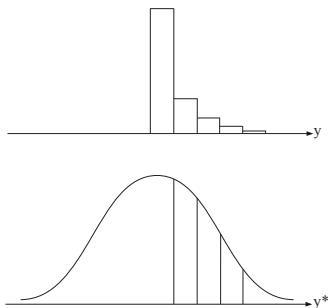
Average score (55% at floor value of 1 - Not at all for all 10 items):



Typical item distribution (66% at lowest value - Not at all):



Ordered Categorical Item Modeling: Proportional Odds Model (Graded Response Model)



- Despite non-normal y , we can have normality of:
 - The latent response variable y^*
 - Any factors in the model
 - The between-level random effects

Mplus Input for Cross-Classified Factor Analysis with One Factor for 10 Ordinal NA Items

TITLE: Bergeman twolevel
DATA: FILE = bergeman.csv;
VARIABLE: NAMES = subject gender age hosp1 chrhlth1 Somhlth1 slfhlth1
psqi neo day afraid1 unhappy1 annoyd1 ashmd1 guilty1 an-
gry1 sad1 hostile1 scared1 upset1 irrtbl1 deprsd1 jttry1 drowsy1
slugish1 worrid1 nervs1 lonely1 fatiged1 distrsd1 nPANAS1;
USEVARIABLES = afraid1 scared1 nervs1 jttry1 guilty1
ashmd1 irrtbl1 hostile1 upset1 distrsd1;
CATEGORICAL = afraid1-distrsd1;
CLUSTER = subject day;
MISSING = all(999);
TINTERVAL = day(1);
ANALYSIS: **TYPE = CROSSCLASSIFIED RANDOM;**
ESTIMATOR = BAYES;
PROCESSORS = 2;
BITERATIONS = (5000);
THIN = 10;

- IRT-style loading equality, setting the factor metric on the subject level

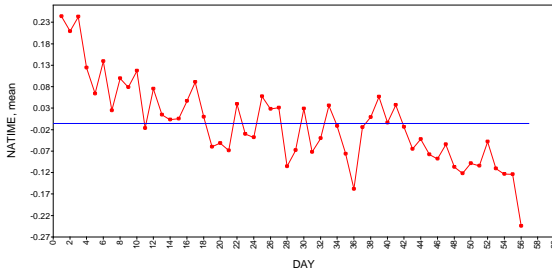
MODEL:	% WITHIN % na_w BY afraid1-distrsd1* (&1 1-10); na_w ON na_w&1; % BETWEEN SUBJECT % na_subj BY afraid1-distrsd1* (1-10); na_subj@1; % BETWEEN DAY % na_time BY afraid1-distrsd1* (1-10);
OUTPUT:	TECH1 TECH8 STDY STDYX TECH4 RESIDUAL FSCOMPARISON;
PLOT:	TYPE = PLOT3; FACTORS = ALL;

Run time: 54 minutes (dichotomized: 34 minutes; continuous: 16 minutes)

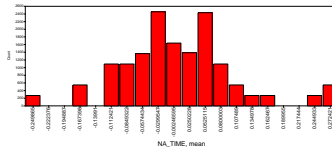
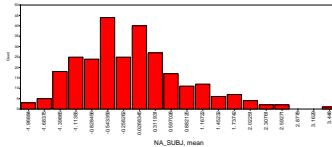
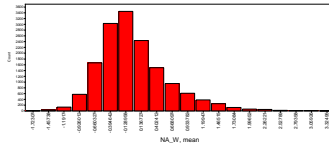
Results of Cross-Classified Factor Analysis with One NA Factor for 10 Ordinal Items

$$na_{factor_{it}} = \underbrace{\alpha + \alpha_i}_{\text{Between subject}} + \underbrace{\alpha_t}_{\text{Between time}} + \underbrace{\beta y_{w,it-1} + \varepsilon_{it}}_{\text{Within subject}}. \quad (9)$$

- $V(na_subject) = 1.00$, $V(na_time) = 0.012$, $V(na_w) = 0.66$
- The factor score plot for the `na_time` factor (on the between day level) shows a drop of 40% of the total factor SD over the 56 days:



Posterior Distributions for the Factor Scores on Within, Between Subject, and Between Time



Feel free to submit your papers to be posted here:

<http://www.statmodel.com/TimeSeries.shtml>

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