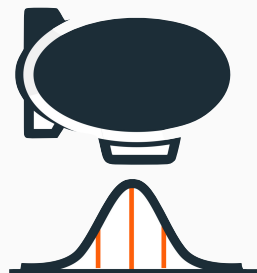


**AN INTRODUCTION TO
BAYESIAN ESTIMATION
AND MISSING DATA IMPUTATION
FOR EDUCATION RESEARCH**

Craig K. Enders & Michael Woller,
UCLA Department of Psychology



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WWW.APPLIEDMISSINGDATA.COM/BLIMP

BLIMP 3.0

Blimp 3 offers powerful latent variable modeling and imputation for incomplete data sets with up to three levels. Blimp's unique Bayesian computational architecture allows easy specification of complex analyses that are difficult or impossible to fit in other software packages.

[Download Now](#)

[User's Guide](#)



2

APPLIED MISSING DATA

[home](#) [analysis examples](#) [blimp](#) [blimp papers](#) [centerstat workshop](#) [quantitude podcast](#)

Workshops and Training

Enders, C. K., & Woller, M. (2023, April). An introduction to Bayesian estimation and missing data imputation for educational research. Professional development workshop presented at the annual meeting of the American Educational Research Association. Chicago, IL.

[» Download Workshop Materials](#)

ACKNOWLEDGEMENTS

Brian Keller & Han Du



WORKSHOP OUTLINE

- Missing data processes
- Introduction to Bayesian estimation
- Fitting regression models in Blimp
- Understanding Blimp output
- Incomplete categorical variables
- Interaction effects in Blimp

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Why go Bayesian?

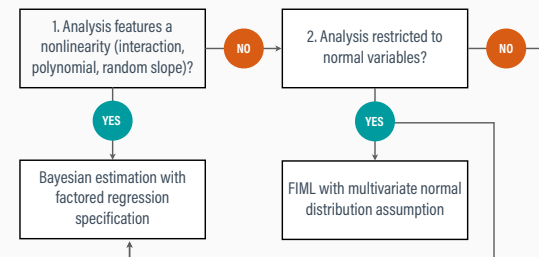
6

THINGS BAYESIAN MCMC IS GOOD AT

- Direct estimation for complex models with missing data
- Mixed metrics (normal, ordinal, nominal, skewed, count, latent)
- Nonlinear effects (interactions, curvilinear effects)
- Multilevel data (random coefficients, interactions, heterogeneous variation)
- Latent variable modeling (interactions, multilevel)

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CHOOSING A MISSING DATA METHOD



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MISSING DATA MECHANISMS

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PARTITIONING THE DATA

Complete			=	Observed			+	Missing			Indicators		
Y ₁	Y ₂	Y ₃		Y ₁	Y ₂	Y ₃		Y ₁	Y ₂	Y ₃	M ₁	M ₂	M ₃
4	4	3		4	4	3					0	0	0
3	3	5		3	NA	5			3		0	1	0
7	1	6		7	1	6					0	0	0
2	1	6		NA	1	6		2			1	0	0
5	9	3	=	5	9	3	+				0	0	0
3	2	2		3	NA	NA			2	2	0	1	1
1	6	7		1	6	7					0	0	0
9	4	9		9	4	9					0	0	0
2	5	6		2	NA	6			5		0	1	0

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RUBIN'S MISSINGNESS MECHANISMS

- Missing data mechanisms describe different ways in which the pattern of 0s and 1s in \mathbf{M} relate to observed or missing values
- Missingness may be independent of the data, or it could relate to the observed or missing parts (or both)
- Mechanisms are essentially models that describe nonresponse

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MISSING COMPLETELY AT RANDOM

- The probability of missing values is completely unrelated to the data

$$f(\mathbf{M} = 1 | \mathbf{Y}_{\text{obs}}, \mathbf{Y}_{\text{mis}}, \phi) = f(\mathbf{M} = 1 | \phi)$$

- Purely haphazard missingness

Relation Between Nonresponse and Data

M			Y _{obs}			Y _{mis}		
M ₁	M ₂	M ₃	Y ₁	Y ₂	Y ₃	Y ₁	Y ₂	Y ₃
0	0	0	4	4	3			
0	1	0	3	NA	5		3	
0	0	0	7	1	6			
1	0	0	NA	1	6	2		
0	0	0	5	9	3			
0	1	1	3	NA	NA	2	2	
0	0	0	1	6	7			
0	0	0	9	4	9			
0	1	0	2	NA	6		5	

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(CONDITIONALLY) MISSING AT RANDOM

- The probability of missing values is unrelated to the missing (latent) data

$$f(\mathbf{M} = 1 | \mathbf{Y}_{\text{obs}}, \mathbf{Y}_{\text{mis}}, \phi) = f(\mathbf{M} = 1 | \mathbf{Y}_{\text{obs}}, \phi)$$

- Missingness is haphazard after conditioning on observed data

Relation Between Nonresponse and Data

M			Y _{obs}			Y _{mis}		
M ₁	M ₂	M ₃	Y ₁	Y ₂	Y ₃	Y ₁	Y ₂	Y ₃
0	0	0	4	4	3			
0	1	0	3	NA	5		3	
0	0	0	7	1	6			
1	0	0	NA	1	6	2		
0	0	0	5	9	3			
0	1	1	3	NA	NA		2	2
0	0	0	1	6	7			
0	0	0	9	4	9			
0	1	0	2	NA	6		5	

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MISSING NOT AT RANDOM

- The probability of missing values is related to the missing (latent) data

$$f(\mathbf{M} = 1 | \mathbf{Y}_{\text{obs}}, \mathbf{Y}_{\text{mis}}, \phi) \text{ or } f(\mathbf{M} = 1 | \mathbf{Y}_{\text{mis}}, \phi)$$

- The observed data may or may not additionally determine missingness

Relation Between Nonresponse and Data

M			Y _{obs}			Y _{mis}		
M ₁	M ₂	M ₃	Y ₁	Y ₂	Y ₃	Y ₁	Y ₂	Y ₃
0	0	0	4	4	3			
0	1	0	3	NA	5		3	
0	0	0	7	1	6			
1	0	0	NA	1	6	2		
0	0	0	5	9	3			
0	1	1	3	NA	NA		2	2
0	0	0	1	6	7			
0	0	0	9	4	9			
0	1	0	2	NA	6		5	

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EDUCATION EXAMPLES

- MCAR = longitudinal planned missing data design where participants provide data at a subset of the repeated measures
- Conditional MAR = students from low SES households are more likely to have missing achievement scores, but missingness is random after controlling for SES
- MNAR = students with low achievement levels are more likely to have missing achievement test scores

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WORKING ASSUMPTIONS

- Like FIML, Bayesian estimation gives consistent estimates (unbiased in large samples) if the process is conditionally MAR
- FIML frequentist inference further assumes that the missingness process replicates across different random samples from the population (missing *always* at random)
- The conditionally MAR assumption is untestable because it involves propositions about the unseen score values

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INTRODUCTION TO BAYESIAN ESTIMATION

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FREQUENTIST VS. BAYESIAN PARADIGMS

Frequentist

- The parameter is a fixed quantity, estimates vary across different samples
- Statements about probability, precision, and confidence refer to estimates
- Probability = long run frequency of outcomes across many samples

Bayesian

- Parameters are random variables with a distribution of plausible realizations
- Statements about probability, precision, and intervals refer to the parameter
- Probability = our degree of certainty about a parameter after analyzing data

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PARAMETERS AS VARIABLES

- Parameters are unknown variables, some realizations (values) are more plausible than others, given our data
- Bayes' theorem is the mathematical tool that converts fixed parameters (frequentist) into variable ones (Bayesian)
- Bayes' theorem is a rule for obtaining conditional probabilities

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BAYES' THEOREM

Posterior = parameters (A) given the data (B)

Likelihood = data (B) given the parameters (A)

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)}$$

Prior = a priori belief about parameters (A)

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PRIOR DISTRIBUTIONS

- Bayesian analyses require prior distributions that encode our beliefs about the parameter values prior to analyzing the data
- Blimp adopts non-informative (diffuse) priors that impart as little information as possible (i.e., let the data do the talking)
- e.g., A diffuse prior for means and coefficients conveys that all possible parameter values are equally likely (a flat distribution)

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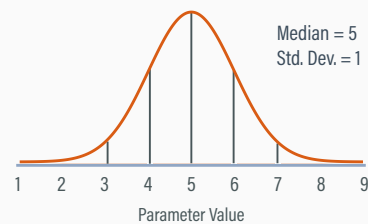
POSTERIOR DISTRIBUTIONS

- The prior and likelihood function as two data sources that merge to define the posterior distribution of the parameters
- The posterior describes a distribution of plausible parameter values that could have produced our particular data set
- Instead of estimates varying around a fixed parameter (frequentist), parameters vary around a fixed data set

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MEDIAN AND STANDARD DEVIATION

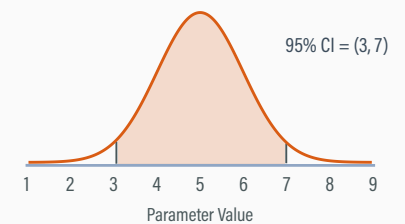
- The posterior median and standard deviation quantify the most likely parameter value and uncertainty
- Analogous to a point estimate and standard error, sans repeated sampling



23

95% CREDIBLE INTERVALS

- The 95% credible interval gives limits spanning 95% of the parameter's range
- Akin to a confidence interval, but references a range of highly plausible parameter values



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AERA WORKSHOP DATA

■ Predictors
■ Outcome

Variable	Definition	Missing %	Scale
<i>STUDENT</i>	Student identifier	0	Integer index
<i>MALE</i>	Gender code	0	0 = Female, 1 = Male
<i>ESL</i>	English as a second language code	5.1	0 = Non-ESL, 1 = ESL
<i>RISKGRP</i>	Emotional/behavioral disorder risk	2.2	1 = Low, 2 = Medium, 3 = High
<i>ATRISK</i>	Emotional/behavioral risk code	2.2	0 = Low, 1 = Medium/high
<i>BEHSYMP1</i>	1st grade behavioral symptoms	3.6	Numeric (17 to 92)
<i>LRNPROB1</i>	1st grade learning problems	0	Numeric (31 to 88)
<i>READ1</i>	1st grade broad reading composite	6.5	Numeric (39 to 153)
<i>READ9</i>	9th grade broad reading composite	17.4	Numeric (41 to 123)
<i>READGRP9</i>	9th grade reading classification	17.4	0 = Below average, 1 = Average/above
<i>STANREAD7</i>	7th grade standardized reading	19.6	Numeric (100 to 399)

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SIMPLE REGRESSION ILLUSTRATION

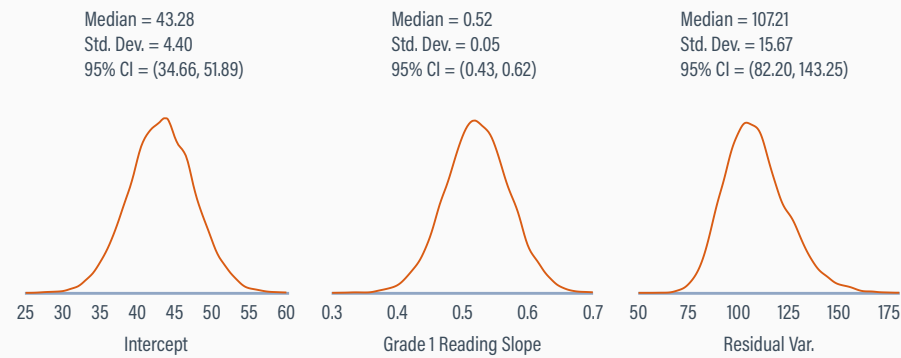
- Study that seeks to determine whether reading levels in 1st grade predict 9th grade reading achievement in middle school

$$READ_9 = \beta_0 + \beta_1(READ_1) + \varepsilon$$

- Both reading tests have missing values to be imputed

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POSTERIOR DISTRIBUTIONS



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ESTIMATOR COMPARISON

The two estimators are numerically equivalent!!!

Parameter	Bayes			FIML		
	Median	SD	95% CI	Est.	SE	95% CI
Intercept	43.28	4.40	(34.66, 51.89)	43.16	4.28	(34.78, 51.54)
1st Grade Reading	0.52	0.05	(0.43, 0.62)	0.52	0.05	(0.43, 0.62)
Residual variance	107.21	15.67	(82.20, 143.25)	102.59	14.19	(74.76, 140.40)
R ²	.50	.06	(.37, .61)	.49	.07	(.35, .63)

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MARKOV CHAIN MONTE CARLO (MCMC)

- A Bayesian analysis involves estimating and sampling from distributions of model parameters and the missing values
- MCMC breaks a complex problem involving multiple unknowns (parameters and missing values) into separate steps
- Each step estimates one unknown at a time, treating the current values of all other quantities as known constants

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MCMC ESTIMATION

Estimate regression models



Impute missing values

- » Do for $t = 1$ to T iterations
 - » Estimate focal model parameters, conditional on filled-in data
 - » Estimate predictor model parameters, conditional on filled-in data
 - » Impute outcome scores, conditional on the focal model parameters
 - » Impute predictors, conditional on the focal and predictor model parameters
- » Repeat

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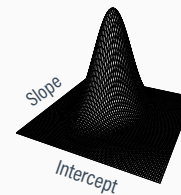
MEANING OF ESTIMATION

- A posterior is a distribution of plausible parameter values that could have produced our particular data set
- MCMC uses computer simulation (random number generation) to "sample" plausible parameter values
- Parameter values and missing data imputations are in a constant state of flux across a long MCMC sequence

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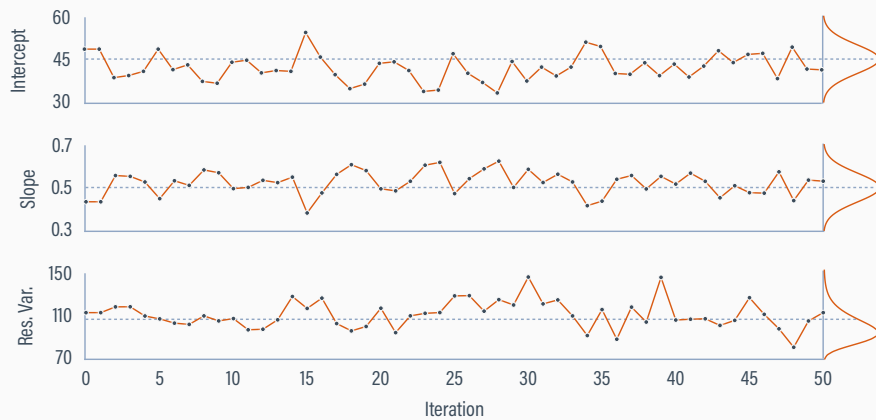
PARAMETER-GENERATING DISTRIBUTIONS

- MCMC draws coefficients from a multivariate normal distribution, with OLS estimates defining its shape
- MCMC draws variances from an inverse gamma distribution with its shape determined by the df and residual SS



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PARAMETERS FROM 50 MCMC CYCLES



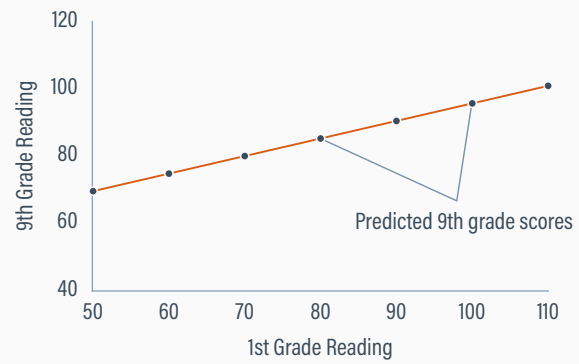
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MISSING DATA IMPUTATION

- Missing scores are imputed by drawing replacement scores at random from a distribution of plausible values
- Each unique set of parameter values combine to define the center and spread of the imputation distributions
- Imputing predictors is more complex than imputing outcomes

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PREDICTED OUTCOME SCORES



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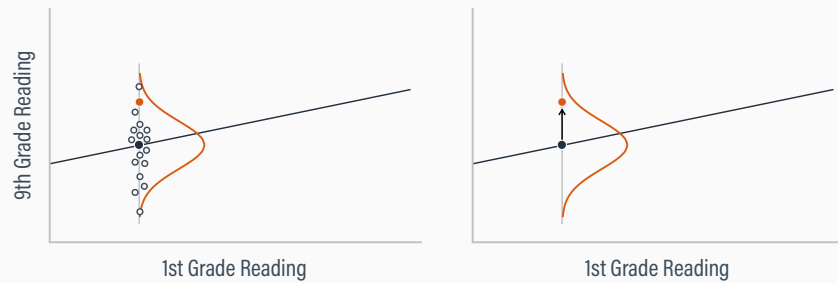
DISTRIBUTIONS OF IMPUTATIONS



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SAMPLING AN IMPUTATION

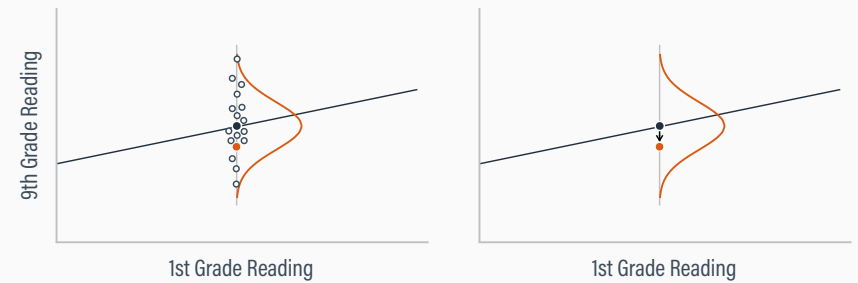
Imputation = predicted value + random normal noise



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SAMPLING AN IMPUTATION

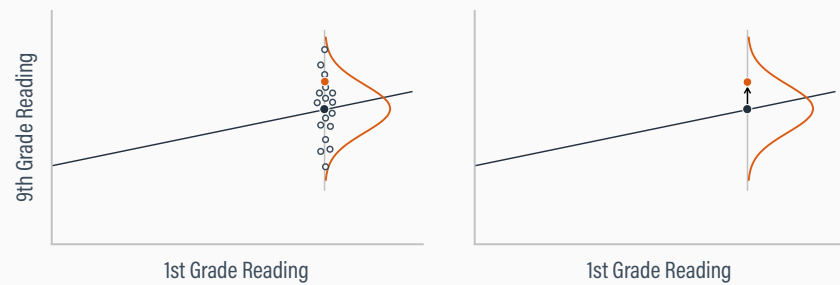
Imputation = predicted value + random normal noise



38

SAMPLING AN IMPUTATION

Imputation = predicted value + random normal noise



39

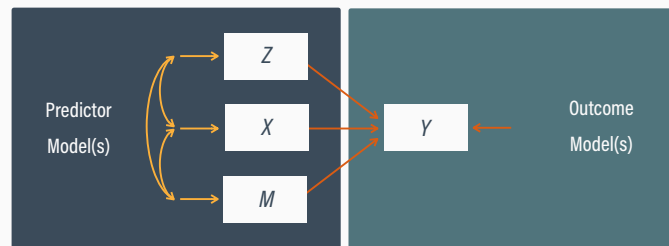
INCOMPLETE PREDICTORS

- Incomplete predictors require a model and distribution
- Multivariate normal methods (e.g., FIML) can mis-specify the data distributions in a way that introduces bias
- Factored regression uses a modular specification where a sequence of models replaces a general multivariate model

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FACTORED REGRESSION OVERVIEW

- Factored regression specifications invoke separate models (and distributions) for incomplete predictors and outcomes

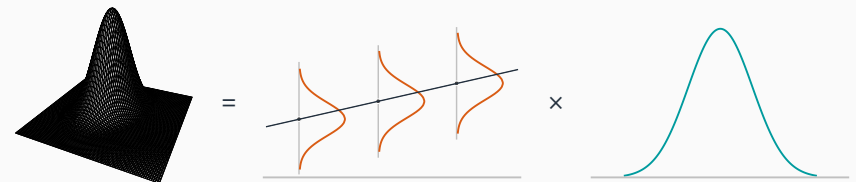


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BIVARIATE FACTORED REGRESSION

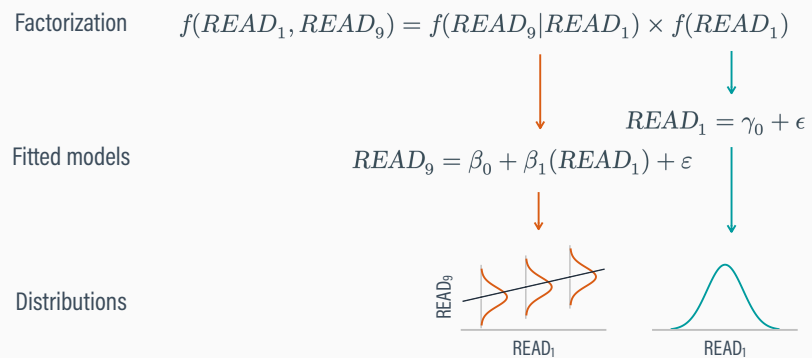
Bivariate Distribution = Univariate Outcome Model \times Univariate Predictor Model

$$f(Y, X) = f(Y|X) \times f(X)$$



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SIMPLE REGRESSION EXAMPLE



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IMPUTING MISSING PREDICTORS

- A missing predictor always appears in two models: as a regressor in the focal model and an outcome in its own model

$$f(READ_1 | READ_9) \propto f(READ_9 | READ_1) \times f(READ_1) = \text{orange bell curves} \times \text{teal bell curve}$$

- The distribution of missing $READ_1$ scores is a composite function that depends on both model-implied distributions

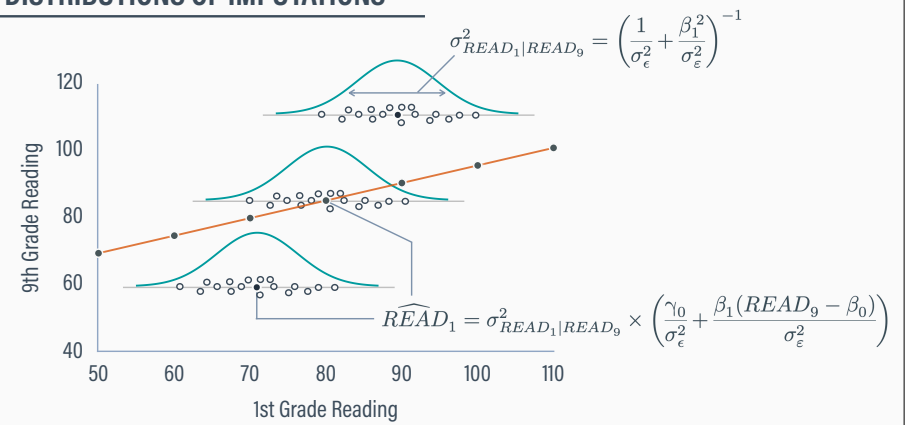
44

DISTRIBUTIONS OF IMPUTATIONS



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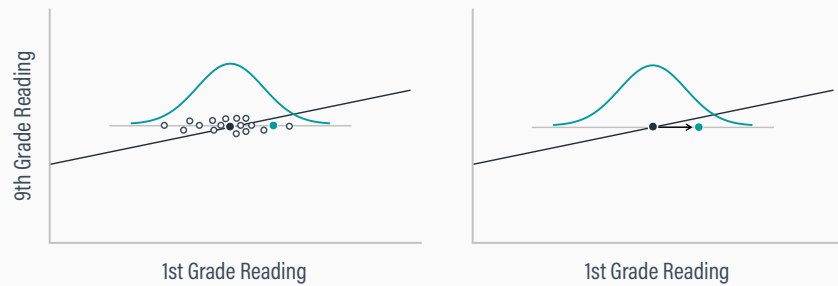
DISTRIBUTIONS OF IMPUTATIONS



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IMPUTATION EXAMPLE

Imputation = predicted value + random normal noise



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FITTING REGRESSION
MODELS IN **BLIMP**



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AERA WORKSHOP DATA

■ Predictors
■ Outcome

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ANALYSIS MODEL

- Multiple regression where reading performance and teacher-rated learning problems in 1st grade predict 9th grade reading

$$READ_9 = \beta_0 + \beta_1(READ_1) + \beta_2(LRNPROB_1) + \beta_3(MALE) + \epsilon$$

- Both reading achievement tests have missing values

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BLIMP SCRIPT

```
DATA: aeraworkshop.dat;  
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;  
MISSING: 999;  
NOMINAL: male;  
FIXED: male lnprob1;  
MODEL:  
read9 ~ read1 lnprob1 male;  
BURN: 1000;  
ITERATIONS: 10000;  
SEED: 90291;
```

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DATA AND VARIABLES

```
DATA: aeraworkshop.dat;  
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;  
MISSING: 999;  
NOMINAL: male;  
FIXED: male lnprob1;  
MODEL:  
read9 ~ read1 lnprob1 male;  
BURN: 1000;  
ITERATIONS: 10000;  
SEED: 90291;
```

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MODEL DETAILS

```
DATA: aeraworkshop.dat;  
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;  
MISSING: 999;  
NOMINAL: male;  
FIXED: male lnprob1;  
MODEL:  
read9 ~ read1 lnprob1 male;  
BURN: 1000;  
ITERATIONS: 10000;  
SEED: 90291;
```

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COMPUTATIONAL DETAILS

```
DATA: aeraworkshop.dat;  
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;  
MISSING: 999;  
NOMINAL: male;  
FIXED: male lnprob1;  
MODEL:  
read9 ~ read1 lnprob1 male;  
BURN: 1000;  
ITERATIONS: 10000;  
SEED: 90291;
```

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DATA AND VARIABLES

```
DATA: aeraworkshop.dat;           # ascii text data
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9
               read9grp stanread7;  # variable order
MISSING: 999;                   # missing value code
NOMINAL: male;                  # binary or multicategorical predictor
```

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MODEL DETAILS

```
FIXED: male lnprob1;           # complete predictors
MODEL:                               # regression equations
read9 ~ read1 lnprob1 male;       # DV ~ predictors
```

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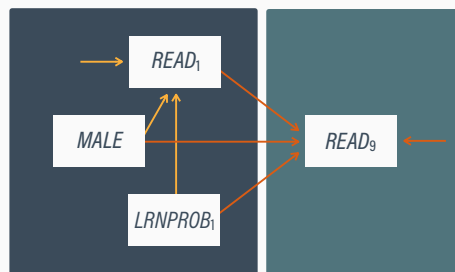
PATH DIAGRAM AND MODEL COMMAND

Multivariate Distribution = Multivariate Predictor Distributions \times Univariate Outcome Distribution

FIXED: male;

MODEL:

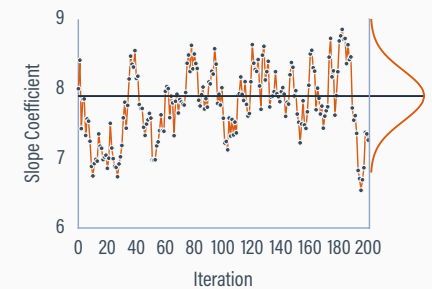
read9 \sim read1 lnrprob1 male;



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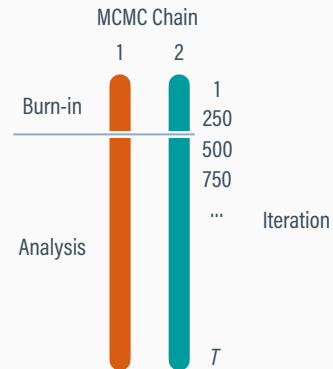
MCMC ESTIMATION

- MCMC uses computer simulation to "draw" or "sample" parameters from a distribution of plausible values
- Estimates continually vary across iterations in a random pattern



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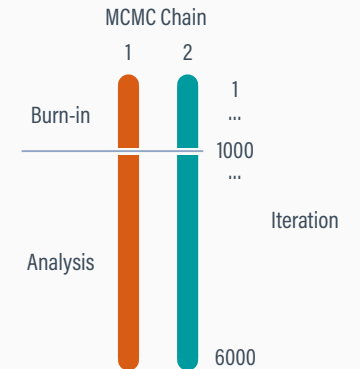
MCMC ALGORITHM



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COMPUTATIONAL DETAILS

BURN: 1000; # burn-in iterations
ITERATIONS: 10000; # analysis iterations
SEED: 90291; # random number seed



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UNDERSTANDING BLIMP OUTPUT



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MCMC CONVERGENCE

- MCMC converges when posterior distributions are stationary
- Parameter estimates oscillate around a stable mean, and variation doesn't change with additional iterations
- Set burn-in cycles > number of iterations needed to converge

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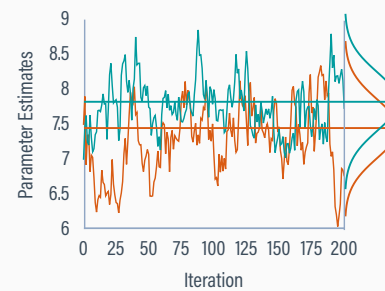
POTENTIAL SCALE REDUCTION

- The potential scale reduction (PSR) factor compares parameter distributions generated from two unique MCMC processes
- MCMC converges when the two chains give estimates with same mean and spread
- PSRs for all parameters should be < 1.05

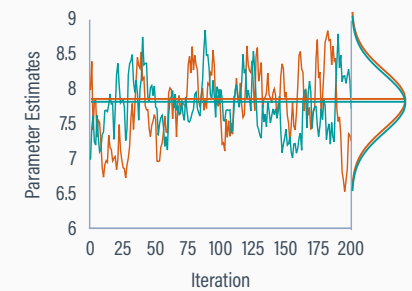
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PSR GRAPHIC

MCMC has not converged (PSR > 1.05)



MCMC has converged (PSR < 1.05)



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PSR DIAGNOSTIC OUTPUT

BURN-IN POTENTIAL SCALE REDUCTION (PSR) OUTPUT:

NOTE: Split chain PSR is being used. This splits each chain's iterations to create twice as many chains.

Comparing iterations across 2 chains	Highest PSR	Parameter #
26 to 50	1.130	13
51 to 100	1.086	7
76 to 150	1.042	1
101 to 200	1.040	8
...
401 to 800	1.008	1
426 to 850	1.006	1
451 to 900	1.008	1
476 to 950	1.008	5
501 to 1000	1.008	8

>> Worst PSR < 1.05

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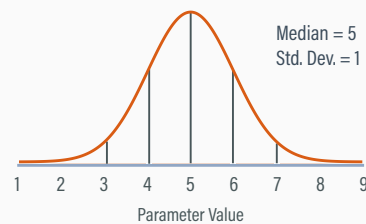
BAYESIAN POSTERIOR SUMMARIES

- Probability distributions are tools for expressing our knowledge about a parameter in a Bayesian analysis
- The posterior distribution describes plausible parameter values that are consistent with the data (no repeated sampling)
- We use summary statistics to describe parameter distributions

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MEDIAN AND STANDARD DEVIATION

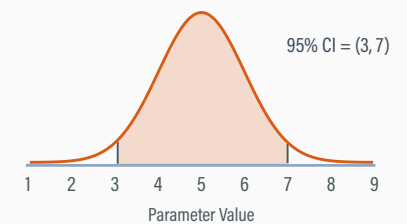
- The posterior median and standard deviation quantify the most likely parameter value and uncertainty
- Analogous to a point estimate and standard error, sans repeated sampling



67

95% CREDIBLE INTERVALS

- The 95% credible interval gives limits spanning 95% of the parameter's range
- Akin to a confidence interval, but references a range of highly plausible parameter values



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POINT ESTIMATES

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lnnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lnnprob1	-0.293	0.067	-0.420	-0.158	1.001	3354.968
male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932



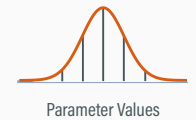
MEASURES OF UNCERTAINTY

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lnnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lnnprob1	-0.293	0.067	-0.420	-0.158	1.001	3354.968
male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932



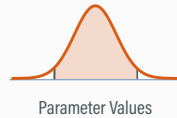
95% CREDIBLE INTERVALS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lrrnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
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male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932



71

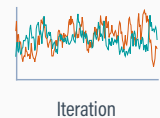
DIAGNOSTICS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lrrnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lrrnprob1	-0.293	0.067	-0.420	-0.158	1.001	3354.968
male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932



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VARIANCES AND COVARIANCES

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lrrnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lrrnprob1	-0.293	0.067	-0.420	-0.158	1.001	3354.968
male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
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by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932

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COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
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male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
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read1	0.696	0.046	0.597	0.775	1.000	4649.513
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male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932

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STANDARDIZED COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lrnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lrnprob1	-0.293	0.067	-0.420	-0.158	1.001	3354.968
male.1	0.064	0.066	-0.065	0.192	1.000	5801.597
Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932

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EFFECT SIZE ESTIMATES

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

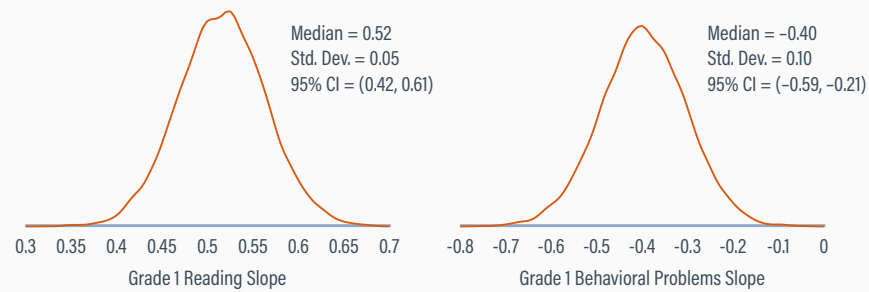
Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
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by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932

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POSTERIOR DISTRIBUTIONS



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COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
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lrnprob1	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
...	READ1 partial regression slope LRNPROB1 partial regression slope MALE partial regression slope					

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INTERPRETATION EXAMPLE

- For two students who share the same gender and learning problems rating, scoring one point higher on the first grade reading test is associated with a 0.52 increase in grade 9
- The slope is significantly different from 0 because the null value falls outside the 95% credible interval limits (0.42, 0.61)

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HOW MANY ITERATIONS?

- MCMC estimates are autocorrelated across iterations
- The effective number of MCMC samples estimates the number of independent estimates after removing autocorrelation
- Gelman et al. (2014, p. 267) recommend at least 100 independent MCMC samples per parameter

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EFFECTIVE NUMBER OF MCMC SAMPLES

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	91.781	13.202	70.514	123.094	1.000	5084.608
Coefficients:						
Intercept	62.976	7.140	48.902	76.899	1.001	4079.222
read1	0.516	0.048	0.421	0.611	1.000	6397.445
lrnprobl	-0.398	0.095	-0.587	-0.212	1.000	3457.935
male.1	1.887	1.946	-1.925	5.703	1.000	5824.649
Standardized Coefficients:						
read1	0.696	0.046	0.597	0.775	1.000	4649.513
lrnprobl	-0.293	0.067	-0.420	-0.158	1.001	3354.968
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Proportion Variance Explained						
by Coefficients	0.575	0.052	0.462	0.663	1.000	5842.932
by Residual Variation	0.425	0.052	0.337	0.538	1.000	5842.932

» Effective number of MCMC samples
for every parameter is > 100

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ESTIMATOR COMPARISON

The two estimators are numerically equivalent!!!

Parameter	Bayes		FIML	
	Median	SD	Est.	SE
Intercept	62.98	7.14	62.56	6.92
1st grade reading	0.52	0.05	0.52	0.05
1st grade learning problems	-0.40	0.10	-0.39	0.09
Male dummy code	1.89	1.95	1.95	1.88
Residual variance	91.78	13.20	86.32	11.78
R ²	0.58	0.05	0.59	0.06

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BAYESIAN WALD TEST

- Asparouhov and Muthén (2021) proposed a Bayesian Wald test that mimics familiar likelihood-based Wald tests

$$T = (\theta - \theta_0)' \Sigma_{\theta}^{-1} (\theta - \theta_0)$$

- T is the sum of squared standardized differences (chi-square metric) between the posterior means and null hypothesis

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BLIMP SCRIPT: TEST STATISTICS

MODEL:

```
read9 ~ read1@beta1 lnprob1@beta2 male@beta3; # label coefficients with @  
TEST: beta1:beta3 = 0; # omnibus test of three slopes  
TEST: beta1 = 0; # test of a single slope  
TEST: beta2 = 0; # test of a single slope  
TEST: beta3 = 0; # test of a single slope
```

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MODEL FIT OUTPUT

MODEL FIT:

INFORMATION CRITERIA

...

WALD TESTS (Asparouhov & Muthén, 2021)

Test #1

Full:

[1] read9 ~ Intercept read1@beta1 lnprob1@beta2 male.1@beta3

Restricted:

[1] read9 ~ Intercept read1@beta1 lnprob1@beta2 male.1@beta3

Constraints in Restricted:

[1] beta1 = 0

[2] beta2 = 0

[3] beta3 = 0

Wald Statistic (Chi-Square) 147.562

Number of Parameters Tested (df) 3

Probability 0.000

85

MODEL FIT OUTPUT

MODEL FIT:

INFORMATION CRITERIA

...

WALD TESTS (Asparouhov & Muthén, 2021)

...

Test #2

Full:

[1] read9 ~ Intercept read1@beta1 lnprob1@beta2 male.1@beta3

Restricted:

[1] read9 ~ Intercept read1@beta1 lnprob1@beta2 male.1@beta3

Constraints in Restricted:

[1] beta1 = 0

Wald Statistic (Chi-Square) 115.118

Number of Parameters Tested (df) 1

Probability 0.000

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REPORTING TEMPLATE

We used Bayesian estimation in Blimp 3 (Keller & Enders, 2021) to treat missing values under the assumption that missingness is random after conditioning on the observed data. Potential scale reduction factor convergence diagnostics (Gelman & Rubin, 1992) from a preliminary run indicated that a burn-in period of 1,000 iterations was sufficiently conservative. Based on this information, we used two MCMC chains with random starting values to generate posterior summaries consisting of 10,000 estimates following the initial burn-in period. We verified this setting was sufficient by examining the effective number of independent MCMC samples for each parameter, all of which were greater than the recommended value of 100 (Gelman et al., 2014, p. 287).

REPORTING TEMPLATE CONTINUED

Table 1 displays the posterior summaries from the analysis. The posterior medians and standard deviations are analogous to frequentist point estimates and standard errors, and the 95% credible interval limits are akin to confidence intervals. These quantities make no reference to repeated samples but instead convey parameter values that are consistent with the observed data. Given the same assumptions and data, Bayesian and likelihood-based missing data handling procedures are numerically equivalent (Enders, 2022).

APA TABLE

Table 1

Parameter Summary From the Bayesian Regression Analysis

Parameter	Median	<i>SD</i>	LCL	UCL
Intercept	62.98	7.14	48.90	76.90
1st grade reading	0.52	0.05	0.42	0.61
1st grade learning problems	-0.40	0.10	-0.59	-0.21
Male dummy code	1.89	1.95	-1.93	5.70
R ²	0.58	0.05	0.46	0.66

REPORTING TEMPLATE CONTINUED

Collectively, the predictors explained approximately 58% of the variation in 9th grade reading scores. The Bayesian Wald test (Asparouhov & Muthén, 2021) of the full model was statistically significant, $\chi^2(3) = 147.56, p < .001$. First grade reading exhibited a significant positive association with 9th grade reading performance ($\beta = 0.52, SD = 0.05, p < .001$), and the measure of teacher-rated learning problems was inversely related to middle-school reading ($\beta = -0.40, SD = 0.10, p < .001$). Student gender was not predictive of 9th reading performance.

INCOMPLETE CATEGORICAL VARIABLES IN **BLIMP**

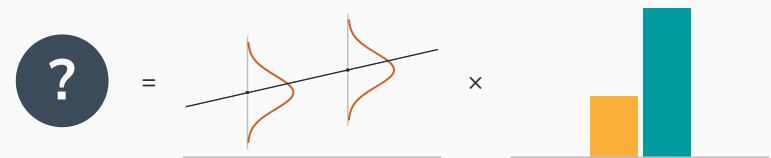


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FACTORED REGRESSION

Bivariate Distribution = Univariate Outcome Distribution \times Univariate Predictor Distribution

$$f(Y, X) = f(Y|X) \times f(X)$$



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LATENT RESPONSE FORMULATION



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AERA WORKSHOP DATA

■ Predictors
■ Outcome

Variable	Definition	Missing %	Scale
<i>STUDENT</i>	Student identifier	0	Integer index
<i>MALE</i>	Gender code	0	0 = Female, 1 = Male
<i>ESL</i>	English as a second language code	5.1	0 = Non-ESL, 1 = ESL
<i>RISKGRP</i>	Emotional/behavioral disorder risk	2.2	1 = Low, 2 = Medium, 3 = High
<i>ATRISK</i>	Emotional/behavioral risk code	2.2	0 = Low, 1 = Medium/high
<i>BEHSYMP1</i>	1st grade behavioral symptoms	3.6	Numeric (17 to 92)
<i>LRNPROB1</i>	1st grade learning problems	0	Numeric (31 to 88)
<i>READ1</i>	1st grade broad reading composite	6.5	Numeric (39 to 153)
<i>READ9</i>	9th grade broad reading composite	17.4	Numeric (41 to 123)
<i>READGRP9</i>	9th grade reading classification	17.4	0 = Below average, 1 = Average/above
<i>STANREAD7</i>	7th grade standardized reading	19.6	Numeric (100 to 399)

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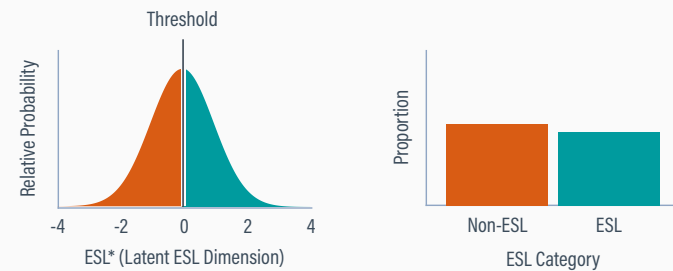
INCOMPLETE BINARY VARIABLES

- Probit regression envisions binary and ordinal variables arising from an underlying normal latent response variable
- Applied to the ESL, the latent variable represents an unobserved, continuous propensity for ESL
- A threshold carves the latent distribution into segments

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LATENT ESL DISTRIBUTION

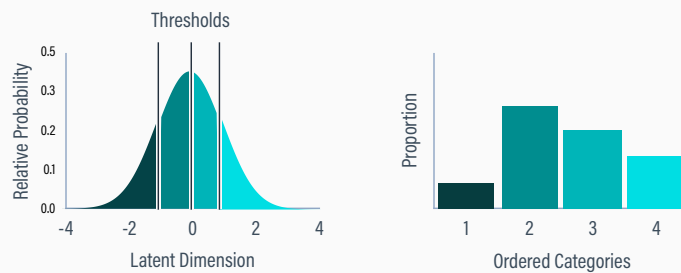
- The threshold parameter divides the latent distribution into segments, with areas under the curve matching the bar plot



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ORDINAL VARIABLES

- Multiple threshold parameters divide the latent distribution into segments, with areas under the curve matching the bar plot



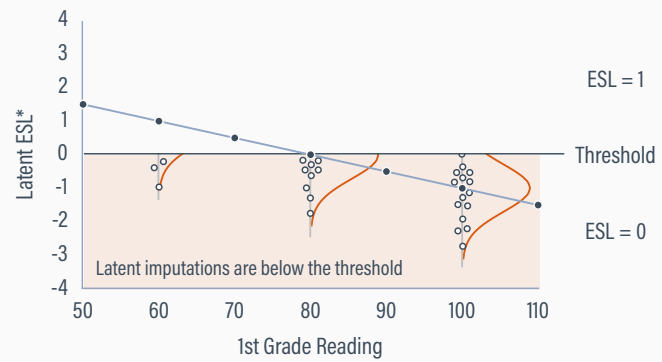
97

IMPUTING LATENT RESPONSE SCORES

- Latent response scores are missing data to be imputed
- MCMC uses computer simulation to "sample" latent response scores distributions, just like any other incomplete variable
- The imputation procedure restricts the range of latent response scores to align with the areas above and below the threshold

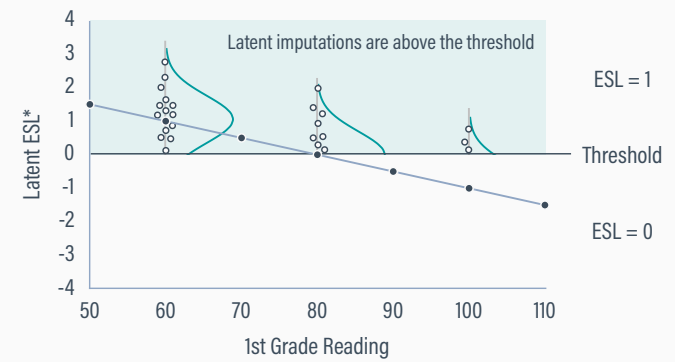
98

LATENT IMPUTATIONS: ESL = 0



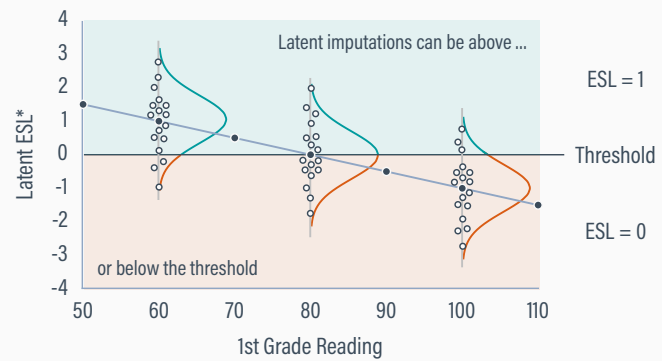
99

LATENT IMPUTATIONS: ESL = 1



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LATENT IMPUTATIONS: ESL = ?



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ANALYSIS MODEL

- Multiple regression model with two continuous and two binary predictor variables

$$READ_9 = \beta_0 + \beta_1(READ_1) + \beta_2(LRNPROB_1) + \beta_3(MALE) + \beta_4(ESL) + \varepsilon$$

- ESL is an incomplete binary dummy code that indicates whether English is the student's second language

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BLIMP SCRIPT

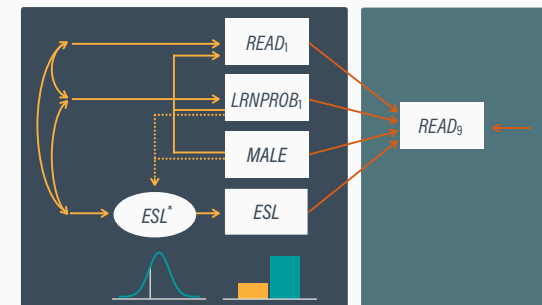
```
DATA: aeraworkshop.dat;  
VARIABLES: id male esl riskgrp atrisk behsymp1 lrnprob1 read1 read9 read9grp stanread7;  
MISSING: 999;  
ORDINAL: esl;  
NOMINAL: male;  
FIXED: male lrnprob1;  
MODEL:  
read9 ~ read1 lrnprob1 male esl;  
BURN: 1000;  
ITERATIONS: 10000;  
SEED: 90291;
```

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PATH DIAGRAM AND MODEL COMMAND

Joint Distribution = Multivariate Predictor Distribution \times Univariate Outcome Distribution

```
ORDINAL: esl;  
NOMINAL: male;  
FIXED: male lrnprob1;  
MODEL:  
read9 ~ read1 lrnprob1  
male esl;
```



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PSR DIAGNOSTIC OUTPUT

BURN-IN POTENTIAL SCALE REDUCTION (PSR) OUTPUT:

NOTE: Split chain PSR is being used. This splits each chain's iterations to create twice as many chains.

Comparing iterations across 2 chains	Highest PSR	Parameter #
26 to 50	1.374	7
51 to 100	1.084	15
76 to 150	1.060	7
101 to 200	1.033	16
...
401 to 800	1.018	14
426 to 850	1.013	14
451 to 900	1.015	14
476 to 950	1.018	14
501 to 1000	1.021	16

» Worst PSR < 1.05

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COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	77.639	11.467	59.343	103.993	1.001	4608.173

Coefficients:						
Intercept	55.844	6.876	42.213	69.103	1.001	3879.836
read1	0.568	0.046	0.481	0.659	1.000	5633.633
lnrprob1	-0.274	0.094	-0.456	-0.091	1.001	2647.338
male.1	2.344	1.804	-1.248	5.844	1.001	5412.478
esl	-7.864	1.852	-11.437	-4.173	1.000	4578.354

Standardized Coefficients:						
...						

ESL vs. non-ESL mean difference

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EXAMPLE INTERPRETATION

- For two students who share the same profile on all other predictors (gender, 1st grade reading, and 1st grade learning problems), speaking English as a second language is associated with a 7.86 decrease in grade 9 reading scores
- The mean difference is significant because 0 falls outside the 95% credible interval limits (-11.43, -4.17)

REPORTING TEMPLATE

We used Bayesian estimation in Blimp 3 (Keller & Enders, 2021) to treat missing values under the assumption that missingness is random after conditioning on the observed data. Potential scale reduction factor convergence diagnostics (Gelman & Rubin, 1992) from a preliminary run indicated that a burn-in period of 1,000 iterations was sufficiently conservative. Based on this information, we used two MCMC chains with random starting values to generate posterior summaries consisting of 10,000 estimates following the initial burn-in period. We verified this setting was sufficient by examining the effective number of independent MCMC samples for each parameter, all of which were greater than the recommended value of 100 (Gelman et al., 2014, p. 287).

REPORTING TEMPLATE CONTINUED

Table 1 displays the posterior summaries from the analysis. The posterior medians and standard deviations are analogous to frequentist point estimates and standard errors, and the 95% credible interval limits are akin to confidence intervals. These quantities make no reference to repeated samples but instead convey parameter values that are consistent with the observed data. Given the same assumptions and data, Bayesian and likelihood-based missing data handling procedures are numerically equivalent. However, Bayesian estimation is preferable because classic FIML estimators in widespread use do not readily accommodate mixtures of discrete and continuous predictors (Enders, 2022).

APA TABLE

Table 1
Parameter Summary From the Bayesian Regression Analysis

Parameter	Median	SD	LCL	UCL
Intercept	55.84	6.88	42.21	69.10
1st grade reading	0.57	0.05	0.48	0.66
1st grade learning problems	-0.27	0.09	-0.46	-0.09
Male dummy code	2.34	1.80	-1.25	5.84
ESL dummy code	-7.86	1.85	-11.44	-4.17
R ²	.64	.05	.54	.72

REPORTING TEMPLATE CONTINUED

Collectively, the predictors explained approximately 64% of the variation in 9th grade reading scores. First grade reading exhibited a significant positive association with 9th grade reading performance ($\beta = 0.57, SD = 0.05, p < .05$), and the measure of teacher-rated learning problems was inversely related to middle-school reading ($\beta = -0.27, SD = 0.09, p < .05$). Students for whom English is a second language scored approximately 7.86 points lower, on average, than native English speakers ($\beta = -7.86, SD = 1.85, p < .05$). Finally, student gender was not predictive of 9th reading performance.

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MULTICATEGORICAL VARIABLES

- Multinomial probit regression envisions a latent normal distribution for each response option
- Like dummy codes, there is a reference group (the lowest category is Blimp's default)
- Latent difference scores compare the latent response scores from the $C - 1$ categories to that of the reference group

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AERA WORKSHOP DATA

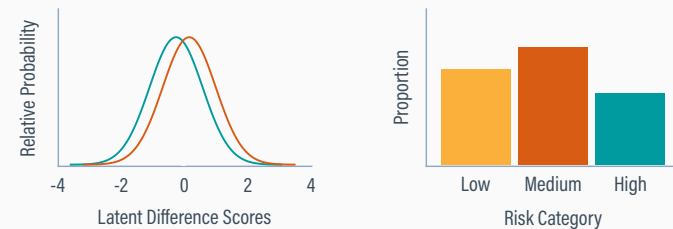
■ Predictors
■ Outcome

Variable	Definition	Missing %	Scale
<i>STUDENT</i>	Student identifier	0	Integer index
<i>MALE</i>	Gender code	0	0 = Female, 1 = Male
<i>ESL</i>	English as a second language code	5.1	0 = Non-ESL, 1 = ESL
» <i>RISKGRP</i>	Emotional/behavioral disorder risk	2.2	1 = Low, 2 = Medium, 3 = High
<i>ATRISK</i>	Emotional/behavioral risk code	2.2	0 = Low, 1 = Medium/high
<i>BEHSYMP1</i>	1st grade behavioral symptoms	3.6	Numeric (17 to 92)
<i>LRNPROB1</i>	1st grade learning problems	0	Numeric (31 to 88)
<i>READ1</i>	1st grade broad reading composite	6.5	Numeric (39 to 153)
<i>READ9</i>	9th grade broad reading composite	17.4	Numeric (41 to 123)
<i>READGRP9</i>	9th grade reading classification	17.4	0 = Below average, 1 = Average/above
<i>STANREAD7</i>	7th grade standardized reading	19.6	Numeric (100 to 399)

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LATENT RISK GROUP DISTRIBUTIONS

- Latent difference scores compare latent response scores for the Medium and High groups to the Low-risk reference category



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ANALYSIS MODEL

- Multiple regression model with two continuous and two binary predictor variables

$$READ_9 = \beta_0 + \beta_1(READ_1) + \beta_2(LRNPROB_1) + \beta_3(MALE) + \beta_4(MEDRSK) + \beta_5(HIGHRSK) + \varepsilon$$

- HIGHRSK and MEDRSK are dummy (1 vs. 0) codes comparing the high and medium risk groups to the low-risk reference

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BLIMP SCRIPT

DATA: aeraworkshop.dat;

VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;

MISSING: 999;

NOMINAL: male riskgrp;

FIXED: male lnprob1;

MODEL:

read9 ~ read1 lnprob1 male riskgrp;

BURN: 2000;

ITERATIONS: 10000;

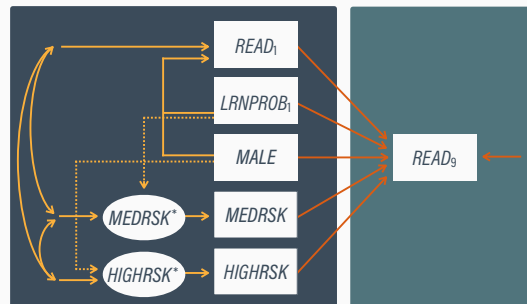
SEED: 90291;

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PATH DIAGRAM AND MODEL COMMAND

Joint Distribution = Multivariate Predictor Distribution \times Univariate Outcome Distribution

NOMINAL: male rskgrp;
FIXED: male lnprob1;
MODEL:
 read9 \sim read1 lnprob1
 male rskgrp;



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PSR DIAGNOSTIC OUTPUT

BURN-IN POTENTIAL SCALE REDUCTION (PSR) OUTPUT:

NOTE: Split chain PSR is being used. This splits each chain's iterations to create twice as many chains.

Comparing iterations across 2 chains	Highest PSR	Parameter #
51 to 100	1.166	15
101 to 200	1.107	16
151 to 300	1.058	21
201 to 400	1.048	21
...
801 to 1600	1.034	22
851 to 1700	1.027	22
901 to 1800	1.044	22
951 to 1900	1.043	22
1001 to 2000	1.028	22

>> Worst PSR < 1.05

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COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Variances:						
Residual Var.	77.639	11.467	59.343	103.993	1.001	4608.173
Coefficients:						
Intercept	67.276	7.551	52.379	81.912	1.000	4099.229
read1	0.483	0.052	0.382	0.586	1.000	6340.240
lnnprobl	-0.395	0.096	-0.582	-0.211	1.000	3622.421
male.1	2.296	1.918	-1.543	6.039	1.000	5188.817
riskgrp.2	-1.831	2.096	-5.913	2.313	1.000	5833.837
riskgrp.3	-4.780	2.875	-10.563	0.797	1.000	4587.357
Standardized Coefficients:						
...						

• Medium- vs. low-risk mean difference
 • High- vs. low-risk mean difference

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EXAMPLE INTERPRETATION

- For two students who share the same profile on all other predictors (gender, 1st grade reading, and 1st grade learning problems), belonging to the medium- (or high-risk) group is associated with a 1.83 (or 4.78) decrease in grade 9 reading scores relative to the low-risk reference group
- Both mean difference parameters are significant because 0 falls outside their 95% credible interval limits

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REPORTING TEMPLATE

We used Bayesian estimation in Blimp 3 (Keller & Enders, 2021) to treat missing values under the assumption that missingness is random after conditioning on the observed data. Potential scale reduction factor convergence diagnostics (Gelman & Rubin, 1992) from a preliminary run indicated that a burn-in period of 2,000 iterations was sufficiently conservative. Based on this information, we used two MCMC chains with random starting values to generate posterior summaries consisting of 10,000 estimates following the initial burn-in period. We verified this setting was sufficient by examining the effective number of independent MCMC samples for each parameter, all of which were greater than the recommended value of 100 (Gelman et al., 2014, p. 287).

REPORTING TEMPLATE CONTINUED

Table 1 displays the posterior summaries from the analysis. The posterior medians and standard deviations are analogous to frequentist point estimates and standard errors, and the 95% credible interval limits are akin to confidence intervals. These quantities make no reference to repeated samples but instead convey parameter values that are consistent with the observed data. Given the same assumptions and data, Bayesian and likelihood-based missing data handling procedures are numerically equivalent. However, Bayesian estimation is preferable because existing FIML estimators cannot accommodate mixtures of continuous and multicategorical nominal predictors (Enders, 2022).

APA TABLE

Table 1

Parameter Summary From the Bayesian Regression Analysis

Parameter	Median	SD	LCL	UCL
Intercept	67.28	7.55	52.38	81.91
1st grade reading	0.48	0.05	0.38	0.59
1st grade learning problems	-0.40	0.10	-0.58	-0.21
Male dummy code	2.30	1.92	-1.54	6.04
Medium- vs. low-risk dummy code	-1.83	2.10	-5.91	2.31
High- vs. low-risk dummy code	-4.78	2.88	-10.56	0.80
R ²	.59	.05	.48	.68

REPORTING TEMPLATE CONTINUED

Collectively, the predictors explained approximately 59% of the variation in 9th grade reading scores. First grade reading exhibited a significant positive association with 9th grade reading performance ($\beta = 0.48$, $SD = 0.05$, $p < .05$), and the measure of teacher-rated learning problems was inversely related to middle-school reading ($\beta = -0.40$, $SD = 0.10$, $p < .05$). Although students classified as having moderate or high risk of emotional and behavioral disorders scored lower, on average, than their low-risk peers, neither mean difference was statistically significant. Similarly, student gender was not predictive of 9th reading performance.

CATEGORICAL OUTCOME VARIABLES

- Outcome variables can be binary, ordinal, multicategorical, or count (in addition to normal, latent, and skewed continuous)
- Ordinal outcomes using probit regression, count outcomes using negative binomial regression with over-dispersion
- Binary and multicategorical outcomes can be modeled using either probit or logistic regression

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BINARY LOGISTIC MODEL

- Logistic regression model with a binary outcome denoting whether a student was reading at an average level in 9th grade

$$\text{logit}(READGRP_9) = \beta_0 + \beta_1(READ_1) + \beta_2(LRNPROB_1) + \beta_3(MALE) + \beta_4(ESL) + \varepsilon$$

- ESL is an incomplete binary dummy code that indicates whether English is the student's second language

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AERA WORKSHOP DATA

■ Predictors
■ Outcome

Variable	Definition	Missing %	Scale
<i>STUDENT</i>	Student identifier	0	Integer index
<i>MALE</i>	Gender code	0	0 = Female, 1 = Male
<i>ESL</i>	English as a second language code	5.1	0 = Non-ESL, 1 = ESL
<i>RISKGRP</i>	Emotional/behavioral disorder risk	2.2	1 = Low, 2 = Medium, 3 = High
<i>ATRISK</i>	Emotional/behavioral risk code	2.2	0 = Low, 1 = Medium/high
<i>BEHSYMP1</i>	1st grade behavioral symptoms	3.6	Numeric (17 to 92)
<i>LRNPROB1</i>	1st grade learning problems	0	Numeric (31 to 88)
<i>READ1</i>	1st grade broad reading composite	6.5	Numeric (39 to 153)
<i>READ9</i>	9th grade broad reading composite	17.4	Numeric (41 to 123)
>> <i>READGRP9</i>	9th grade reading classification	17.4	0 = Below average, 1 = Average/above
<i>STANREAD7</i>	7th grade standardized reading	19.6	Numeric (100 to 399)

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BLIMP SCRIPT

```

DATA: aeraworkshop.dat;
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;
MISSING: 999;
NOMINAL: male;
ORDINAL: esl read9grp;
FIXED: male lnprob1;
MODEL:
  logit(read9grp) ~ read1 lnprob1 male esl;
BURN: 2000;
ITERATIONS: 10000;
SEED: 90291;
  
```

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PSR DIAGNOSTIC OUTPUT

BURN-IN POTENTIAL SCALE REDUCTION (PSR) OUTPUT:

NOTE: Split chain PSR is being used. This splits each chain's iterations to create twice as many chains.

Comparing iterations across 2 chains	Highest PSR	Parameter #
51 to 100	1.101	6
101 to 200	1.055	3
151 to 300	1.052	14
201 to 400	1.045	14
...
801 to 1600	1.006	22
851 to 1700	1.011	14
901 to 1800	1.010	14
951 to 1900	1.009	14
1001 to 2000	1.012	14

>> Worst PSR < 1.05

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COEFFICIENTS

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **logit(read9grp)**

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff
Coefficients:						
Intercept	-3.549	1.397	-6.354	-0.864	1.000	4358.138
read1	0.073	0.015	0.047	0.104	1.000	2921.149
lnnprob1	-0.052	0.023	-0.099	-0.009	1.001	3005.165
male.1	0.442	0.462	-0.462	1.366	1.000	4807.380
es1	-0.934	0.505	-1.965	0.023	1.000	3602.590
Odds Ratios:						
Intercept	0.029	0.141	0.002	0.422	1.000	6928.599
read1	1.076	0.016	1.048	1.109	1.000	2919.172
lnnprob1	0.950	0.022	0.906	0.991	1.001	3021.609
male.1	1.556	0.875	0.630	3.921	1.000	5005.948
es1	0.393	0.230	0.140	1.024	1.001	3925.777
...						

- Odds ratios
- Logistic coefficients

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INTERACTION EFFECTS IN **BLIMP**



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MODERATED REGRESSION

- Moderation occurs when a focal predictor's influence on an outcome depends on a third variable called a moderator
- Moderated regression answers the question, for whom does an effect apply?

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MODERATED REGRESSION MODEL

- β_1 and β_2 are conditional effects: β_1 is the influence of X when M equals 0, and β_2 is the influence of M when X is 0

$$Y = \beta_0 + \beta_1 X + \beta_2 M + \beta_3 XM + \varepsilon$$

- β_3 captures the change in the β_1 slope for every one-unit increase in M

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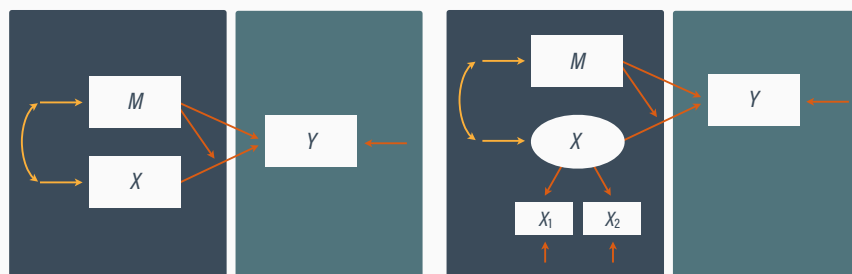
INCOMPLETE PRODUCT TERMS

- Factored regression specifications readily accommodate incomplete interactive and other nonlinear effects
- Product terms appear as deterministic functions of lower-order terms in the focal regression model rather than free variables
- The models and distributions of the predictors are unchanged

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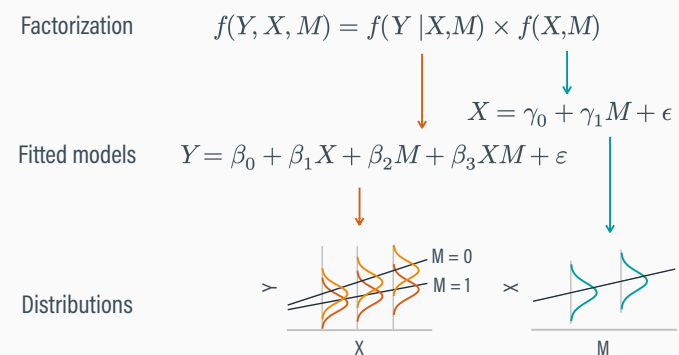
FACTORED SPECIFICATIONS FOR INTERACTIONS

Joint Distribution = Multivariate Predictor Distribution \times Univariate Outcome Distribution



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MODERATED REGRESSION EXAMPLE



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IMPUTING MISSING PREDICTORS

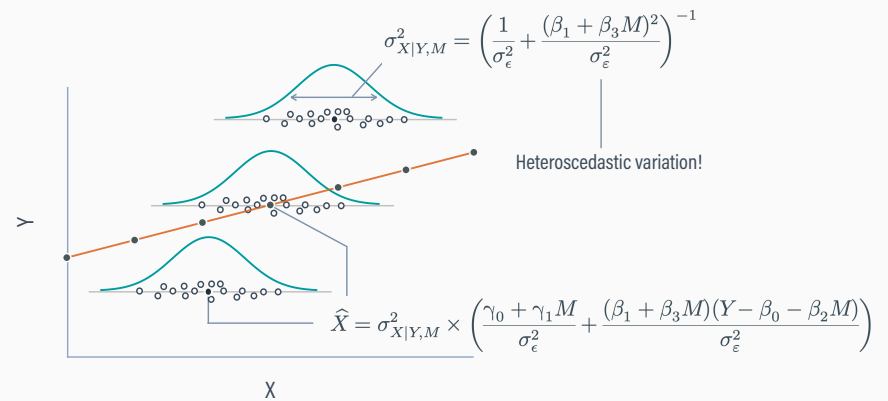
- A missing predictor always appears in two models: as a regressor in the focal model and an outcome in its own model

$$f(X|Y, M) \propto f(Y|X, M) \times f(X|M) = \text{[orange bell curve]} \times \text{[blue bell curve]}$$

- The distribution of missing X scores is a composite function that depends on both model-implied distributions

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DISTRIBUTIONS OF IMPUTATIONS



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AERA WORKSHOP DATA

■ Predictors
■ Outcome

Variable	Definition	Missing %	Scale
<i>STUDENT</i>	Student identifier	0	Integer index
<i>MALE</i>	Gender code	0	0 = Female, 1 = Male
<i>ESL</i>	English as a second language code	5.1	0 = Non-ESL, 1 = ESL
<i>RISKGRP</i>	Emotional/behavioral disorder risk	2.2	1 = Low, 2 = Medium, 3 = High
<i>ATRISK</i>	Emotional/behavioral risk code	2.2	0 = Low, 1 = Medium/high
<i>BEHSYMP1</i>	1st grade behavioral symptoms	3.6	Numeric (17 to 92)
<i>LRNPROB1</i>	1st grade learning problems	0	Numeric (31 to 88)
<i>READ1</i>	1st grade broad reading composite	6.5	Numeric (39 to 153)
<i>READ9</i>	9th grade broad reading composite	17.4	Numeric (41 to 123)
<i>READGRP9</i>	9th grade reading classification	17.4	0 = Below average, 1 = Average/above
<i>STANREAD7</i>	7th grade standardized reading	19.6	Numeric (100 to 399)

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ANALYSIS MODEL

- The influence of 1st grade reading performance on 9th grade test scores is moderated by learning problems in 1st grade

$$\begin{aligned}
 READ_9 = & \beta_0 + \beta_1(READ_1) + \beta_2(LRNPROB_1) + \beta_3(READ_1)(LRNPROB_1) \\
 & + \beta_4(MALE) + \beta_5(ESL) + \varepsilon
 \end{aligned}$$

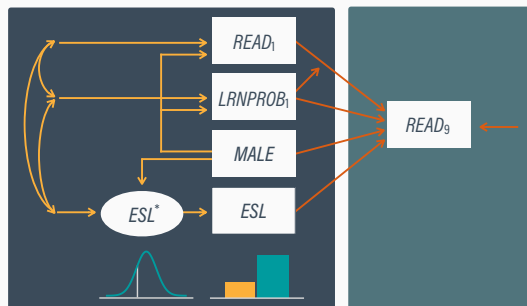
- 1st grade reading and learning problems scores are centered at the grand mean to facilitate interpretation of lower-order terms

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PATH DIAGRAM AND MODEL COMMAND

Joint Distribution = Multivariate Predictor Distribution \times Univariate Outcome Distribution

FIXED: male;
CENTER: read1 lnprob1;
MODEL:
 read9 \sim read1 lnprob1
 read1*lnprob1 male esl;



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BLIMP SCRIPT

DATA: aeraworkshop.dat;
VARIABLES: id male esl riskgrp atrisk behsymp1 lnprob1 read1 read9 read9grp stanread7;
MISSING: 999;
ORDINAL: esl;
NOMINAL: male;
FIXED: male;
CENTER: read1 lnprob1;
MODEL:
 read9 \sim read1 lnprob1 read1*lnprob1@interaction male esl;
TEST: interaction = 0;
BURN: 2000;
ITERATIONS: 10000;
SEED: 90291;

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PSR DIAGNOSTIC OUTPUT

BURN-IN POTENTIAL SCALE REDUCTION (PSR) OUTPUT:

NOTE: Split chain PSR is being used. This splits each chain's iterations to create twice as many chains.

Comparing iterations across 2 chains	Highest PSR	Parameter #
51 to 100	1.461	26
101 to 200	1.286	21
151 to 300	1.197	26
201 to 400	1.142	26
...
801 to 1600	1.019	26
851 to 1700	1.015	21
901 to 1800	1.017	21
951 to 1900	1.012	21
1001 to 2000	1.018	26

» Worst PSR < 1.05

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COEFFICIENT OUTPUT

OUTCOME MODEL ESTIMATES:

Summaries based on 10000 iterations using 2 chains.

Outcome Variable: **read9**

» Grand Mean Centered: lnrnprob1 read1

Parameters	Median	StdDev	2.5%	97.5%	PSR	N_Eff

Variances:						
Residual Var.	68.188	9.878	52.375	90.753	1.000	5133.493
Coefficients:						
Intercept	90.118	1.755	86.723	93.590	1.002	1163.979
read1	0.602	0.047	0.510	0.696	1.002	3470.201
lnrnprob1	-0.255	0.094	-0.442	-0.072	1.001	2120.825
male.1	3.712	1.700	0.296	6.984	1.000	5492.460
es1	-7.340	1.757	-10.752	-3.918	1.001	4364.216
read1*lnrnprob1	0.016	0.005	0.008	0.025	1.001	2414.527
Standardized Coefficients:						
...						

Change in READ1 slope for a 1-unit increase in LRNPB1
 Conditional effect of LRNPB1 at READ1 = 0 (the mean)
 Conditional effect of READ1 at LRNPB1 = 0 (the mean)

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MODEL FIT OUTPUT

MODEL FIT:

INFORMATION CRITERIA

...

WALD TESTS (Asparouhov & Muthén, 2021)

Test #1

Full:

[1] read9 ~ Intercept read1 lnprob1 male.1 esl read1*lnprob1@interaction

Restricted:

[1] read9 ~ Intercept read1 lnprob1 male.1 esl read1*lnprob1@interaction

Constraints in Restricted:

[1] interaction = 0

Wald Statistic (Chi-Square)	13.206
Number of Parameters Tested (df)	1
Probability	0.000

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BLIMP SCRIPT: CONDITIONAL EFFECTS

CENTER: read1 lnprob1;

MODEL: read9 ~ read1 lnprob1 read1*lnprob1@interaction male esl;

SIMPLE: read1 | lnprob1; # focal predictor | moderator

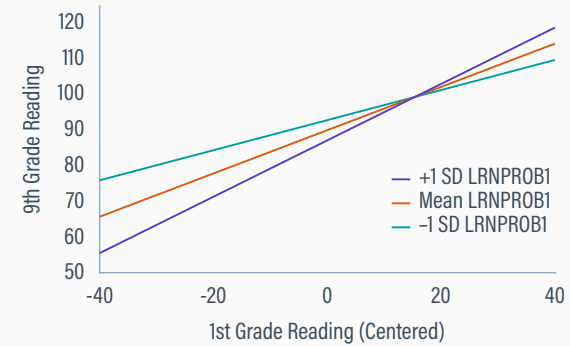
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CONDITIONAL EFFECT OUTPUT

Conditional Effects	Median	StdDev	2.5%	97.5%	PSR	N_Eff
...						
read1 lrnprob1 @ +1 SD						
Intercept	87.267	2.377	82.576	91.919	1.000	985.997
Slope	0.787	0.076	0.642	0.942	1.001	2811.774
read1 lrnprob1 @ 0						
Intercept	90.100	1.816	86.592	93.650	1.000	1082.863
Slope	0.604	0.047	0.512	0.695	1.001	3485.920
read1 lrnprob1 @ -1 SD						
Intercept	92.909	1.807	89.439	96.471	1.001	2013.538
Slope	0.421	0.062	0.294	0.538	1.000	4577.480
...						

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CONDITIONAL EFFECTS (SIMPLE SLOPES)



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REPORTING TEMPLATE

We used Bayesian estimation in Blimp 3 (Keller & Enders, 2021) to treat missing values under the assumption that missingness is random after conditioning on the observed data. Potential scale reduction factor convergence diagnostics (Gelman & Rubin, 1992) from a preliminary run indicated that a burn-in period of 2,000 iterations was sufficiently conservative. Based on this information, we used two MCMC chains with random starting values to generate posterior summaries consisting of 10,000 estimates following the initial burn-in period. We verified this setting was sufficient by examining the effective number of independent MCMC samples for each parameter, all of which were greater than the recommended value of 100 (Gelman et al., 2014, p. 287).

REPORTING TEMPLATE CONTINUED

Table 1 displays the posterior summaries from the analysis. The posterior medians and standard deviations are analogous to frequentist point estimates and standard errors, and the 95% credible interval limits are akin to confidence intervals. These quantities make no reference to repeated samples but instead convey parameter values that are consistent with the observed data. Given the same assumptions and data, Bayesian and likelihood-based missing data handling procedures are numerically equivalent. However, Bayesian estimation is preferable because classic FIML estimator is known to introduce bias when applied to interactive effects (Enders, 2022).

APA TABLE

Table 1

Parameter Summary From the Bayesian Moderated Regression Analysis

Parameter	Median	SD	LCL	UCL
Intercept	90.12	1.76	86.72	93.59
1st grade reading	0.60	0.05	0.51	0.70
1st grade learning problems	-0.26	0.09	-0.44	-0.07
Male dummy code	3.71	1.70	0.30	6.98
ESL dummy code	-7.34	1.76	-10.75	-3.92
Reading by learning problems	0.02	0.01	0.01	0.03
R ²	.69	.04	.60	.76

REPORTING TEMPLATE CONTINUED

Collectively, the predictors explained approximately 69% of the variation in 9th grade reading scores. The Bayesian Wald test (Asparouhov & Muthén, 2021) of the interaction effect was statistically significant, $\chi^2(1) = 13.21, p < .001$. At the learning problems mean, first grade reading exhibited a significant positive association with 9th grade reading performance ($\beta = 0.60, SD = 0.05, p < .001$), controlling for other predictors. The positive interaction coefficient indicates that the first grade reading slope increases as learning problems increase ($\beta = 0.02, SD = 0.01, p < .001$), such that first grade test scores become increasingly predictive of later achievement. Figure 1 displays the simple slopes at three levels of learning problems.



For more information go to
WWW.APPLIEDMISSINGDATA.COM