

Multilevel Multilingual

Multilevel Models in Stata, R and Julia

Andrew Grogan-Kaylor

2024-05-15

Table of contents

1	Multilevel Multilingual	4
1.1	Introduction	4
1.2	The Data	6
1.3	An Introduction To Equations and Syntax	6
1.3.1	Stata	7
1.3.2	R	7
1.3.3	Julia	7
2	Descriptive Statistics	8
2.1	Descriptive Statistics	8
2.1.1	Stata	8
2.1.2	R	9
2.1.3	Julia	10
2.2	Interpretation	11
3	Unconditional Model	12
3.1	The Equation	12
3.2	Run Models	12
3.2.1	Stata	12
3.2.2	R	13
3.2.3	Julia	15
3.3	Interpretation	15
4	Cross Sectional Multilevel Models	16
4.1	The Equation	16
4.2	Correlated and Uncorrelated Random Effects	16
4.3	Run Models	17
4.3.1	Stata	17
4.3.2	R	19
4.3.3	Julia	21
4.4	Interpretation	22
5	Longitudinal Multilevel Models	23
5.1	The Data	23
5.2	The Equation	23

5.3	Run Models	23
5.3.1	Stata	23
5.3.2	R	26
5.3.3	Julia	31
5.4	Interpretation	33
References		34

List of Tables

1.1	Software for Multilevel Modeling	4
1.2	Sample of Simulated Multilevel Data	6
1.2	Table continues below	6
1.3	Sample of Simulated Multilevel Data	6
4.1	Correlated and Uncorrelated Random Effects	17

1 Multilevel Multilingual

“This curious world which we inhabit is more wonderful than it is convenient...”
(Thoreau, 1975)

“Mathematics is my secret. My secret weakness. I feel like a stubborn, helpless fool in the middle of a problem. Trapped and crazed. Also, thrilled.” (Schanen, 2021)

1.1 Introduction

Below, I describe the use of [Stata](#) (StataCorp, 2021), [R](#) (Bates et al., 2015; R Core Team, 2023), and [Julia](#) (Bates, 2024; Bezanson et al., 2017) to estimate multilevel models.

All of these software packages can estimate multilevel models. However, there are substantial differences between the different packages: Stata is proprietary *for cost* software, which is very well documented and very intuitive. While it costs money to purchase Stata, the price is often very reasonable for academic and educational use. R is free open source software which is less intuitive, but there are many excellent resources for learning R. There is often a cost associated with purchasing books and other materials for learning R. Julia is newer open source software, and ostensibly much faster than either Stata or R, which may be an important advantage when running multilevel models with very large data sets. At this point in time, both Stata and R feel much more *stable* than Julia which is still evolving software.

While any of these software packages can be used for learning and estimating multilevel models, I will offer my own opinion—based upon 15 years of teaching multilevel models at the doctoral level—that Stata offers the quickest pathway for learning the basic and advanced uses of multilevel models. I also believe the intuitive nature of Stata syntax contributes to accurate and replicable work in this area.

Table 1.1: Software for Multilevel Modeling

Software	Cost	Ease of Use
Stata	some cost	learning curve, but very intuitive for both multilevel modeling and graphing.

Software	Cost	Ease of Use
R	free	learning curve: intuitive for multilevel modeling; but steeper learning curve for graphing (<code>ggplot</code>).
Julia	free	steep learning curve in general: steep learning curve for multilevel modeling; and very steep learning curve for graphing. Graphics libraries are very much under development and in flux.

💡 Results Will Vary Somewhat

Estimating multilevel models is a complex endeavor. The software details of how this is accomplished are beyond the purview of this book. Suffice it to say that across different software packages there will be differences in estimation routines, resulting in some numerical differences in the results provided by different software packages. Substantively speaking, however, results should agree across software.

💡 Multi-Line Commands

Sometimes I have written commands out over multiple lines. I have done this for especially long commands, but have also sometimes done this simply for the sake of clarity. The different software packages have different approaches to multi-line commands.

1. By default, *Stata* ends a command at the end of a line. If you are going to write a multi-line command you should use the `///` line continuation characters.
2. *R* is the software that most naturally can be written using multiple lines, as *R* commands are usually clearly encased in parentheses `()` or continued with `+` signs.
3. Like *Stata*, *Julia* expects commands to end at the end of a line. If you are going to write a multi-line command, all commands except for the last line should end in a character that clearly indicates continuation, like a `+` sign. An alternative is to encase the entire *Julia* command in an outer set of parentheses `()`.

💡 Running Statistical Packages in Quarto

I used Quarto (<https://quarto.org/>) to create this Appendix. Quarto is a programming and publishing environment that can run multiple programming languages, including *Stata*, *R* and *Julia*, and that can write to multiple output formats including HTML, PDF, and MS Word. To run *Stata*, I used the `Statamarkdown` library in *R* to connect *Stata* to Quarto. Quarto has a built in connection to *R*, and runs *R* without issue. To

run Julia, I used the `JuliaCall` library in R to connect Quarto to Julia. Of course, each of these programs can be run by itself, if you have them installed on your computer.

1.2 The Data

The examples use the `simulated_multilevel_data.dta` file from *Multilevel Thinking*. Here is a [direct link](#) to download the data.

Table 1.2: Sample of Simulated Multilevel Data

Table 1.2: Table continues below

country	HDI	family	id	identity	intervention	physical_punishment
1	69	1	1.1	2	0	3
1	69	2	1.2	2	1	2
1	69	3	1.3	1	1	3
1	69	4	1.4	2	0	0
1	69	5	1.5	2	0	4
1	69	6	1.6	1	1	5

Table 1.3: Sample of Simulated Multilevel Data

warmth	outcome
3	57.47
1	50.1
2	52.92
5	60.17
4	55.05
3	49.81

1.3 An Introduction To Equations and Syntax

To explain statistical syntax for each software, I consider the general case of a multilevel model with dependent variable y , independent variables \mathbf{x} and \mathbf{z} , clustering variable `group`, and a random slope for \mathbf{x} . i is the index for the person, while j is the index for the `group`.

$$y = \beta_0 + \beta_1 x_{ij} + \beta_2 z_{ij} + u_{0j} + u_{1j} \times x_{ij} + e_{ij} \quad (1.1)$$

1.3.1 Stata

In Stata `mixed`, the syntax for a multilevel model of the form described in Equation 1.1 is:

```
mixed y x || group: x
```

1.3.2 R

In R `lme4`, the general syntax for a multilevel model of the form described in Equation 1.1 is:

```
library(lme4)

lmer(y ~ x + z + (1 + x || group), data = ...)
```

1.3.3 Julia

In Julia `MixedModels`, the general syntax for a multilevel model of the form described in Equation 1.1 is:

```
using MixedModels

fit(MixedModel, @formula(y ~ x + z + (1 + x | group)), data)
```


2 Descriptive Statistics

2.1 Descriptive Statistics

2.1.1 Stata

```
use simulated_multilevel_data.dta // use data
```

We use `summarize` for *continuous* variables, and `tabulate` for *categorical* variables.

```
summarize outcome warmth physical_punishment HDI
```

```
tabulate identity
```

```
tabulate intervention
```

Variable	Obs	Mean	Std. dev.	Min	Max
-----+-----					
outcome	3,000	52.43327	6.530996	29.60798	74.83553
warmth	3,000	3.521667	1.888399	0	7
physical_p~t	3,000	2.478667	1.360942	0	5
HDI	3,000	64.76667	17.24562	33	87

hypothetica			
1 identity			
group			
variable	Freq.	Percent	Cum.
-----+-----			
1	1,507	50.23	50.23
2	1,493	49.77	100.00
-----+-----			
Total	3,000	100.00	

recieved interventio	n	Freq.	Percent	Cum.
0	1,547	51.57	51.57	
1	1,453	48.43	100.00	
Total	3,000	100.00		

2.1.2 R

```
library(haven) # read data in Stata format

df <- read_dta("simulated_multilevel_data.dta")
```

R's descriptive statistics functions rely heavily on whether a variable is a *numeric* variable, or a *factor* variable. Below, I convert two variables to factors (`factor`) before using `summary`¹ to generate descriptive statistics.

```
df$country <- factor(df$country)

df$identity <- factor(df$identity)

df$intervention <- factor(df$intervention)

summary(df)
```

```

country      HDI      family      id      identity
1      : 100  Min.   :33.00  Min.   : 1.00  Length:3000  1:1507
2      : 100  1st Qu.:53.00  1st Qu.: 25.75  Class :character 2:1493
3      : 100  Median :70.00  Median : 50.50  Mode  :character
4      : 100  Mean   :64.77  Mean   : 50.50
5      : 100  3rd Qu.:81.00  3rd Qu.: 75.25
6      : 100  Max.   :87.00  Max.   :100.00
(Other):2400
intervention physical_punishment  warmth      outcome
0:1547      Min.   :0.000      Min.   :0.000  Min.   :29.61
1:1453      1st Qu.:2.000      1st Qu.:2.000  1st Qu.:48.02
```

¹`skimr` is an excellent new alternative library for generating descriptive statistics in R.

Median	:2.000	Median	:4.000	Median	:52.45
Mean	:2.479	Mean	:3.522	Mean	:52.43
3rd Qu.	:3.000	3rd Qu.	:5.000	3rd Qu.	:56.86
Max.	:5.000	Max.	:7.000	Max.	:74.84

2.1.3 Julia

```
using Tables, MixedModels, MixedModelsExtras, StatFiles, DataFrames, CategoricalArrays, DataAPI

df = DataFrame(load("simulated_multilevel_data.dta"))
```

Similarly to R, Julia relies on the idea of *variable type*. I use `transform` to convert the appropriate variables to *categorical* variables.

```
@transform!(df, :country = categorical(:country))

@transform!(df, :identity = categorical(:identity))

@transform!(df, :intervention = categorical(:intervention))
```

```
describe(df) # descriptive statistics
```

```
9×7 DataFrame
 Row  variable          mean    min    median  max    nmissing  eltype
      Symbol          Union... Any    Union... Any    Int64     Union
  1  country              1.0      30.0
  2  HDI                 64.7667  33.0   70.0    87.0     0  Union{
  3  family                50.5     1.0   50.5   100.0    0  Union{
  4  id                    1.1      9.99
  5  identity              1.0      2.0
  6  intervention          0.0      1.0
  7  physical_punishment  2.47867  0.0    2.0     5.0     0  Union{
  8  warmth                3.52167  0.0    4.0     7.0     0  Union{
  9  outcome               52.4333 29.608 52.449 74.8355  0  Union{

1 column omitted
```

2.2 Interpretation

Examining descriptive statistics is an important first step in any analysis. It is important to examine your descriptive statistics first, before skipping ahead to more sophisticated analyses, such as multilevel models.

In examining the descriptive statistics for this data, we get a sense of the data.

- `outcome` has a mean of approximately 52 and ranges from approximately 30 to 75.
- `warmth` and `physical punishment` are both variables that represent the number of times that parents use each of these forms of discipline in a week. The average of the former is about 3.5, while the average of the latter is about 2.5.
- `HDI`, the Human Development Index has an average of about 65, and a wide range.
- `identity` is a categorical variable for a hypothetical identity group, and has values of 1 and 2.
- `intervention` is also a categorical variable, and has values of 0 and 1.

3 Unconditional Model

An *unconditional* multilevel model is a model with no independent variables. One should always run an unconditional model as the first step of a multilevel model in order to get a sense of the way that variation is apportioned in the model across the different levels.

3.1 The Equation

$$\text{outcome}_{ij} = \beta_0 + u_{0j} + e_{ij} \quad (3.1)$$

The Intraclass Correlation Coefficient (ICC) is given by:

$$\text{ICC} = \frac{\text{var}(u_{0j})}{\text{var}(u_{0j}) + \text{var}(e_{ij})} \quad (3.2)$$

In a two level multilevel model, the ICC provides a measure of the amount of variation attributable to Level 2.

3.2 Run Models

3.2.1 Stata

```
use simulated_multilevel_data.dta // use data
```

```
mixed outcome || country: // unconditional model
```

```
Performing EM optimization ...
```

```
Performing gradient-based optimization:
```

```
Iteration 0: Log likelihood = -9802.8371
```

```
Iteration 1: Log likelihood = -9802.8371
```

Computing standard errors ...

Mixed-effects ML regression
Group variable: country

Number of obs = 3,000
Number of groups = 30
Obs per group:
min = 100
avg = 100.0
max = 100
Wald chi2(0) = .
Prob > chi2 = .

Log likelihood = -9802.8371

outcome	Coefficient	Std. err.	z	P> z	[95% conf. interval]	
_cons	52.43327	.3451217	151.93	0.000	51.75685	53.1097

Random-effects parameters	Estimate	Std. err.	[95% conf. interval]	
country: Identity				
var(_cons)	3.178658	.9226737	1.799552	5.614658
var(Residual)	39.46106	1.024013	37.50421	41.52

LR test vs. linear model: chibar2(01) = 166.31 Prob >= chibar2 = 0.0000

```
estat icc // ICC
```

Intraclass correlation

Level	ICC	Std. err.	[95% conf. interval]	
country	.0745469	.0201254	.0434963	.1248696

3.2.2 R

```
library(haven)

df <- read_dta("simulated_multilevel_data.dta")
```

```
library(lme4) # estimate multilevel models

fit0 <- lmer(outcome ~ (1 | country),
             data = df) # unconditional model

summary(fit0)
```

```
Linear mixed model fit by REML ['lmerMod']
Formula: outcome ~ (1 | country)
Data: df
```

```
REML criterion at convergence: 19605.9
```

```
Scaled residuals:
```

Min	1Q	Median	3Q	Max
-3.3844	-0.6655	-0.0086	0.6725	3.6626

```
Random effects:
```

Groups	Name	Variance	Std.Dev.
country	(Intercept)	3.302	1.817
	Residual	39.461	6.282

Number of obs: 3000, groups: country, 30

```
Fixed effects:
```

	Estimate	Std. Error	t value
(Intercept)	52.433	0.351	149.4

```
library(performance)

performance::icc(fit0) # ICC
```

```
# Intraclass Correlation Coefficient
```

```
Adjusted ICC: 0.077
Unadjusted ICC: 0.077
```

3.2.3 Julia

```
using Tables, MixedModels, MixedModelsExtras,  
StatFiles, DataFrames, CategoricalArrays, DataFramesMeta
```

```
df = DataFrame(load("simulated_multilevel_data.dta"))
```

```
@transform!(df, :country = categorical(:country))
```

```
m0 = fit(MixedModel,  
         @formula(outcome ~ (1 | country)), df) # unconditional model
```

Linear mixed model fit by maximum likelihood

outcome ~ 1 + (1 | country)

	logLik	-2 logLik	AIC	AICc	BIC
	-9802.8371	19605.6742	19611.6742	19611.6822	19629.6933

Variance components:

	Column	Variance	Std.Dev.
country	(Intercept)	3.17863	1.78287
Residual		39.46106	6.28180

Number of obs: 3000; levels of grouping factors: 30

Fixed-effects parameters:

	Coef.	Std. Error	z	Pr(> z)
(Intercept)	52.4333	0.345121	151.93	<1e-99

```
icc(m0) # ICC
```

```
0.07454637475695493
```

3.3 Interpretation

In each case, the software finds that nearly 8% of the variation in the outcome is explainable by the clustering of the observations in each country.

4 Cross Sectional Multilevel Models

4.1 The Equation

Recall the general model of Equation 1.1, and the syntax outlined in Section 1.3. Below in Equation 4.1, we consider a more substantive example.

$$\begin{aligned} \text{outcome}_{ij} = & \beta_0 + \beta_1 \text{warmth}_{ij} + \\ & \beta_2 \text{physical punishment}_{ij} + \\ & \beta_3 \text{identity}_{ij} + \beta_4 \text{intervention}_{ij} + \beta_5 \text{HDI}_{ij} + \\ & u_{0j} + u_{1j} \times \text{warmth}_{ij} + e_{ij} \end{aligned} \tag{4.1}$$

4.2 Correlated and Uncorrelated Random Effects

Consider the covariance matrix of random effects (e.g. u_{0j} and u_{1j}). In Equation 4.2 the covariances of the random effects are constrained to be zero.

$$\begin{bmatrix} \text{var}(u_{0j}) & 0 \\ 0 & \text{var}(u_{1j}) \end{bmatrix} \tag{4.2}$$

As discussed in the Chapter on multilevel models with cross-sectional data, however, one can consider a multilevel model in which the random effects are correlated, as is the case in Equation 4.3.

$$\begin{bmatrix} \text{var}(u_{0j}) & \text{cov}(u_{0j}, u_{1j}) \\ \text{cov}(u_{0j}, u_{1j}) & \text{var}(u_{1j}) \end{bmatrix} \tag{4.3}$$

Procedures for estimating models with uncorrelated and correlated random effects are detailed below (Bates et al., 2015; Bates, 2024; StataCorp, 2021).

Table 4.1: Correlated and Uncorrelated Random Effects

Software	Uncorrelated Random Effects	Correlated Random Effects
Stata	default	add option: <code>, cov(uns)</code>
R	separate random effects from grouping variable with <code> </code>	separate random effects from grouping variable with <code> </code>
Julia	separate terms for each random effect e.g. <code>(1 group) + (0 + x group)</code>	separate random effects from grouping variable with <code> .</code>

All models in the examples below are run with *uncorrelated* random effects, but could just as easily be run with *correlated* random effects.

4.3 Run Models

4.3.1 Stata

4.3.1.1 Get The Data

```
use simulated_multilevel_data.dta
```

4.3.1.2 Run The Model

```
mixed outcome warmth physical_punishment i.identity i.intervention HDI || country: warmth
```

Performing EM optimization ...

Performing gradient-based optimization:

Iteration 0: Log likelihood = -9626.6279

Iteration 1: Log likelihood = -9626.607

Iteration 2: Log likelihood = -9626.607

Computing standard errors ...

Mixed-effects ML regression
Group variable: country

Number of obs = 3,000
Number of groups = 30
Obs per group:
min = 100
avg = 100.0
max = 100
Wald chi2(5) = 334.14
Prob > chi2 = 0.0000

Log likelihood = -9626.607

outcome	Coefficient	Std. err.	z	P> z	[95% conf. interval]	
warmth	.8345368	.0637213	13.10	0.000	.7096453	.9594282
physical_punishment	-.9916657	.0797906	-12.43	0.000	-1.148052	-.8352791
2.identity	-.3004767	.2170295	-1.38	0.166	-.7258466	.1248933
1.intervention	.6396427	.2174519	2.94	0.003	.2134448	1.065841
HDI	-.003228	.0199257	-0.16	0.871	-.0422817	.0358256
_cons	51.99991	1.371257	37.92	0.000	49.3123	54.68753

Random-effects parameters	Estimate	Std. err.	[95% conf. interval]	
country: Independent				
var(warmth)	.0227504	.0257784	.0024689	.2096436
var(_cons)	2.963975	.9737647	1.556777	5.643163
var(Residual)	34.97499	.9097109	33.23668	36.80422

LR test vs. linear model: chi2(2) = 205.74

Prob > chi2 = 0.0000

Note: LR test is conservative and provided only for reference.

4.3.2 R

4.3.2.1 Get The Data

```
library(haven)

df <- read_dta("simulated_multilevel_data.dta")
```

4.3.2.2 Run The Model

Caution

`lme4` does not directly provide p values in results, because of some disagreement over exactly how these p values should be calculated. Therefore, in this Appendix, I also call library `lmerTest` to provide p values for `lme4` results.

Tip

R prefers to use scientific notation when possible. I find that the use of scientific notation can be confusing in reading results. I turn off scientific notation by setting a penalty for its use: `options(scipen = 999)`.

```
library(lme4)

library(lmerTest)

options(scipen = 999)

fit1 <- lmer(outcome ~ warmth + physical_punishment +
             identity + intervention + HDI +
             (1 + warmth || country),
             data = df)

summary(fit1)
```

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method [
lmerModLmerTest]
Formula: outcome ~ warmth + physical_punishment + identity + intervention +
        HDI + (1 + warmth || country)
```

Data: df

REML criterion at convergence: 19268.8

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.9774	-0.6563	0.0187	0.6645	3.6730

Random effects:

Groups	Name	Variance	Std.Dev.
country	(Intercept)	3.19056	1.786
country.1	warmth	0.02465	0.157
Residual		35.01782	5.918

Number of obs: 3000, groups: country, 30

Fixed effects:

	Estimate	Std. Error	df	t value
(Intercept)	52.311714	1.446735	33.113738	36.158
warmth	0.834562	0.064252	41.896966	12.989
physical_punishment	-0.991892	0.079845	2968.010901	-12.423
identity	-0.300350	0.217179	2970.106304	-1.383
intervention	0.639059	0.217603	2971.185215	2.937
HDI	-0.003395	0.020596	27.598517	-0.165

Pr(>|t|)

(Intercept)	< 0.0000000000000002 ***
warmth	0.000000000000000277 ***
physical_punishment	< 0.0000000000000002 ***
identity	0.16678
intervention	0.00334 **
HDI	0.87027

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	(Intr)	warmth	physc_	idntty	intrvn
warmth		-0.119			
physcl_pnsh	-0.145		-0.003		
identity	-0.220	-0.012		-0.003	
interventin	-0.077	0.034	0.022		-0.018
HDI	-0.922	-0.006	0.009	-0.001	0.000

4.3.3 Julia

4.3.3.1 Get The Data

```
using Tables, MixedModels, StatFiles, DataFrames, CategoricalArrays, DataFramesMeta

df = DataFrame(load("simulated_multilevel_data.dta"))
```

4.3.3.2 Change Country To Categorical

```
@transform!(df, :country = categorical(:country))
```

4.3.3.3 Run The Model

```
m1 = fit(MixedModel, @formula(outcome ~ warmth + physical_punishment +
                             identity + intervention + HDI +
                             (1 | country) +
                             (0 + warmth | country)), df)
```

Linear mixed model fit by maximum likelihood

```
outcome ~ 1 + warmth + physical_punishment + identity + intervention + HDI + (1 | country)
logLik    -2 logLik      AIC      AICc      BIC
-9626.6070 19253.2140 19271.2140 19271.2742 19325.2713
```

Variance components:

	Column	Variance	Std.Dev.	Corr.
country	(Intercept)	2.963849	1.721583	
	warmth	0.022756	0.150852	.
Residual		34.974984	5.913965	

Number of obs: 3000; levels of grouping factors: 30

Fixed-effects parameters:

	Coef.	Std. Error	z	Pr(> z)
(Intercept)	52.3004	1.40406	37.25	<1e-99
warmth	0.834537	0.0637228	13.10	<1e-38

physical_punishment	-0.991665	0.0797906	-12.43	<1e-34
identity	-0.300475	0.217029	-1.38	0.1662
intervention	0.639641	0.217452	2.94	0.0033
HDI	-0.0032286	0.0199255	-0.16	0.8713

4.4 Interpretation

Models suggest that parental warmth is associated with increases in the beneficial outcome, while physical punishment is associated with decreases in the beneficial outcome. Membership in the group represented by `identity` is not associated with the outcome. The intervention is associated with increases in the outcome. The Human Development Index is not associated with the outcome.

5 Longitudinal Multilevel Models

5.1 The Data

The data employed in these examples are a longitudinal extension of the data described in Section 1.2.

5.2 The Equation

$$\text{outcome}_{itj} = \beta_0 + \beta_1 \text{parental warmth}_{itj} + \beta_2 \text{physical punishment}_{itj} + \beta_3 \text{time}_{itj} + \quad (5.1)$$

$$\beta_4 \text{identity}_{itj} + \beta_5 \text{intervention}_{itj} + \beta_6 \text{HDI}_{itj} +$$

$$u_{0j} + u_{1j} \times \text{parental warmth}_{itj} +$$

$$v_{0i} + v_{1i} \times \text{time}_{itj} + e_{itj}$$

5.3 Run Models

5.3.1 Stata

5.3.1.1 Get The Data

```
use simulated_multilevel_longitudinal_data.dta
```


5.3.1.2 Run The Model

5.3.1.2.1 Main Effects Only

```
mixed outcome t warmth physical_punishment i.identity i.intervention HDI || country: warmth
```

Performing EM optimization ...

Performing gradient-based optimization:

Iteration 0: Log likelihood = -28739.506

Iteration 1: Log likelihood = -28739.506

Computing standard errors ...

Mixed-effects ML regression

Group variable: country

Number of obs = 9,000

Number of groups = 30

Obs per group:

min = 300

avg = 300.0

max = 300

Wald chi2(6) = 1119.81

Prob > chi2 = 0.0000

Log likelihood = -28739.506

outcome	Coefficient	Std. err.	z	P> z	[95% conf. interval]	
t	.9443446	.0756408	12.48	0.000	.7960914	1.092598
warmth	.9123903	.0430042	21.22	0.000	.8281035	.996677
physical_punishment	-.9881587	.0451732	-21.87	0.000	-1.076696	-.8996209
2.identity	-.1241465	.1242225	-1.00	0.318	-.367618	.1193251
1.intervention	.8575839	.1245179	6.89	0.000	.6135332	1.101635
HDI	-.0025173	.0191696	-0.13	0.896	-.0400891	.0350544
_cons	50.54528	1.304146	38.76	0.000	47.9892	53.10136

Random-effects parameters	Estimate	Std. err.	[95% conf. interval]	
country: Independent				
var(warmth)	.0229349	.0135353	.0072136	.0729194
var(_cons)	3.0009	.8550708	1.716768	5.245553

```

var(Residual) | 34.31935 .5130963 33.3283 35.33988
-----
LR test vs. linear model: chi2(2) = 767.22 Prob > chi2 = 0.0000

```

Note: LR test is conservative and provided only for reference.

5.3.1.2.2 Interactions With Time

```
mixed outcome c.t##(c.warmth c.physical_punishment i.identity i.intervention c.HDI) || country
```

Performing EM optimization ...

Performing gradient-based optimization:

Iteration 0: Log likelihood = -28738.554

Iteration 1: Log likelihood = -28738.554

Computing standard errors ...

```

Mixed-effects ML regression      Number of obs    =    9,000
Group variable: country          Number of groups  =     30
                                Obs per group:
                                    min =     300
                                    avg  =    300.0
                                    max  =     300
                                Wald chi2(11)    =   1122.75
Log likelihood = -28738.554      Prob > chi2       =    0.0000

```

```

-----
outcome | Coefficient  Std. err.      z    P>|z|    [95% conf. interval]
-----+-----
      t |   .7537359   .3719996     2.03   0.043    .0246301   1.482842
  warmth |   .8198365   .0911059     9.00   0.000    .6412723   .9984008
physical_punishment | -1.000348   .1198049    -8.35   0.000   -1.235162  -.7655353
  2.identity | -.2340191   .3271243    -0.72   0.474   -.875171   .4071327
  1.intervention |   .6597456   .3275877     2.01   0.044    .0176856   1.301806
      HDI |  -.0005531   .0210866    -0.03   0.979   -.041882   .0407757
      |
  c.t#c.warmth |   .0463746   .0402459     1.15   0.249   -.0325059   .1252551
      |
      c.t#|
c.physical_punishment |   .0061255   .0551491     0.11   0.912   -.1019647   .1142157

```

identity#c.t							
2		.0548965	.1513015	0.36	0.717	-.241649	.3514421
intervention#c.t							
1		.0990704	.151503	0.65	0.513	-.19787	.3960108
c.t#c.HDI		-.0009791	.0043888	-0.22	0.823	-.0095811	.0076229
_cons		50.92503	1.494157	34.08	0.000	47.99654	53.85352

Random-effects parameters		Estimate	Std. err.	[95% conf. interval]	
country: Independent					
var(warmth)		.0228292	.0135078	.0071588	.0728013
var(_cons)		3.001849	.8552796	1.71738	5.247001
var(Residual)		34.31227	.5129896	33.32141	35.33258

LR test vs. linear model: $\chi^2(2) = 767.35$ Prob > $\chi^2 = 0.0000$

Note: LR test is conservative and provided only for reference.

5.3.2 R

5.3.2.1 Get The Data

```
library(haven)

dfL <- read_dta("simulated_multilevel_longitudinal_data.dta")
```

5.3.2.2 Run The Model

Caution

`lme4` does not directly provide p values in results, because of some disagreement over exactly how these p values should be calculated. Therefore, in this Appendix, I also call library `lmerTest` to provide p values for `lme4` results.

Tip

R prefers to use scientific notation when possible. I find that the use of scientific notation can be confusing in reading results. I turn off scientific notation by setting a penalty for its use: `options(scipen = 999)`.

5.3.2.2.1 Main Effects Only

```
library(lme4)

library(lmerTest)

options(scipen = 999)

fit2A <- lmer(outcome ~ t + warmth + physical_punishment +
              identity + intervention + HDI +
              (1 | country/id),
              data = dfL)

summary(fit2A)
```

Linear mixed model fit by REML. t-tests use Satterthwaite's method [
lmerModLmerTest]

Formula:

outcome ~ t + warmth + physical_punishment + identity + intervention +
HDI + (1 | country/id)

Data: dfL

REML criterion at convergence: 57022.7

Scaled residuals:

	Min	1Q	Median	3Q	Max
	-3.6850	-0.6094	-0.0035	0.6133	3.6792

Random effects:

Groups	Name	Variance	Std.Dev.
id:country	(Intercept)	8.438	2.905
country	(Intercept)	3.675	1.917
	Residual	26.036	5.103

Number of obs: 9000, groups: id:country, 3000; country, 30

Fixed effects:

	Estimate	Std. Error	df	t value
(Intercept)	50.5161891	1.4296454	31.1737942	35.335
t	0.9433806	0.0658755	5998.3764616	14.321
warmth	0.9140307	0.0379336	4745.3496835	24.096
physical_punishment	-1.0087537	0.0497972	6483.6770989	-20.257
identity	-0.1319548	0.1517350	2968.7829265	-0.870
intervention	0.8591494	0.1520510	2971.8112001	5.650
HDI	0.0007909	0.0207656	28.0001836	0.038

	Pr(> t)
(Intercept)	< 0.0000000000000002 ***
t	< 0.0000000000000002 ***
warmth	< 0.0000000000000002 ***
physical_punishment	< 0.0000000000000002 ***
identity	0.385
intervention	0.0000000175 ***
HDI	0.970

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	(Intr) t	warmth	physc_	idntty	intrvn
t	-0.091				
warmth	-0.088	-0.002			
physcl_pnsh	-0.090	-0.007	-0.012		
identity	-0.156	0.000	-0.013	-0.003	
interventin	-0.055	0.000	0.039	0.019	-0.018
HDI	-0.941	0.000	-0.004	0.005	0.000

5.3.2.2.2 Interactions With Time

```
fit2B <- lmer(outcome ~ t *(warmth + physical_punishment +
  identity + intervention + HDI) +
  (1 | country/id),
```

```
data = dfL)

summary(fit2B)
```

Linear mixed model fit by REML. t-tests use Satterthwaite's method [
lmerModLmerTest]

Formula:

outcome ~ t * (warmth + physical_punishment + identity + intervention +
HDI) + (1 | country/id)

Data: dfL

REML criterion at convergence: 57042.8

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.7118	-0.6092	-0.0024	0.6150	3.6779

Random effects:

Groups	Name	Variance	Std.Dev.
id:country	(Intercept)	8.436	2.905
country	(Intercept)	3.675	1.917
	Residual	26.046	5.104

Number of obs: 9000, groups: id:country, 3000; country, 30

Fixed effects:

	Estimate	Std. Error	df	t value
(Intercept)	51.0036725	1.6087742	49.9583024	31.703
t	0.6989769	0.3746882	6131.2125222	1.865
warmth	0.8170912	0.0805355	8274.9994610	10.146
physical_punishment	-1.0097729	0.1113557	8084.6085126	-9.068
identity	-0.2446453	0.3041604	8695.8966126	-0.804
intervention	0.6604671	0.3046286	8697.0843469	2.168
HDI	0.0026692	0.0221295	36.1037721	0.121
t:warmth	0.0486211	0.0356217	6404.8722416	1.365
t:physical_punishment	0.0004964	0.0494590	6753.0158846	0.010
t:identity	0.0563140	0.1318043	5993.4518199	0.427
t:intervention	0.0995037	0.1319917	5994.1433047	0.754
t:HDI	-0.0009379	0.0038233	5993.9091197	-0.245

Pr(>|t|)

(Intercept)	<0.0000000000000002 ***
t	0.0622 .
warmth	<0.0000000000000002 ***

```

physical_punishment    <0.0000000000000002 ***
identity               0.4212
intervention           0.0302 *
HDI                   0.9047
t:warmth               0.1723
t:physical_punishment 0.9920
t:identity             0.6692
t:intervention         0.4510
t:HDI                  0.8062

```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	(Intr)	t	warmth	physc_	idntty	intrvn	HDI	t:wrmt	t:phy_
t	-0.466								
warmth	-0.169	0.285							
physcl_pnsh	-0.183	0.313	-0.005						
identity	-0.278	0.450	-0.013	-0.002					
interventin	-0.100	0.162	0.039	0.019	-0.017				
HDI	-0.892	0.230	-0.007	0.012	-0.001	0.003			
t:warmth	0.150	-0.324	-0.882	0.001	0.011	-0.035	0.006		
t:physcl_pn	0.164	-0.351	0.004	-0.894	-0.001	-0.017	-0.010	-0.003	
t:identity	0.242	-0.519	0.011	0.000	-0.867	0.014	0.001	-0.013	0.002
t:intervntn	0.087	-0.187	-0.035	-0.017	0.014	-0.867	-0.003	0.041	0.019
t:HDI	0.310	-0.666	0.015	-0.027	0.002	-0.007	-0.346	-0.016	0.029
		t:dntt	t:ntrv						
t									
warmth									
physcl_pnsh									
identity									
interventin									
HDI									
t:warmth									
t:physcl_pn									
t:identity									
t:intervntn	-0.016								
t:HDI	-0.002	0.008							

5.3.3 Julia

5.3.3.1 Get The Data

```
using Tables, MixedModels, StatFiles, DataFrames, CategoricalArrays, DataFramesMeta

dfL = DataFrame(load("simulated_multilevel_longitudinal_data.dta"))
```

5.3.3.2 Run The Model

5.3.3.2.1 Change Country To Categorical

```
@transform!(dfL, :country = categorical(:country))
```

5.3.3.2.2 Main Effects Only

```
m2A = fit(MixedModel, @formula(outcome ~ t + warmth +
                                physical_punishment +
                                identity + intervention +
                                HDI +
                                (1 | country) +
                                (0 + warmth | country) +
                                (1 | id)), dfL)
```

Linear mixed model fit by maximum likelihood

	outcome ~ 1 + t + warmth + physical_punishment + identity + intervention + HDI + (1 count			
logLik	-2 logLik	AIC	AICc	BIC
-28499.6031	56999.2063	57021.2063	57021.2356	57099.3610

Variance components:

	Column	Variance	Std.Dev.	Corr.
id	(Intercept)	8.387351	2.896092	
country	(Intercept)	3.166939	1.779590	
	warmth	0.010760	0.103732	.
Residual		26.027290	5.101695	

Number of obs: 9000; levels of grouping factors: 3000, 30

Fixed-effects parameters:

	Coef.	Std. Error	z	Pr(> z)
(Intercept)	50.5949	1.35491	37.34	<1e-99
t	0.943864	0.0658716	14.33	<1e-45
warmth	0.913496	0.0423739	21.56	<1e-99
physical_punishment	-1.0079	0.0497622	-20.25	<1e-90
identity	-0.127692	0.151584	-0.84	0.3996
intervention	0.858997	0.15191	5.65	<1e-07
HDI	-0.000565882	0.0196433	-0.03	0.9770

5.3.3.2.3 Interactions With Time

```
m2B = fit(MixedModel, @formula(outcome ~ t * (warmth +
                                physical_punishment +
                                identity + intervention +
                                HDI) +
                                (1 | country) +
                                (0 + warmth | country) +
                                (1 | id)), dfL)
```

Linear mixed model fit by maximum likelihood

```
outcome ~ 1 + t + warmth + physical_punishment + identity + intervention + HDI + t & warmth
logLik   -2 logLik      AIC      AICc      BIC
-28498.3091 56996.6182 57028.6182 57028.6788 57142.2979
```

Variance components:

	Column	Variance	Std.Dev.	Corr.
id	(Intercept)	8.391746	2.896851	
country	(Intercept)	3.170031	1.780458	
	warmth	0.010609	0.102999	.
Residual		26.015906	5.100579	

Number of obs: 9000; levels of grouping factors: 3000, 30

Fixed-effects parameters:

	Coef.	Std. Error	z	Pr(> z)
(Intercept)	51.0751	1.54284	33.10	<1e-99
t	0.702771	0.374539	1.88	0.0606
warmth	0.817076	0.0826636	9.88	<1e-22

physical_punishment	-1.00903	0.111293	-9.07	<1e-18
identity	-0.238714	0.303996	-0.79	0.4323
intervention	0.660761	0.30445	2.17	0.0300
HDI	0.00136065	0.0210842	0.06	0.9485
t & warmth	0.0483635	0.0356074	1.36	0.1744
t & physical_punishment	0.000542203	0.0494355	0.01	0.9912
t & identity	0.0554385	0.131745	0.42	0.6739
t & intervention	0.0992809	0.131925	0.75	0.4517
t & HDI	-0.000955067	0.00382162	-0.25	0.8027

5.4 Interpretation

The *main effects only model* suggests that time is associated with increases in the outcome. In the main effects model, main effects other than time, indicate whether a particular variable is associated with higher or lower intercepts of the time trajectory, at the beginning of the study time. Warmth is again associated with increases in the outcome, while physical punishment is associated with decreases in the outcome. Identity is again not associated with the outcome, while the intervention is associated with higher levels of the outcome. The Human Development Index is again not associated with the outcome.

The second model adds interactions with time to the first model. Results are largely similar to the prior model. However, here we not only examine whether main effects other than time are associated with higher or lower time trajectories, but also whether particular variables are associated with differences in the slope of the time trajectory. In this case, we find that no independent variable is associated with changes in the slope of the time trajectory.

However, it may be illustrative to imagine how we would interpret the results had a particular interaction term been statistically significant. Let us consider one of the interaction terms with the largest coefficient, *intervention#time*. The interaction of the intervention with time is positive. Had this coefficient been statistically significant, it would have indicated that the intervention was associated with more rapid increases in the outcome over time *in addition to* the fact that the intervention is associated with higher initial levels of the outcome.

References

- Bates, D. (2024). *MixedModels.jl Documentation*. <https://juliastats.org/MixedModels.jl/stable/>
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1), 1–48. <https://doi.org/10.18637/jss.v067.i01>
- Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, 59(1), 65–98. <https://doi.org/10.1137/141000671>
- R Core Team. (2023). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org/>
- Schanen, J. (2021). *Math person (Strogatz Prize entry)*. National Museum of Mathematics.
- StataCorp. (2021). *Stata 17 multilevel mixed effects reference manual*. Stata Press.
- Thoreau, H. D. (1975). The commercial spirit of modern times [1837]. In J. J. Moldenhauer, E. Moser, & A. C. Kern (Eds.), *Early essays and miscellanies*. Princeton University Press.