Project 4

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Introduction

Typing Dynamics

- Highlighted in the paper *"Comparing Anomaly-Detection Algorithms for Keystroke Dynamics"* (Dr. Roy Maxion et al.).
  - Typing patterns vary significantly between individuals.
  - Keystroke dynamics can provide an additional layer of security by analyzing unique typing behaviors.

Study Design:

- **Passcode**: **".tie5Roanl"** – designed as a **strong, representative password**.
- **Subjects**: 51 participants recruited at Carnegie Mellon University (CMU).
- **Sessions**: 8 sessions, 1 per day.
- **Repetitions**: Each subject typed the passcode **50 times per session**.

Project Goal:

- Investigate whether individuals' typing patterns remain **consistent over time**.

Participant and Password Details

Participant Demographics:

- **51 subjects**:
  - **30 males, 21 females**
  - **8 left-handed, 43 right-handed**
  - Age range: **18–70 years** (Median: 31–40 years).

Password Design:

- Created using a **password generator and strength checker**.
- Criteria:
  - **10 characters** (letters, numbers, punctuation).
  - Modified for punctuation and casing to reflect a "strong" password.
- Rated **strong** because it includes:
  - More than **7 characters**
  - A **capital letter**
  - A **number**
  - **Punctuation**

The top rating requires **>13 characters**, but **10 characters** is typical in real-world studies.

Linear Mixed Effects Model

Random Intercept Model

- Assumes that each subject has a different baseline typing speed (intercept), but they all change at the same rate (slope) across sessions.

Random Slope and Intercept Model

- It allows for heterogeneity in both slope and intercept.
- we are assuming that the repeated measures on each individual in our study can be characterized by their own individual regression model.

Dataset Overview

- **Dataset Overview**:
  - **20,400 observations** and **34 variables**.
  - Provides a robust foundation for analysis.
- **Dataset Variables and Timing Definitions**
  - **Hold Time (H)**:
    - Duration a key is held down (e.g., H.period, H.t, H.Return).
  - **Down-Down Time (DD)**:
    - Time between pressing down one key to pressing down another subsequent key.
      - Examples:
        - DD.period.t: From pressing "." to pressing "t".
        - DD.a.n: From pressing "a" to pressing "n".
  - **Up-Down Time (UD)**:
    - Time from releasing one key to pressing down the next key.
      - Examples:
        - UD.period.t: From releasing "." to pressing "t".
        - UD.n.l: From releasing "n" to pressing "l".

- **Key Data Checks**:
  - No missing values identified.
  - <u>Largest Outliers:</u>
    - DD.i.e exhibited an outlier value of **25.9873**, which is **25.8279 above the mean.**
    - UD.i.e exhibited an outlier value of **25.9158**, which is **25.8380 above the mean.**
    - DD.period.t exhibited an outlier value of **12.5061**, which is 1**2.242 above the mean.**
    - UD.period.t exhibited an outlier value of **12.4517**, which is **12.2809 above the mean.**
    - DD.five.Shift.r exhibited an outlier value of **8.3702**, which is **7.9313 above the mean.**
    - UD.five.Shift.r exhibited an outlier value of **8.2908**, which is **7.9288 above the mean.**

```
   H.period          DD.period.t       UD.period.t          H.t              DD.t.i
Min.   :0.00140   Min.   : 0.0187   Min.   :-0.2358   Min.   :0.00930   Min.   :0.0011
1st Qu.:0.07440   1st Qu.: 0.1469   1st Qu.: 0.0498   1st Qu.:0.06600   1st Qu.:0.1136
Median :0.08950   Median : 0.2059   Median : 0.1087   Median :0.08100   Median :0.1404
Mean   :0.09338   Mean   : 0.2641   Mean   : 0.1708   Mean   :0.08573   Mean   :0.1691
3rd Qu.:0.10790   3rd Qu.: 0.3064   3rd Qu.: 0.2124   3rd Qu.:0.09980   3rd Qu.:0.1839
Max.   :0.37610   Max.   :12.5061   Max.   :12.4517   Max.   :0.24110   Max.   :4.9197
    UD.t.i              H.i              DD.i.e            UD.i.e             H.e
Min.   :-0.16210   Min.   :0.00320   Min.   : 0.0014   Min.   :-0.16000   Min.   :0.00210
1st Qu.: 0.02720   1st Qu.:0.06200   1st Qu.: 0.0893   1st Qu.: 0.00740   1st Qu.:0.06860
Median : 0.05780   Median :0.07710   Median : 0.1209   Median : 0.04120   Median :0.08340
Mean   : 0.08336   Mean   :0.08157   Mean   : 0.1594   Mean   : 0.07781   Mean   :0.08914
3rd Qu.: 0.09640   3rd Qu.:0.09690   3rd Qu.: 0.1731   3rd Qu.: 0.09340   3rd Qu.:0.10270
Max.   : 4.79990   Max.   :0.33120   Max.   :25.9873   Max.   :25.91580   Max.   :0.32540
  DD.e.five          UD.e.five           H.five        DD.five.Shift.r   UD.five.Shift.r
Min.   :0.0013   Min.   :-0.1505   Min.   :0.0014   Min.   :0.1694   Min.   :0.0856
1st Qu.:0.2166   1st Qu.: 0.1332   1st Qu.:0.0610   1st Qu.:0.3079   1st Qu.:0.2297
Median :0.2890   Median : 0.2004   Median :0.0742   Median :0.3775   Median :0.3020
Mean   :0.3774   Mean   : 0.2883   Mean   :0.0769   Mean   :0.4389   Mean   :0.3620
3rd Qu.:0.4568   3rd Qu.: 0.3694   3rd Qu.:0.0906   3rd Qu.:0.4860   3rd Qu.:0.4089
Max.   :4.9618   Max.   : 4.8827   Max.   :0.1989   Max.   :8.3702   Max.   :8.2908
```

Subject Review

- **51 Subjects Reported**:
  - Recruited for the study with repeated typing sessions.
- **Data Discrepancy**:
  - Observed that some subjects may have been **removed** or **renamed** in the dataset.
  - Resulted in inconsistencies with the reported subject count.

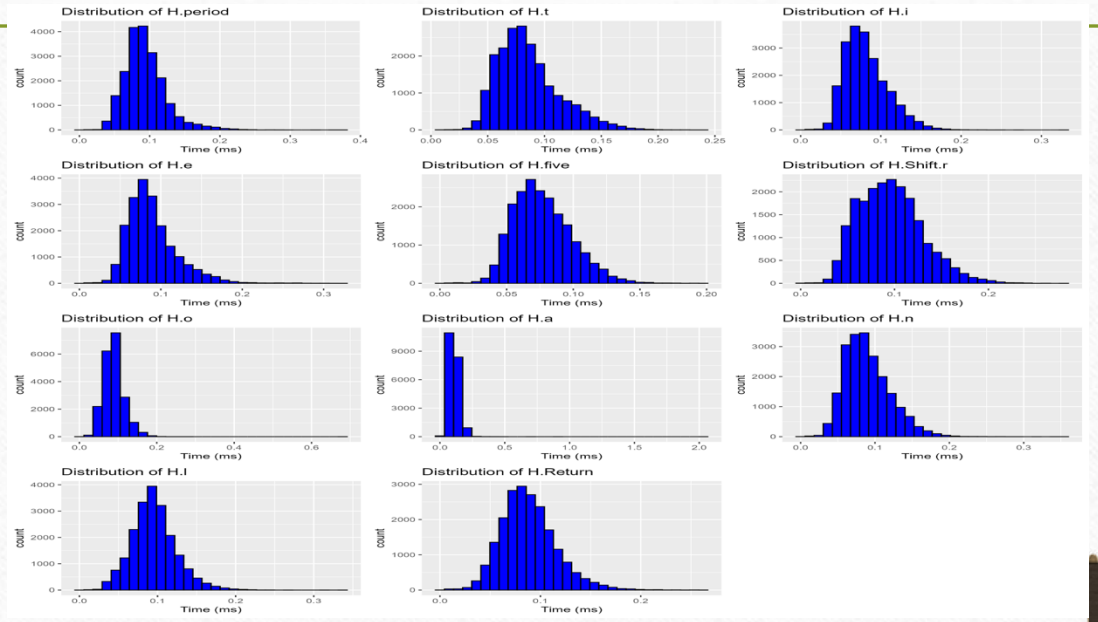
```
Subjects:
 s002, s003, s004, s005, s007, s008, s010, s011, s012, s013, s015, s016, s017, s018, s019, s020, s021, s022,
s024, s025, s026, s027, s028, s029, s030, s031, s032, s033, s034, s035, s036, s037, s038, s039, s040, s041,
s042, s043, s044, s046, s047, s048, s049, s050, s051, s052, s053, s054, s055, s056, s057
```

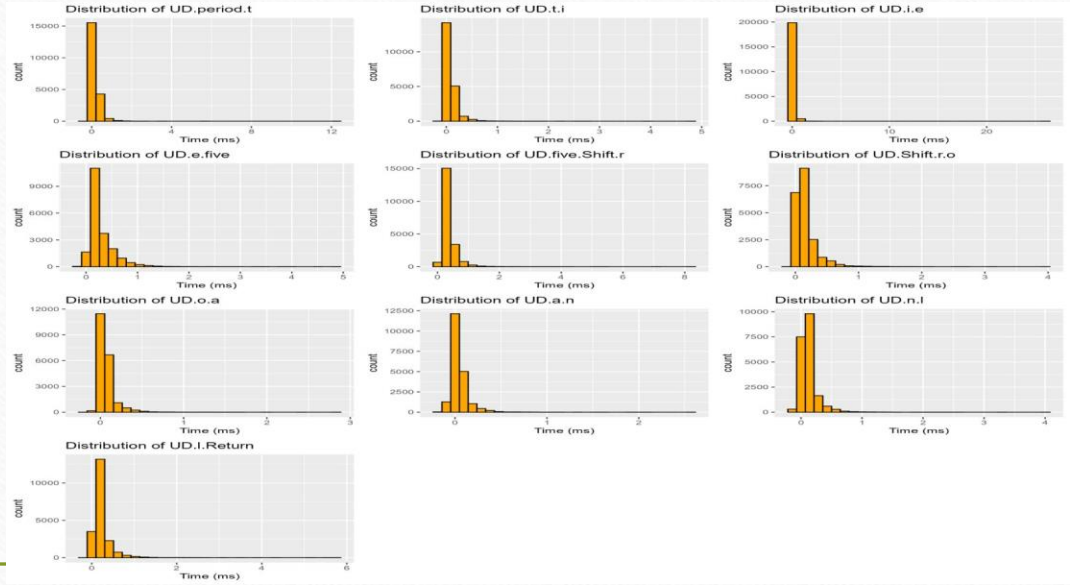
EDA - Histograms

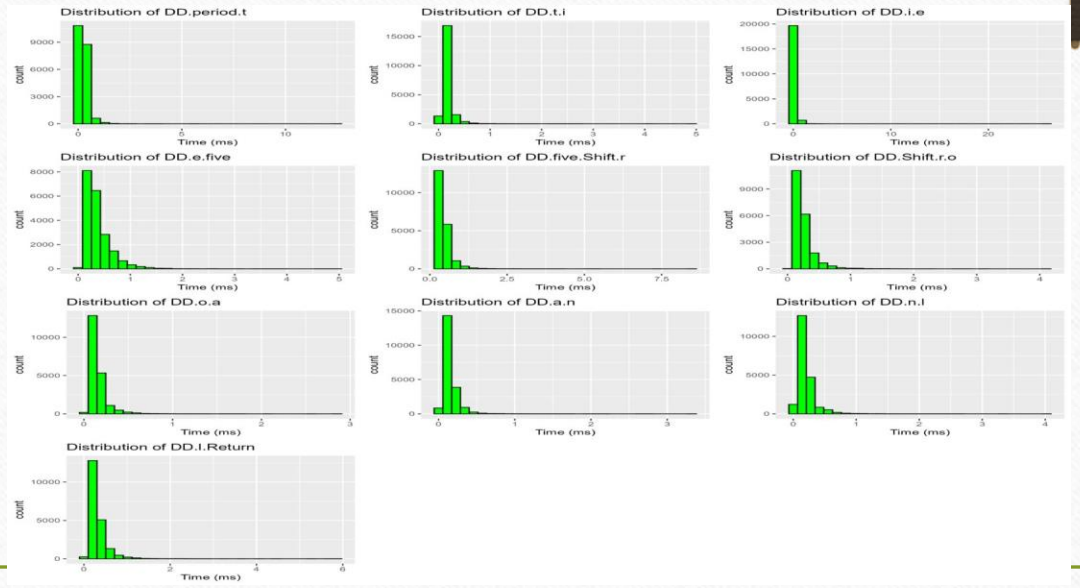
Exploratory Data Analysis: Distributions of Key Metrics

- **Focus Metrics**:
  - Hold Times (H.*)
  - Down-Down Times (DD.*)
  - Up-Down Times (UD.*)
- **Distributions**:
  - Histograms were created to visualize the **distribution** of each metric.
  - The histograms highlight variability and patterns within the dataset.

Distribution of Down-Down Key time, Up-Down Key time and Hold time

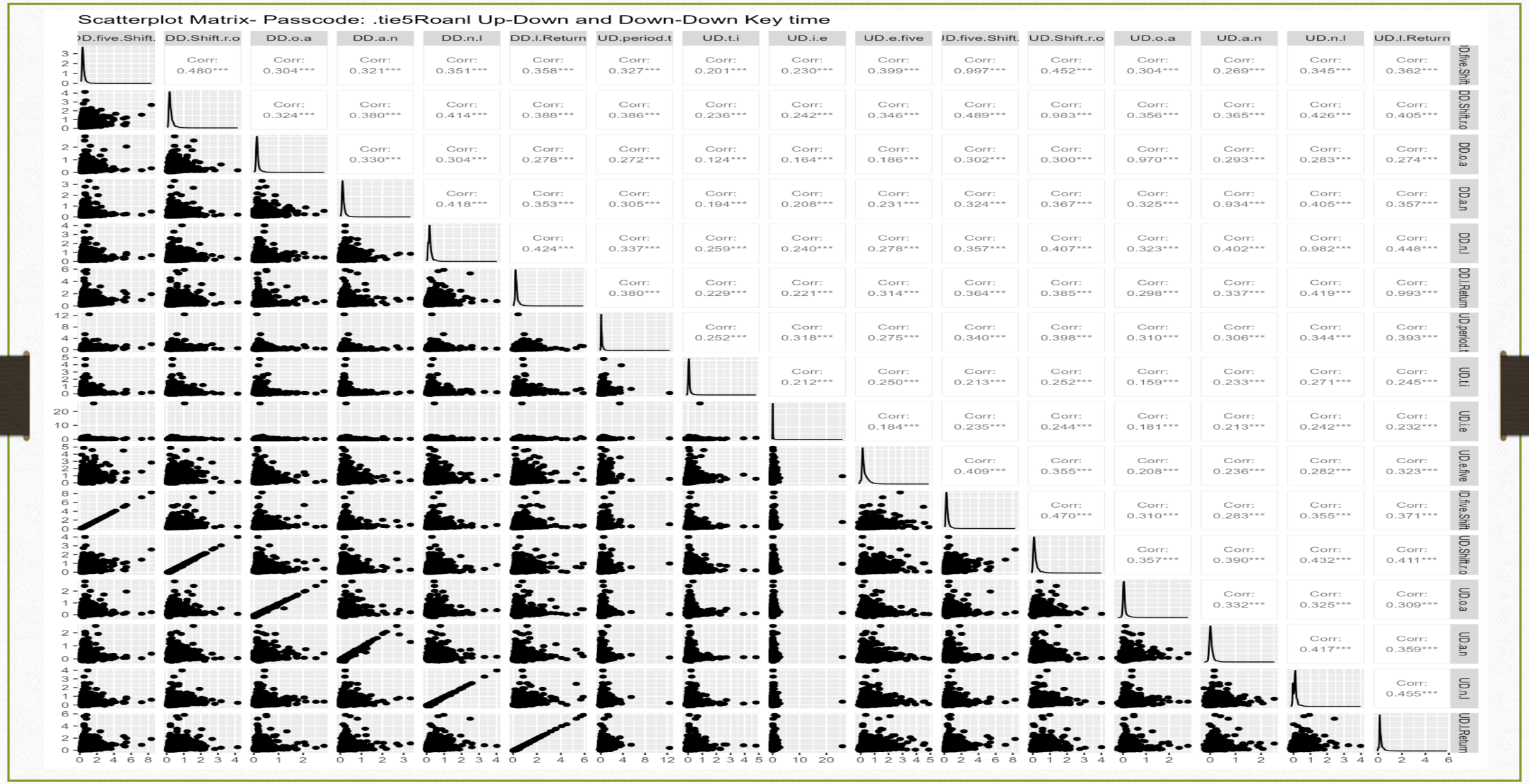






EDA - Correlation Analysis

- **Goal**:
  - Explore relationships between **Down-Down Times (DD.*)** and **Up-Down Times (UD.*)**.
- **Key Finding**:
  - **Positive Correlations**: Most relationships indicate that as one timing variable increases, the others tend to increase as well.
- **Observation**:
  - Variables like DD.* and UD.* show strong linear trends, suggesting a high degree of interdependence.


Scatterplot Matrix- Passcode: .tie5Roanl Up-Down and Down-Down Key time
DD.five.Shift.
DD.Shift.r.o
DD.o.a
DD.a.n
DD.n.l
DD.l.Return
UD.period.t
UD.t.i
UD.i.e
UD.e.five
UD.five.Shift.
UD.Shift.r.o
UD.o.a
UD.a.n
UD.n.l
UD.l.Return

Response Variables

We created two response variables for analysis:

- **TotalTypingTime**
  - **Definition**:
    - Represents the total time taken to type the passcode.
    - Calculated as the **sum of H*** (hold times) and **UD*** (up-down times).
  - **Key Observations**:
    - **DD*** (down-down times) are equivalent to the sum of H* and UD*.
    - To avoid redundancy, H* and UD* were used to efficiently calculate typing time.
  - **Streamlined Dataset**:
    - A simplified dataset, passcode.total.dat, was created with the following variables:
      - **subject** (participant ID)
      - **sessionIndex** (session number)
      - **rep** (trial within the session)
      - **TotalTypingTime**
- **ud_sum**
  - **Definition**:
    - Represents the sum of all **UD*** (up-down) variables for each participant across sessions.
  - **Key Observations**:
    - UD* provides insights into key press transitions, independent of hold times.
    - This variable allows us to analyze how participants' typing transitions change over sessions.

TotalTypingTime Analysis

Model Setup:

- **Fixed Effect**:
  - sessionIndex (to see how typing time changes across sessions).
- **Random Effect**:
  - Subjects (to capture individual variability).

Key Steps:

- Fit a **Random Intercept Model** and **Random Slope Model**.
  - Random slope model performed better.

Model Diagnostics:

- Checked model residuals for patterns and normality.

Random Intercept Model for Total Typing Time

```
Error in install.packages : Updating loaded packages
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: TotalTypingTime ~ sessionIndex + (1 | subject)
   Data: passcode.total.dat

REML criterion at convergence: 43284.8

Scaled residuals:
   Min     1Q Median     3Q    Max
-3.252 -0.466 -0.130  0.273 43.972

Random effects:
 Groups   Name        Variance Std.Dev.
 subject  (Intercept) 0.7515   0.8669
 Residual             0.4806   0.6933
Number of obs: 20400, groups:  subject, 51

Fixed effects:
             Estimate Std. Error         df t value Pr(>|t|)
(Intercept)   3.144e+00  1.219e-01  5.062e+01   25.80   <2e-16 ***
sessionIndex -1.252e-01  2.118e-03  2.035e+04  -59.11   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr)
sessionIndx -0.078
```

The model analyzes "TotalTypingTime" as the response variable which is the total time taken to type the given passcode. SessionIndex used as a predictor suggesting that the study looks at how typing time changes over multiple sessions. The result shows that on an average the total typing time is 3.144 seconds which significantly decreases by 0.12522 seconds per session.

The variance for subject (Intercept) tells us about the variance in starting period per individual which is 0.7515 seconds.

Random Slope and Intercept Model of Total Typing Time

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: TotalTypingTime ~ sessionIndex + (sessionIndex | subject)
   Data: passcode.total.dat

REML criterion at convergence: 40789.2

Scaled residuals:
   Min     1Q Median     3Q    Max
-5.247 -0.466 -0.148  0.256 43.727

Random effects:
 Groups   Name         Variance Std.Dev. Corr
 subject  (Intercept)  1.59117  1.2614
          sessionIndex 0.01142  0.1069   -0.88
 Residual              0.42168  0.6494
Number of obs: 20400, groups:  subject, 51

Fixed effects:
             Estimate Std. Error       df t value Pr(>|t|)
(Intercept)   3.14373    0.17692 50.00290  17.769  < 2e-16 ***
sessionIndex -0.12522    0.01509 50.00389  -8.296 5.82e-11 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr)
sessionIndx -0.880
```

The output shows that the average starting total time is 3.143 second which significantly decreases by 0.12522 seconds per session.
The Random effect variance, sessionIndex 0.01142 represents that the effect of sessionIndex is different for different subject. The Random Intercept Variance subject (Intercept) 1.59117 represents that subjects have different starting points (baseline) for total typing time.

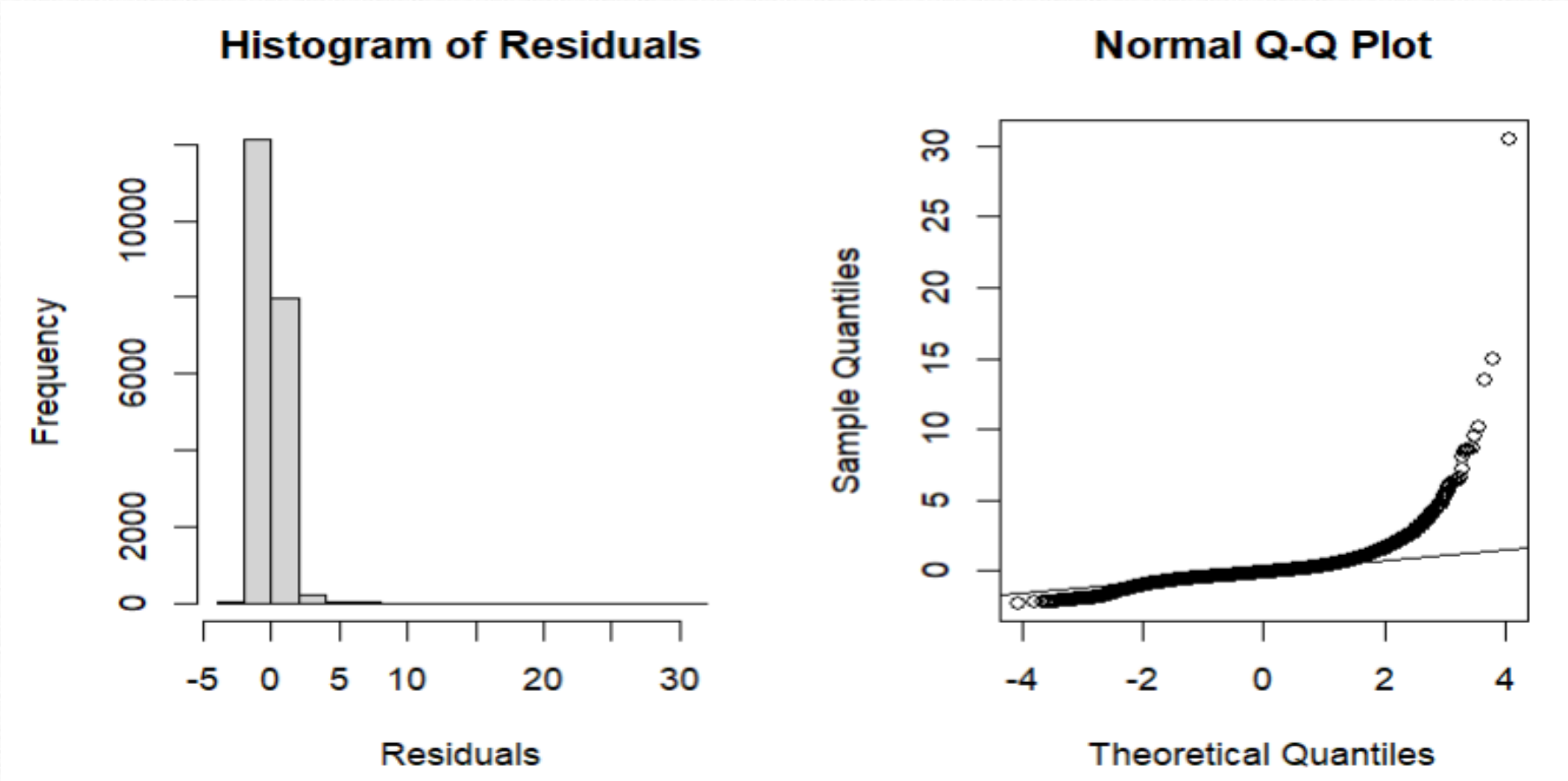
Model Comparison of Random Intercept and Random Slope Models

```
Data: passcode.total.dat
Models:
lmer_model: TotalTypingTime ~ sessionIndex + (1 | subject)
lmer_model_slope: TotalTypingTime ~ sessionIndex + (sessionIndex | subject)
                  npar   AIC   BIC logLik deviance  Chisq Df Pr(>Chisq)
lmer_model           4 43280 43312 -21636    43272
lmer_model_slope     6 40791 40839 -20390    40779 2492.5  2  < 2.2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

The results compare two models to understand how Total Typing Time changes across sessions while accounting for individual differences. Both models show that typing time improves with each session. The simpler model assumes everyone improves at the same rate but starts at different typing times, while the more flexible model lets each person have their own starting time and improvement rate.

The flexible model fits the data much better (p-value < 2.2e-16), showing that some participants improve faster than others. A strong negative correlation (-0.88) between starting times and improvement rates suggests that slower starters improved the most. The Random Slope and Intercept model also has lower AIC and BIC values and a higher log likelihood, confirming it as the better fit.

Check Assumption of Normality: Residuals are not normally distributed



Log Transformation of Total Typing Time

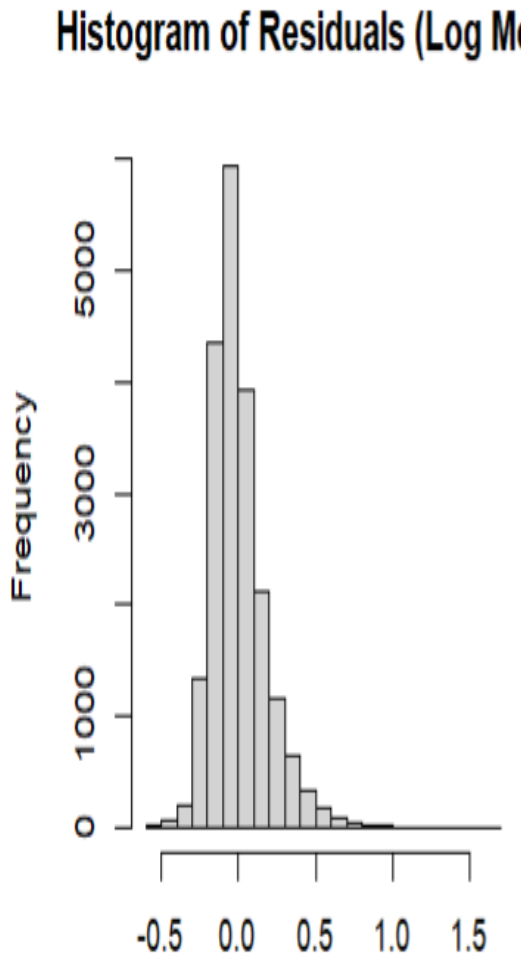
During model diagnostics, we observed large outliers in the residuals, which could impact the model's accuracy. To address this:

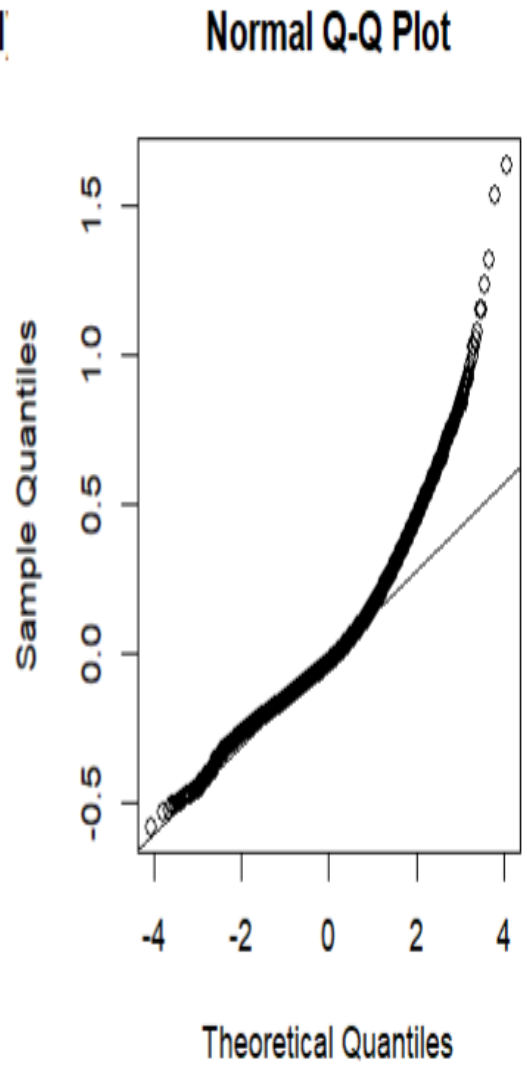
- Applied a **Log Transformation** to the TotalTypingTime variable.
  - This helped to normalize the data and reduce the effect of outliers.
- The updated model outputs showed improved residual behavior.

Key Impact:

- The transformation allowed for more reliable conclusions regarding changes in typing time across sessions.

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: log_TotalTypingTime ~ sessionIndex + (sessionIndex | subject)
   Data: passcode.total.dat
Control: lmerControl(optimizer = "nloptwrap", optCtrl = list(maxfun = 1e+05))

REML criterion at convergence: -12183.9

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.2723 -0.6507 -0.1763  0.4627  9.2367

Random effects:
 Groups   Name         Variance  Std.Dev. Corr
 subject  (Intercept)  0.1013954 0.31843
          sessionIndex 0.0003607 0.01899  -0.47
 Residual              0.0313951 0.17719
Number of obs: 20400, groups:  subject, 51

Fixed effects:
             Estimate Std. Error       df t value Pr(>|t|)
(Intercept)  1.073962   0.044672 50.009895   24.04   <2e-16 ***
sessionIndex -0.043441   0.002714 49.997597  -16.01   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr)
sessionIndx -0.469
optimizer (nloptwrap) convergence code: 0 (OK)
Model failed to converge with max|grad| = 0.00257757 (tol = 0.002, component 1)
```

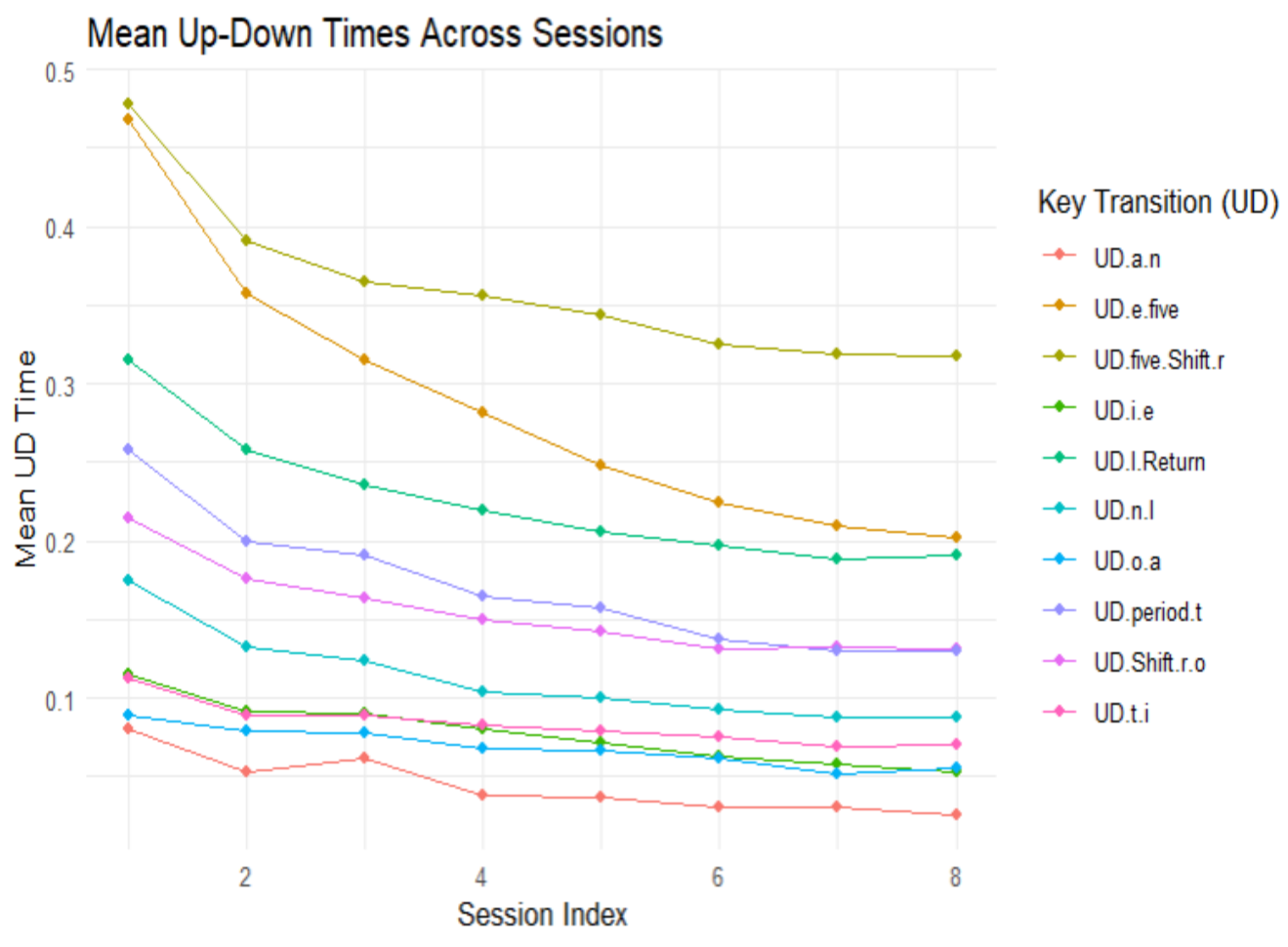




ud_sum Analysis

Model Setup:

- The model includes **sessionIndex** as the fixed effect to evaluate how the sum of UD* values varies across sessions.
- A random effect for **subjects** is included to account for individual differences in typing patterns and to capture within-subject variability over time.
- The goal is to understand how the up-down (UD) transition times* change across sessions and whether subjects show improvement or consistency in their typing transitions over repeated sessions.



```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: Sum_UD_Value ~ sessionIndex + (1 | subject)
   Data: ud_sum
Control: lmerControl(optimizer = "nloptwrap", optCtrl = list(maxfun = 1e+05))

REML criterion at convergence: 3671.8

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.2165 -0.2891  0.0338  0.2721 12.1469

Random effects:
 Groups   Name        Variance Std.Dev.
 subject  (Intercept) 2037.9   45.14
 Residual              320.3   17.90
Number of obs: 408, groups:  subject, 51

Fixed effects:
             Estimate Std. Error      df t value Pr(>|t|)
(Intercept)   115.206      6.800  64.230  16.942  < 2e-16 ***
sessionIndex2 -23.783      3.544 350.000  -6.710 7.83e-11 ***
sessionIndex3 -29.653      3.544 350.000  -8.367 1.43e-15 ***
sessionIndex4 -38.054      3.544 350.000 -10.737  < 2e-16 ***
sessionIndex5 -42.668      3.544 350.000 -12.039  < 2e-16 ***
sessionIndex6 -48.262      3.544 350.000 -13.617  < 2e-16 ***
sessionIndex7 -51.512      3.544 350.000 -14.534  < 2e-16 ***
sessionIndex8 -52.045      3.544 350.000 -14.685  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:
            (Intr) sssnI2 sssnI3 sssnI4 sssnI5 sssnI6 sssnI7
sessinIndx2 -0.261
sessinIndx3 -0.261  0.500
sessinIndx4 -0.261  0.500  0.500
sessinIndx5 -0.261  0.500  0.500  0.500
sessinIndx6 -0.261  0.500  0.500  0.500  0.500
sessinIndx7 -0.261  0.500  0.500  0.500  0.500  0.500
sessinIndx8 -0.261  0.500  0.500  0.500  0.500  0.500  0.500
```

The output shows that the average starting UD sum is **115.206 ms** in session 1, which significantly decreases by **23.783 ms** in session 2 and continues to decrease across sessions, with a reduction of **52.045 ms** by session 8.

The random effect variance for subjects (**2037.9**) indicates that participants have different starting points (baseline) for their UD sums. The residual variance (**320.3**) reflects the variability in UD sums within each session. These results demonstrate that while all participants improved their typing efficiency over time, the rate and extent of improvement varied across individuals.

Total Typing Time Pairwise Comparison

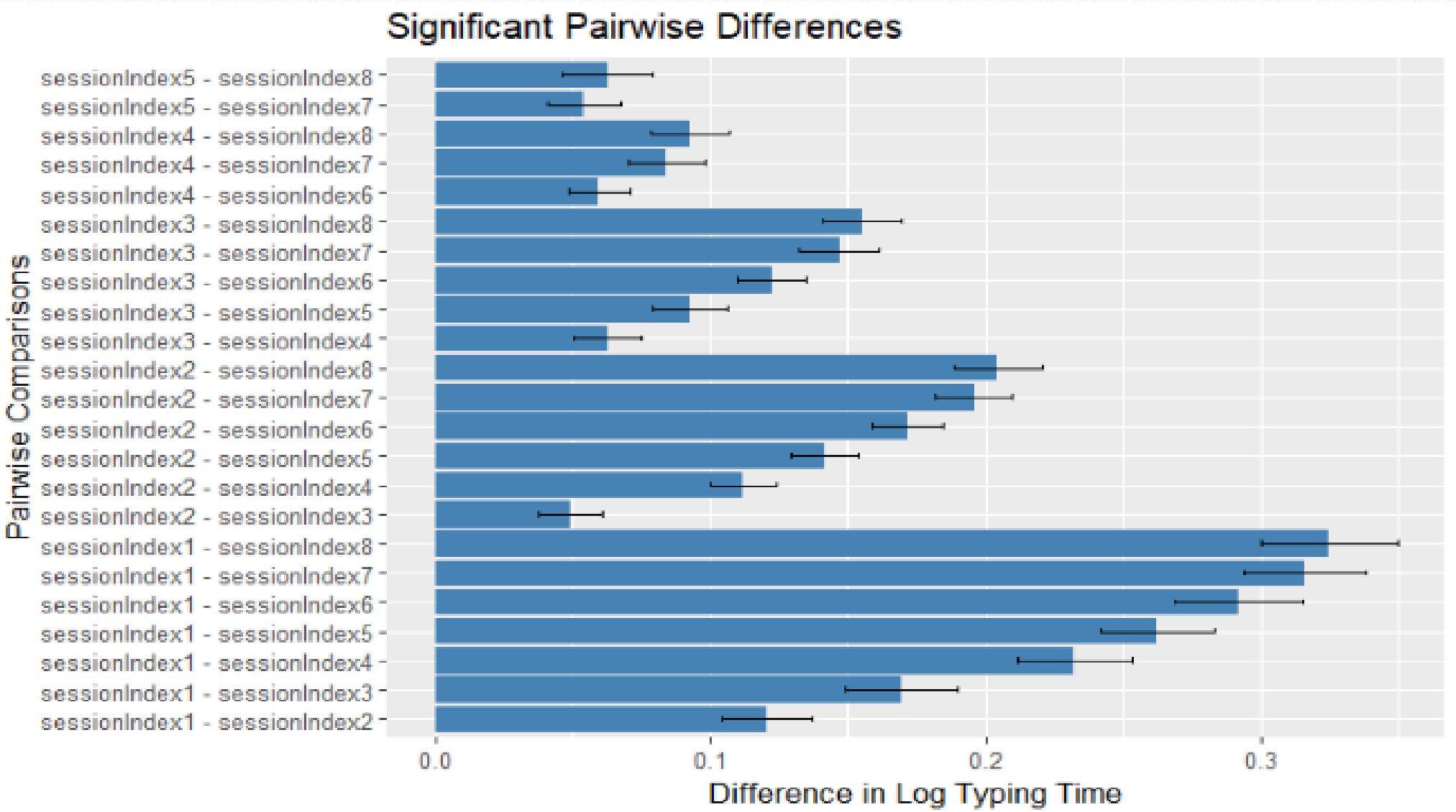
```
$emmeans
 sessionIndex emmean     SE  df asymp.LCL asymp.UCL
 1             1.093 0.0466 Inf     1.002     1.184
 2             0.973 0.0403 Inf     0.894     1.052
 3             0.924 0.0427 Inf     0.840     1.007
 4             0.861 0.0430 Inf     0.777     0.945
 5             0.831 0.0411 Inf     0.750     0.912
 6             0.801 0.0397 Inf     0.723     0.879
 7             0.777 0.0383 Inf     0.702     0.852
 8             0.768 0.0412 Inf     0.687     0.849

Degrees-of-freedom method: asymptotic
Confidence level used: 0.95

$contrasts
 contrast                        estimate      SE  df z.ratio p.value
 sessionIndex1 - sessionIndex2    0.12030 0.01620 Inf   7.438  <.0001
 sessionIndex1 - sessionIndex3    0.16935 0.02030 Inf   8.331  <.0001
 sessionIndex1 - sessionIndex4    0.23227 0.02100 Inf  11.080  <.0001
 sessionIndex1 - sessionIndex5    0.26211 0.02080 Inf  12.618  <.0001
 sessionIndex1 - sessionIndex6    0.29181 0.02290 Inf  12.749  <.0001
 sessionIndex1 - sessionIndex7    0.31603 0.02180 Inf  14.488  <.0001
 sessionIndex1 - sessionIndex8    0.32474 0.02470 Inf  13.139  <.0001
 sessionIndex2 - sessionIndex3    0.04904 0.01150 Inf   4.248  0.0006
 sessionIndex2 - sessionIndex4    0.11196 0.01200 Inf   9.327  <.0001
 sessionIndex2 - sessionIndex5    0.14180 0.01220 Inf  11.613  <.0001
 sessionIndex2 - sessionIndex6    0.17151 0.01280 Inf  13.382  <.0001
 sessionIndex2 - sessionIndex7    0.19573 0.01410 Inf  13.889  <.0001
 sessionIndex2 - sessionIndex8    0.20444 0.01580 Inf  12.970  <.0001
 sessionIndex3 - sessionIndex4    0.06292 0.01220 Inf   5.141  <.0001
 sessionIndex3 - sessionIndex5    0.09276 0.01370 Inf   6.764  <.0001
 sessionIndex3 - sessionIndex6    0.12246 0.01260 Inf   9.711  <.0001
 sessionIndex3 - sessionIndex7    0.14668 0.01450 Inf  10.135  <.0001
 sessionIndex3 - sessionIndex8    0.15539 0.01430 Inf  10.890  <.0001
 sessionIndex4 - sessionIndex5    0.02984 0.01060 Inf   2.802  0.1422
 sessionIndex4 - sessionIndex6    0.05954 0.01100 Inf   5.401  <.0001
 sessionIndex4 - sessionIndex7    0.08376 0.01390 Inf   6.012  <.0001
 sessionIndex4 - sessionIndex8    0.09247 0.01420 Inf   6.513  <.0001
 sessionIndex5 - sessionIndex6    0.02970 0.00987 Inf   3.008  0.0736
 sessionIndex5 - sessionIndex7    0.05392 0.01340 Inf   4.039  0.0015
 sessionIndex5 - sessionIndex8    0.06263 0.01610 Inf   3.890  0.0028
 sessionIndex6 - sessionIndex7    0.02422 0.01110 Inf   2.184  0.8106
 sessionIndex6 - sessionIndex8    0.03293 0.01420 Inf   2.322  0.5670
 sessionIndex7 - sessionIndex8    0.00871 0.01150 Inf   0.756  1.0000

Degrees-of-freedom method: asymptotic
P value adjustment: bonferroni method for 28 tests
```

To ensure model treated sessions as a distinct categories (rather than numeric values), we converted sessionIndex into a categorical factor for the **Total Typing Time** variable

We then refitted the linear mixed-effects model and performed pairwise comparisons to evaluate differences in typing times across sessions.

This allowed us to identify significant differences between sessions while accounting for multiple comparisons.

The results show that the average log typing time decreases across sessions, starting at **1.093** in session 1 and dropping to **0.768** by session 8. Pairwise comparisons confirm significant differences between earlier sessions (e.g., session 1 - session 2 = **0.1203**, $p < 0.0001$) but show smaller, insignificant differences between later sessions (e.g., session 7 - session 8 = **0.0087**, $p = 1.0$). This indicates rapid initial improvement in typing speed that slows down over time.


Significant Pairwise Differences
Pairwise Comparisons
sessionIndex5 - sessionIndex8
sessionIndex5 - sessionIndex7
sessionIndex4 - sessionIndex8
sessionIndex4 - sessionIndex7
sessionIndex4 - sessionIndex6
sessionIndex3 - sessionIndex8
sessionIndex3 - sessionIndex7
sessionIndex3 - sessionIndex6
sessionIndex3 - sessionIndex5
sessionIndex3 - sessionIndex4
sessionIndex2 - sessionIndex8
sessionIndex2 - sessionIndex7
sessionIndex2 - sessionIndex6
sessionIndex2 - sessionIndex5
sessionIndex2 - sessionIndex4
sessionIndex2 - sessionIndex3
sessionIndex1 - sessionIndex8
sessionIndex1 - sessionIndex7
sessionIndex1 - sessionIndex6
sessionIndex1 - sessionIndex5
sessionIndex1 - sessionIndex4
sessionIndex1 - sessionIndex3
sessionIndex1 - sessionIndex2
0.0
0.1
0.2
0.3
Difference in Log Typing Time

Ud_sum Pairwise comparison

sessionIndex	emmean	SE	df	lower.CL	upper.CL
1	115.2	6.8	64.2	101.6	128.8
2	91.4	6.8	64.2	77.8	105.0
3	85.6	6.8	64.2	72.0	99.1
4	77.2	6.8	64.2	63.6	90.7
5	72.5	6.8	64.2	59.0	86.1
6	66.9	6.8	64.2	53.4	80.5
7	63.7	6.8	64.2	50.1	77.3
8	63.2	6.8	64.2	49.6	76.7

Degrees-of-freedom method: kenward-roger
Confidence level used: 0.95

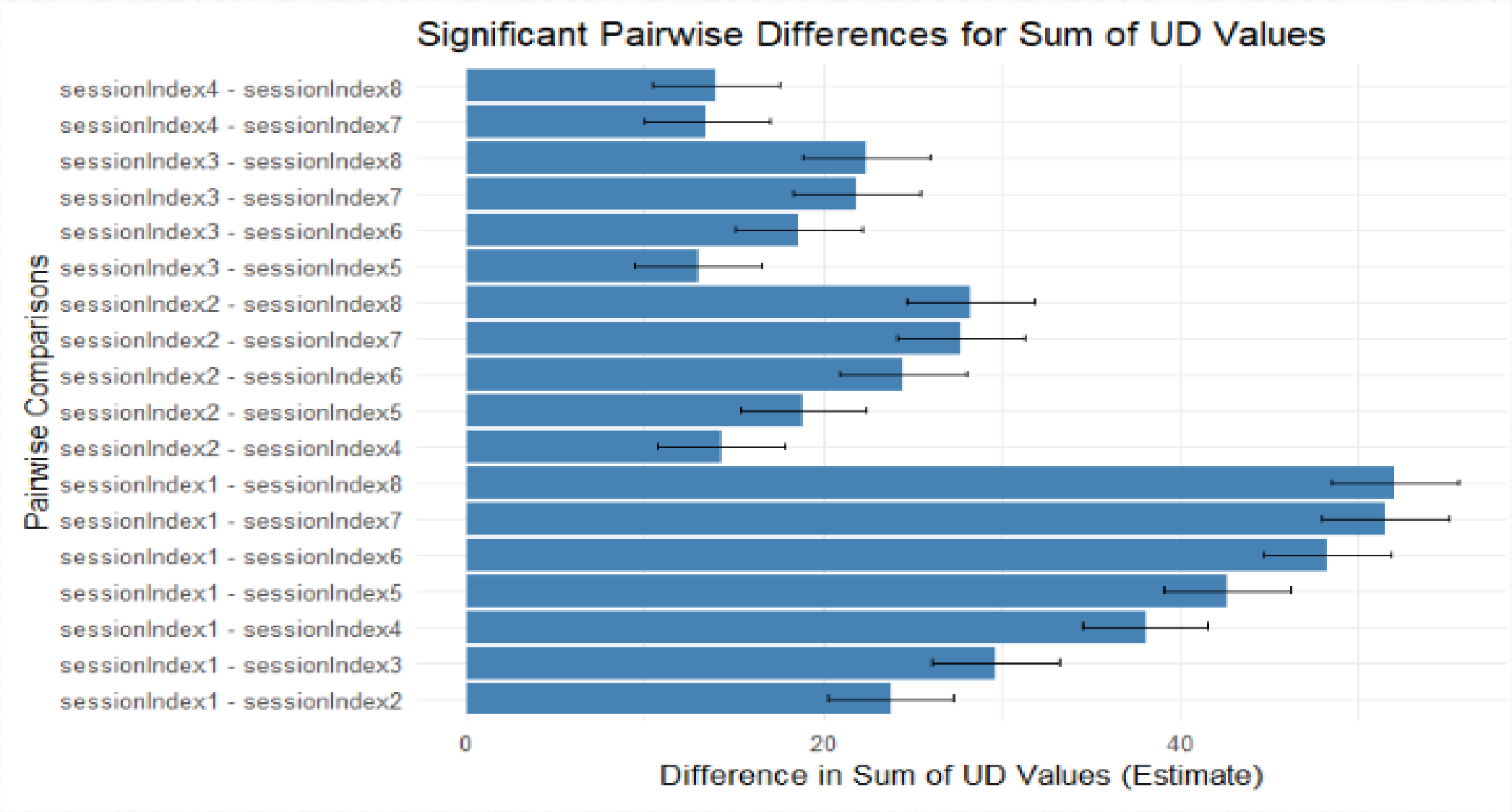
contrast	estimate	SE	df	t.ratio	p.value
sessionIndex1 - sessionIndex2	23.783	3.54	350	6.710	<.0001
sessionIndex1 - sessionIndex3	29.653	3.54	350	8.367	<.0001
sessionIndex1 - sessionIndex4	38.054	3.54	350	10.737	<.0001
sessionIndex1 - sessionIndex5	42.668	3.54	350	12.039	<.0001
sessionIndex1 - sessionIndex6	48.262	3.54	350	13.617	<.0001
sessionIndex1 - sessionIndex7	51.512	3.54	350	14.534	<.0001
sessionIndex1 - sessionIndex8	52.045	3.54	350	14.685	<.0001
sessionIndex2 - sessionIndex3	5.871	3.54	350	1.656	1.0000
sessionIndex2 - sessionIndex4	14.272	3.54	350	4.027	0.0019
sessionIndex2 - sessionIndex5	18.886	3.54	350	5.329	<.0001
sessionIndex2 - sessionIndex6	24.480	3.54	350	6.907	<.0001
sessionIndex2 - sessionIndex7	27.729	3.54	350	7.824	<.0001
sessionIndex2 - sessionIndex8	28.263	3.54	350	7.974	<.0001
sessionIndex3 - sessionIndex4	8.401	3.54	350	2.370	0.5126
sessionIndex3 - sessionIndex5	13.015	3.54	350	3.672	0.0078
sessionIndex3 - sessionIndex6	18.609	3.54	350	5.251	<.0001
sessionIndex3 - sessionIndex7	21.858	3.54	350	6.167	<.0001
sessionIndex3 - sessionIndex8	22.392	3.54	350	6.318	<.0001
sessionIndex4 - sessionIndex5	4.614	3.54	350	1.302	1.0000
sessionIndex4 - sessionIndex6	10.208	3.54	350	2.880	0.1181
sessionIndex4 - sessionIndex7	13.457	3.54	350	3.797	0.0048
sessionIndex4 - sessionIndex8	13.991	3.54	350	3.948	0.0027
sessionIndex5 - sessionIndex6	5.594	3.54	350	1.578	1.0000
sessionIndex5 - sessionIndex7	8.843	3.54	350	2.495	0.3653
sessionIndex5 - sessionIndex8	9.377	3.54	350	2.646	0.2385
sessionIndex6 - sessionIndex7	3.249	3.54	350	0.917	1.0000
sessionIndex6 - sessionIndex8	3.783	3.54	350	1.067	1.0000
sessionIndex7 - sessionIndex8	0.534	3.54	350	0.151	1.0000

Degrees-of-freedom method: kenward-roger
P value adjustment: bonferroni method for 28 tests

For the **ud_sum** variable, sessionIndex was left as a numeric variable, as its progression over time better reflects trends in the sum of **Up-Down (UD)** times.

This approach allowed us to analyze the relationship between sessions and ud_sum without categorizing sessions explicitly.

The results show that the average sum of UD times decreases across sessions, starting at 115.2 in session 1 and dropping to 63.2 by session 8. Pairwise comparisons confirm significant differences between earlier sessions (e.g., session 1 - session 2 = 23.783, $p < 0.0001$) but show smaller, insignificant differences between later sessions (e.g., session 7 - session 8 = 0.534, $p = 1.0$). This suggests that improvements in UD times are substantial in the initial sessions but taper off as participants become more consistent over time.


Significant Pairwise Differences for Sum of UD Values
Pairwise Comparisons
sessionIndex4 - sessionIndex8
sessionIndex4 - sessionIndex7
sessionIndex3 - sessionIndex8
sessionIndex3 - sessionIndex7
sessionIndex3 - sessionIndex6
sessionIndex3 - sessionIndex5
sessionIndex2 - sessionIndex8
sessionIndex2 - sessionIndex7
sessionIndex2 - sessionIndex6
sessionIndex2 - sessionIndex5
sessionIndex2 - sessionIndex4
sessionIndex1 - sessionIndex8
sessionIndex1 - sessionIndex7
sessionIndex1 - sessionIndex6
sessionIndex1 - sessionIndex5
sessionIndex1 - sessionIndex4
sessionIndex1 - sessionIndex3
sessionIndex1 - sessionIndex2
0
20
40
Difference in Sum of UD Values (Estimate)

Conclusion

This analysis explored typing dynamics by investigating how two response variables, TotalTypingTime and ud_sum, change over multiple sessions. The results show significant reductions in both total typing time and UD times as participants completed repeated sessions, highlighting consistent improvement in typing speed and efficiency. Linear Mixed-Effects Models revealed that improvements vary among participants, with those starting slower showing greater gains.

References

- Hothorn, T., & Everitt, B. S. (2014). A Handbook of Statistical Analyses using R. In Chapman and Hall/CRC eBooks.
- Killourhy, K. S., & Maxion, R. A. (2009). Comparing anomaly-detection algorithms for keystroke dynamics.
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