

LA Nurse BP

Case Study 1*

Kunwu Lyu

Katie St. Clair, STAT 330
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Executive Summary

Here is what I did.

1 Introduction

Certain traits such as family history and mood are expected to increase one's ambulatory blood pressure (BP). Goldstein and Shapiro (2000) studied potential factors that contribute to hypertension. They collected information about the participants' BP, activity levels, work status, and mood ratings throughout the day, as well as relevant family history and information about their menstrual phases, to establish links that lead to elevated BP. Towards the end, they sought to uncover preventative measures for individuals who may be at a higher risks of developing hypertension. The objectives of this project is much simpler. I am interested in exactly what traits are *associated* with elevating one's BP, given the longitudinal structure and various time-dependent metrics in the dataset (given by Goldstein & Shapiro, 2000; cited by Roback & Legler, 2021).

1.1 Methods

The dataset includes repeated measures over the course of two work and off-work days on 203 registered nurses between the ages of 24 and 50 years working in Los Angeles, in the year 2000. Of those 203 nurses, 172 has complete data on all of the variables recorded.¹ BP of the participants were measured 30 minutes before their normal start of work, and measured repeatedly every 20 minutes for the rest of the day. This led to around 40-60 observations per nurse (9573 total observations). Each time the BP was taken, participants were asked to give several mood ratings including happiness, stress, and tiredness. In addition, participants wore an actigraph on their waist to record frequency of movements in one-minute intervals; the researchers obtained an activity measure for the ten-minute periods before each BP reading.

*Code used for this project is available at this [GitHub Repository](#).

¹In the original paper by Goldstein and Shapiro (pp. 228–29), they reported 171 nurses who completed all sessions. It is likely that this is due to Roback and Legler (2021) or Weiss (2005) excluding other personality variables used in the original study. Because I am not investigating personality traits in this project, 172 suffices being my total subject counts. Additionally, Goldstein and Shapiro mention that “[s]imilar patterns of findings were obtained in the sample of 171 as in the total sample” (p. 229).

| Variable Name | Variable Description |
|---------------|--|
| ID (Cluster) | Unique identification number for each participant |
| BP (Response) | Systolic blood pressure (in mmHg) |
| <i>Act</i> | Activity level (frequency of movements in 1-minute intervals, over a 10-minute period) |
| Phase | Menstrual phase (follicular or luteal) |
| Day | Workday or non-workday |
| Posture | Position during BP measurement (sitting, standing, or reclining) |
| HAP | Self-ratings of happiness by each nurse at the time of each BP measurement on a 5-point scale (5 strongest and 1 weakest) |
| STR | Self-ratings of stress by each nurse at the time of each BP measurement on a 5-point scale (5 strongest and 1 weakest) |
| TIR | Self-ratings of tiredness by each nurse at the time of each BP measurement on a 5-point scale (5 strongest and 1 weakest) |
| Age | Age (in years) |
| Full FH | Family history, coded as either NO (no family history of hypertension), YES (1 hypertensive parent), or YESYES (both parents hypertensive) |
| Timepass | Number of minutes since the first measurement |
| <i>Stand</i> | Indicator variable for standing, where it equals 0 if Posture is either sitting or reclining and 1 when Posture is standing |
| <i>Mood</i> | Combined mood ratings: HAP - (STR + TIR)/2 |
| FH | Indicator variable for having family history of hypertension (1 for YES and YESYES, 0 for NO) |
| <i>Age24</i> | Recentered Age: Age - 24 |

Note: *emphasis* added to re-parameterized variables; colors represent levels.

Table 1: Variable Descriptions

2 Exploratory Data Analysis

The variables (original and re-parameterized) used in this project are given in [Table 1](#). Variable missingness was explored in [Figure 1](#). We see that the data were missing primarily mood ratings and some activity levels from several participants. Because I am interested in how both of these variables relate to BP, I will proceed the analysis with the missing rows removed, leaving us with a total of 172 participants and 7877 observations. The visuals and statistics below will be given in terms of that subset of the data, unless otherwise specified.

Because of the longitudinal nature of our data, it is worth noting our levels of analysis and to which our variables belong. I will call time-dependent measurements *Level 1* data (variables) and the rest of the subject-level measurements *Level 2* data (variables). Each participant has a unique identification number; this will distinguish between different clusters. Our primary response is systolic blood pressure (BP), and I will use our exploratory data analysis below to guide our model selection process from the bottom-up.

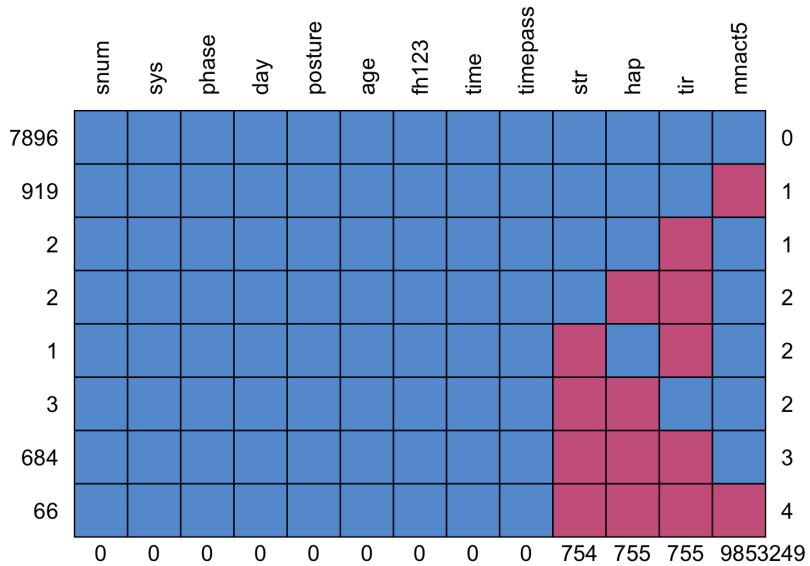


Figure 1: Data Missingness

Note that I created three additional variables from the original dataset to help simplify the modeling process. In the original dataset, **Posture** is a factor variable with three levels: Recline ($n = 530$), Sit ($n = 3644$), and Stand ($n = 3703$). Because the relatively small number of observations where participants were reclining (presumably sleeping at night or resting), I collapsed the three levels into either Standing or non-Standing. Similarly, because of the relatively small number of participants have both parents with hypertension ($n = 13$), I collapsed it together with having one parent with hypertension ($n = 66$) to compare against those without any family history ($n = 103$). Lastly, a general **Mood** measurement was created by subtracting the average of tiredness and stress from happiness.

2.1 Level 1 by Clusters

I will first explore how BP vary among participants and how it relates to the level 1 predictors to examine if there is any sign of clustering between different participants (which is the premise of a longitudinal study). From [Figure 2](#), we see that BP readings do tend to vary among different participants, though variations within each participant do not seem to be pronounced. This suggests that a Linear Mixed Model (LMM) might be more appropriate than a regular Multiple Linear Regression (MLR).

Since our data is ordered in time, one might be interested in answering how the participants' BP evolve over time. For sake of brevity, I show a random subsets of subjects and their BP readings over time in [Figure 3a](#). From this plot alone, not much could be deciphered; some trends (e.g., participant 1116) seem to decrease over time while others either slightly increase (e.g., participant 1267) or do not see much fluctuation overall. Indeed, when I fit separate linear smoothers for each participant, I see various different intercepts and slopes for each

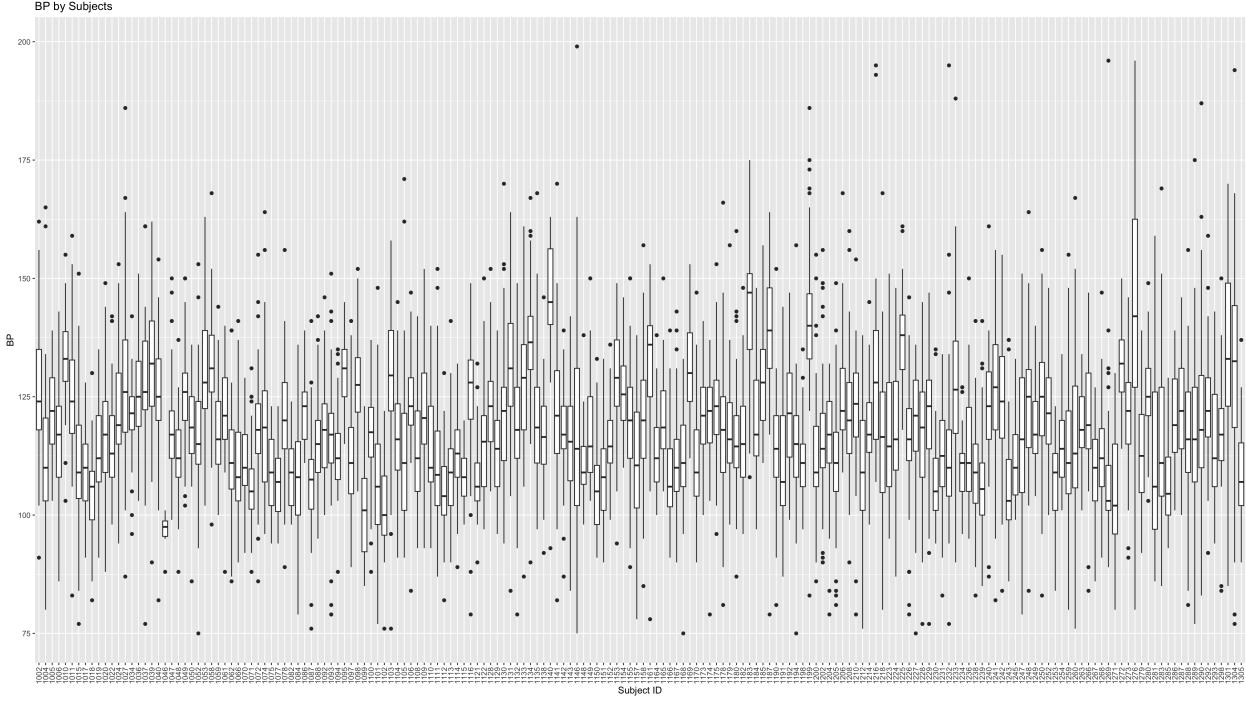


Figure 2: BP by Subjects

participant (see [Figure 3b](#)). This suggests that a random effect for both the intercept and slope of time.

We perform similar analysis for other level 1 covariates (see [Figure 4](#)). We see the most prominent effect in `Mood`, where the slopes and intercepts for each participant differs the most. They all show, to a certain extend, signs of varying slopes and intercepts, but I cannot definitely conclude anything at this point.

2.2 Level 2 Covariates

We then want to understand the distributions of our level two covariates before we look at any interactions between the two levels. Because our level 2 covariates contains the same measurement over time (whereas our primary response `BP` is level 1 and hence time-dependent), we will compare the level 2 covariates with the *average* `BP` of a given participant.

From [Figure 5a](#), we do not see that being on a different menstrual phase impacts the participants' average `BP` much at all, suggesting that we likely do not need to control for `Phase` as a level 2 predictor. We see that in a workday, as opposed to a non-workday, the average `BP` of the participants appears to have a higher mean (see [Figure 5b](#)).

Similarly for family history; having at least one parent with hypertension bumps the participants' average `BP` by a marginal amount ([Figure 5d](#)). This suggest that we might want to look into having `Day` and `FH` in our model as control or predictors; we will return to their interaction with level 1 predictors in the next section.

Lastly, it is unclear how age impacts average `BP`, since [Figure 5c](#) shows that the effect of age varies significantly (though a smoother line shows slight positive increase as age increases). We will test this formally in [Section 3](#).

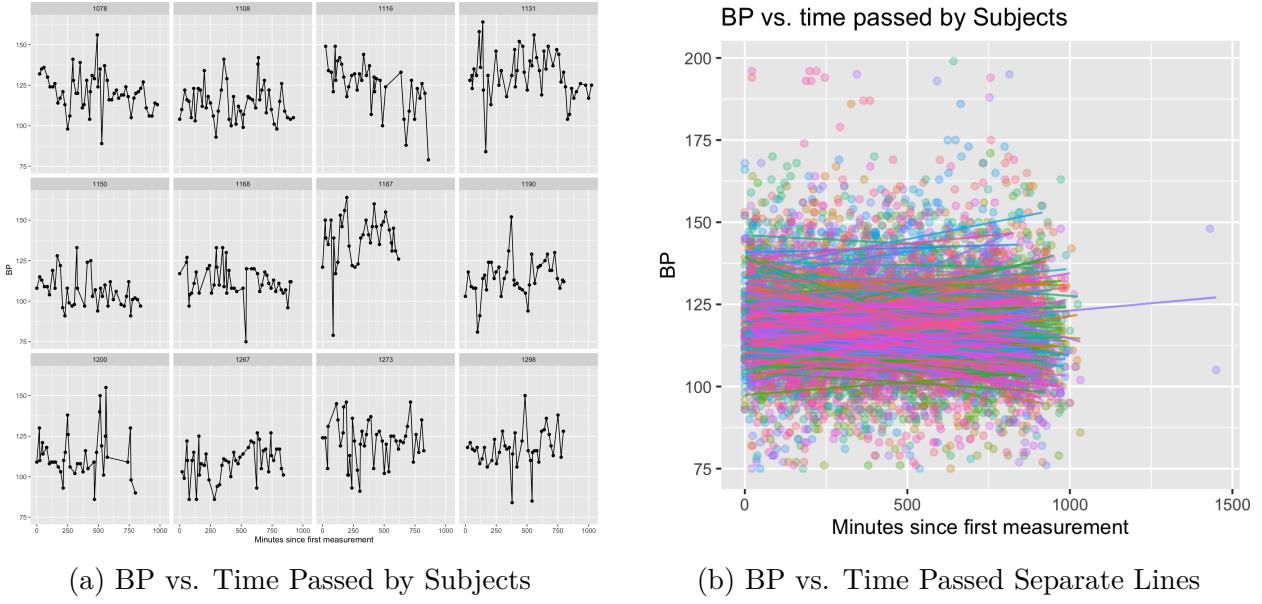


Figure 3: BP vs. Minutes since first measurement

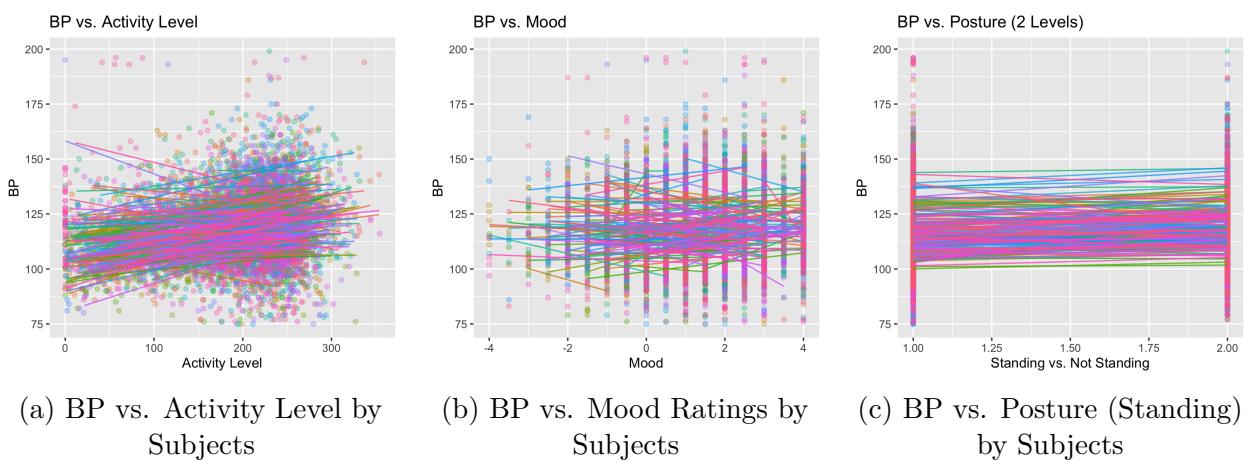
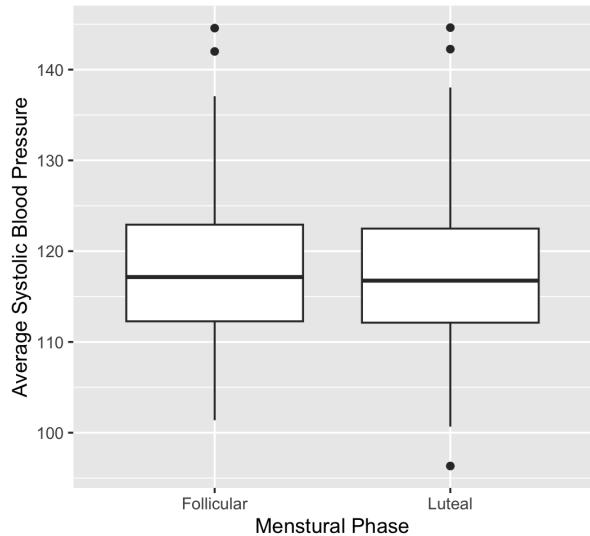
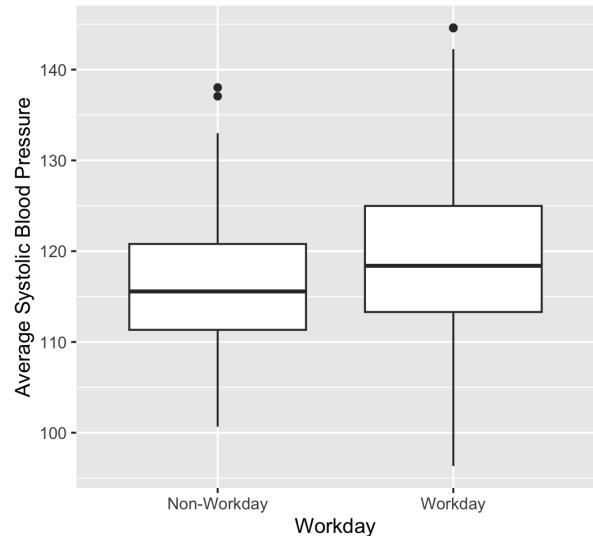


Figure 4: BP vs. Level 1

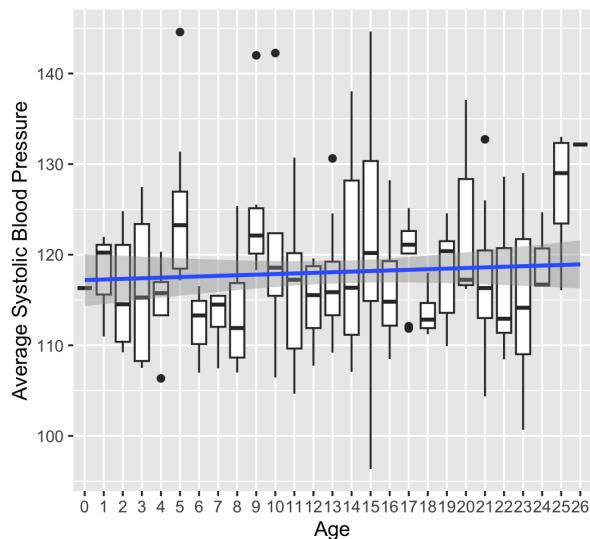


(a) Avg BP vs. Menstrual Phase

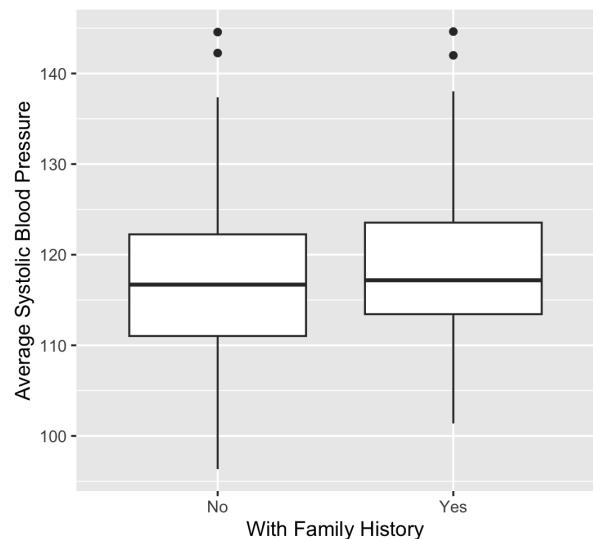


(b) Avg BP vs. Workday

Figure 5: Average BP vs. Level 2 Covariates



(c) Avg BP vs. Age



(d) Avg BP vs. Family History

Figure 5: Average BP vs. Level 2 Covariates

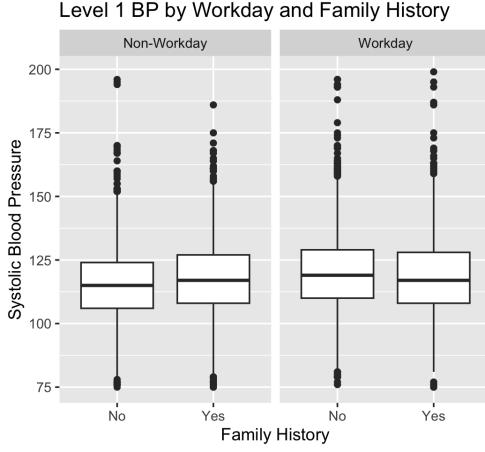


Figure 6: Level 1 BP by Workday and Family History

2.3 Level 1 by Level 2 Covariates

Next we investigate whether our level 1 covariates depend, in any way, on our level 2 covariates. There are several ways one could explore this.² In Section 2.2, we suspect that BP depends on Workday and FH. Instead of showing the average BP, we can also show simply the level 1 responses, faceted by workday and family history (see Figure 6).

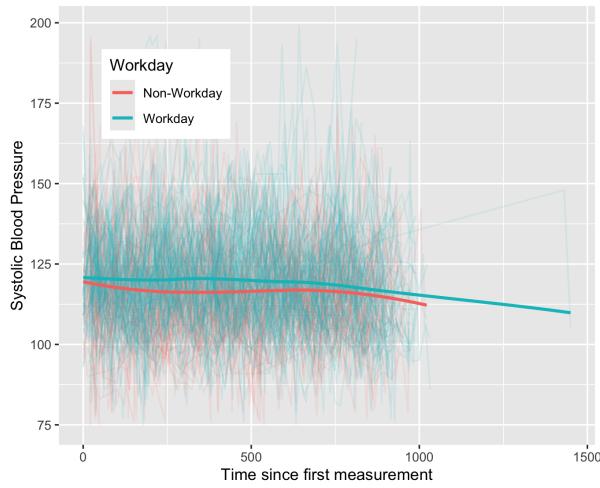
To better understand the interaction between level 2 covariates and the level 1 covariates, however, it is most clear to explore with spaghetti plots or separate LS models to see the difference in intercepts and slopes. We first explore with spaghetti plots. From Figure 7 alone, it is hard to say anything conclusive about whether one of the level one covariates depend on Workday; there all seem to be marginal difference in intercepts, but slopes seem largely similar. Figure 8 likewise shows inconclusive results in terms of Family History (though there appears to be some difference in slopes in Mood by FH). We proceed to analyze separate MLR models containing level 1 variables for each participant. This also allows us to better understand the continuous variable Age24.

After fitting separate MLR models for each participant, we see that the intercepts appears to depend on Workday and Age (see Figure 9b and Figure 9a), the slopes for Time appears to depend on Family History and Workday (see Figure 10c and Figure 10b), and the fixed effect for Standing appears to depend on Age and Workday (see Figure 12a and Figure 12b).

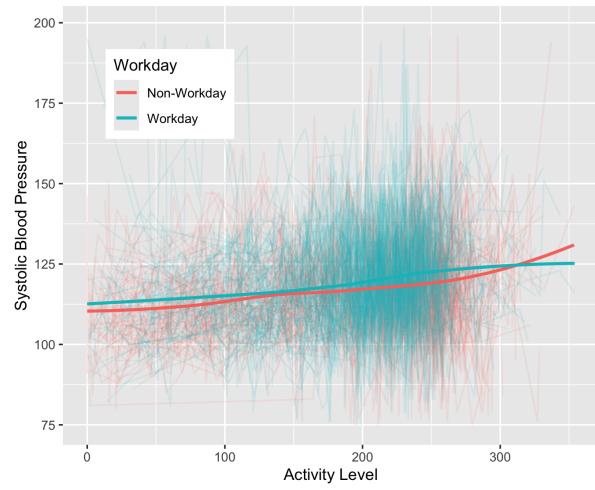
3 Model Selection

We will use a bottom-up approach to build a saturated model from scratch. Since, our data is ordered by time, we start with a base model (Model 1) with only the random intercept and level 1 covariate time: for the j^{th} measurement in the i^{th} participant, where $i = 1, \dots, n$

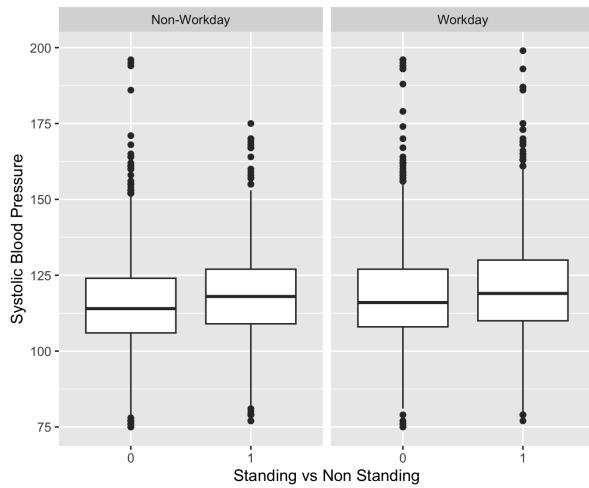
²Additional visualizations are shown in Appendix A.



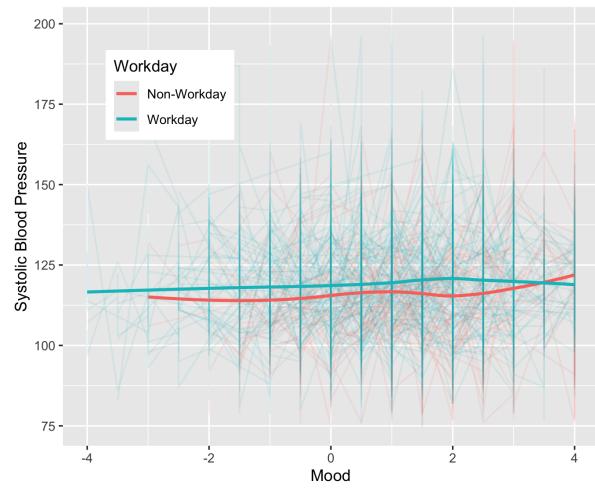
(a) L1 BP vs. Time by Workday



(b) L1 BP vs. Activity by Workday

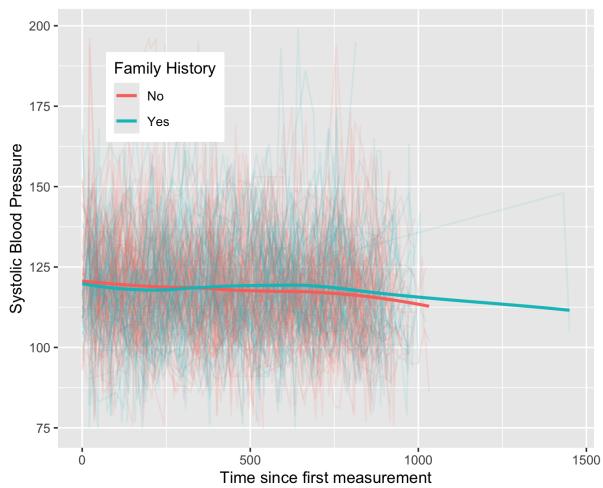


(c) L1 BP vs. Standing by Workday

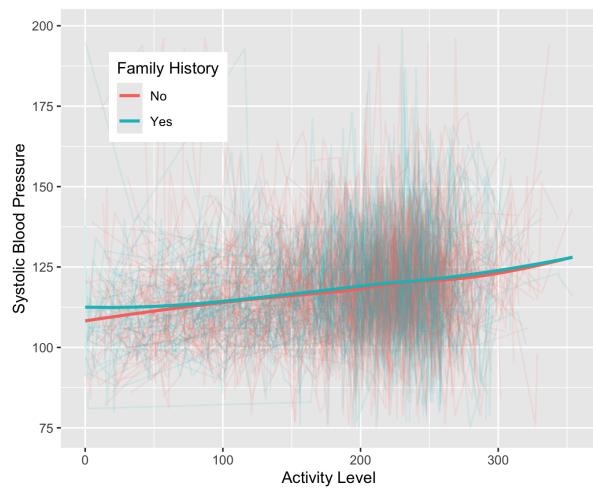


(d) L1 BP vs. Mood by Workday

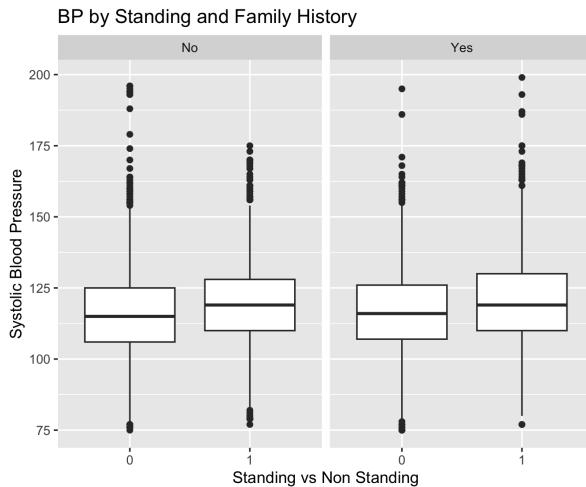
Figure 7: L1 BP vs. Level 1 Covariates by Workday



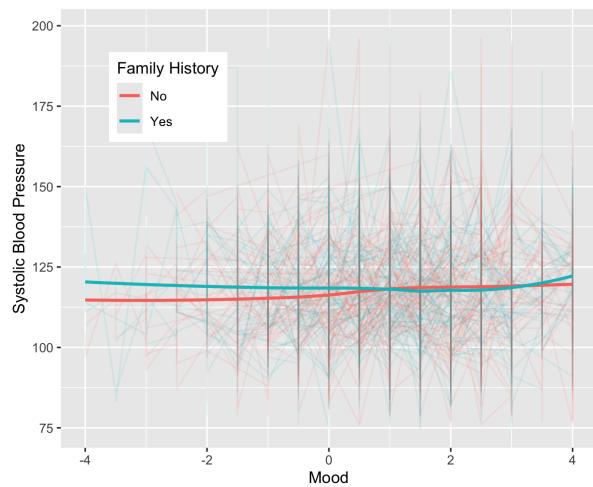
(a) L1 BP vs. Time by Family History



(b) L1 BP vs. Activity by Family History

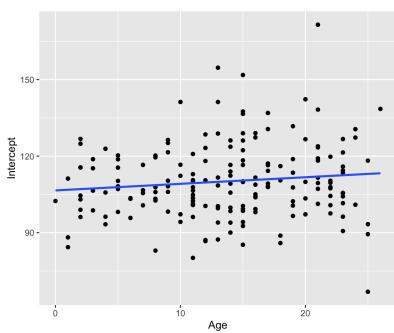


(c) L1 BP vs. Standing by Family History

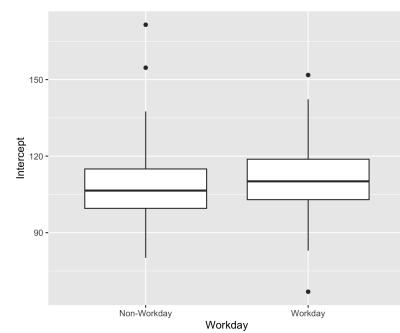


(d) L1 BP vs. Mood by Family History

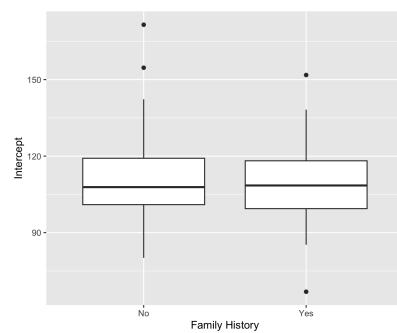
Figure 8: L1 BP vs. Level 1 Covariates by Family History



(a) MLR Intercepts by Age



(b) MLR Intercepts by Workday



(c) Intercepts by Family History

Figure 9: MLR Intercepts by Level 2 Covariates

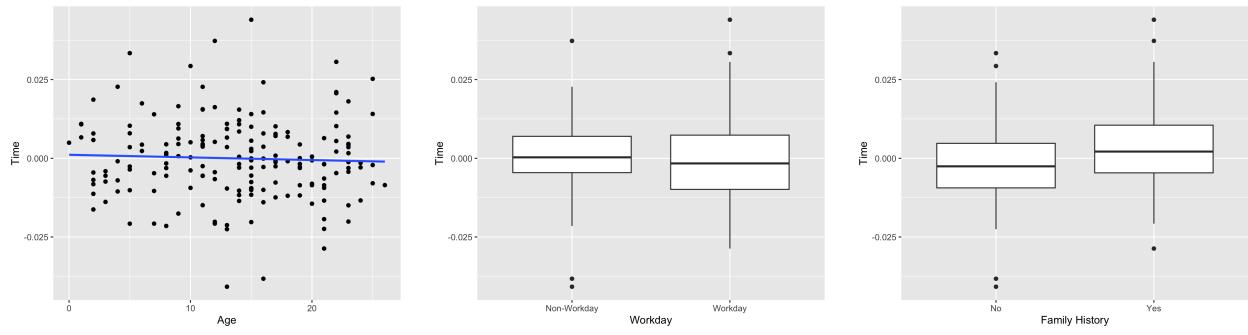


Figure 10: MLR Time Slopes by Level 2 Covariates

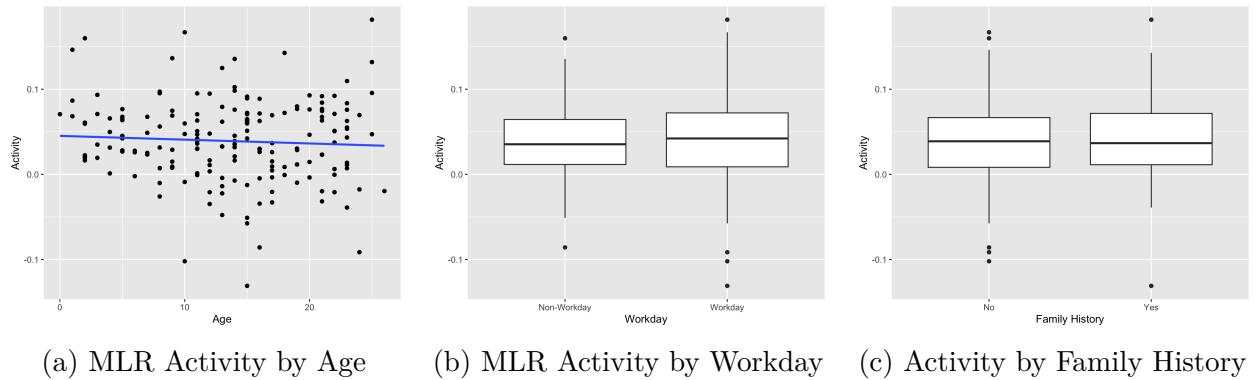


Figure 11: MLR Activity Slopes by Level 2 Covariates

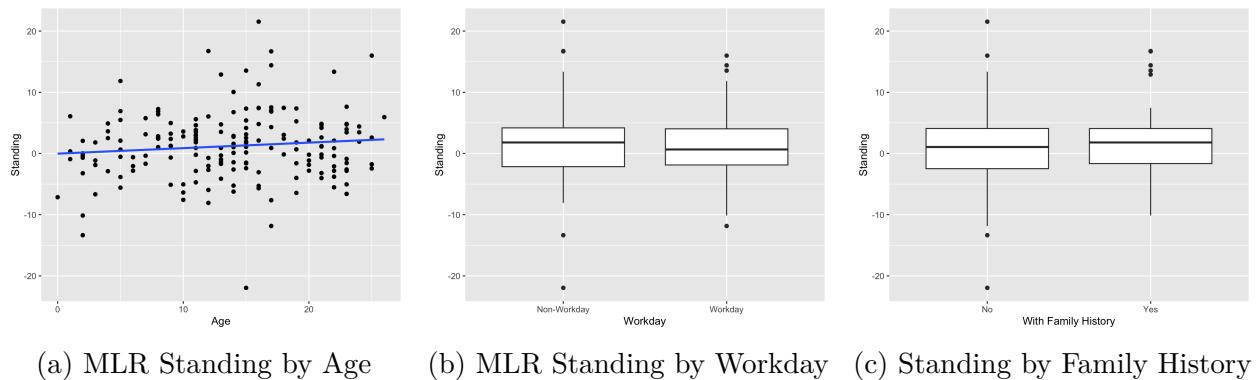
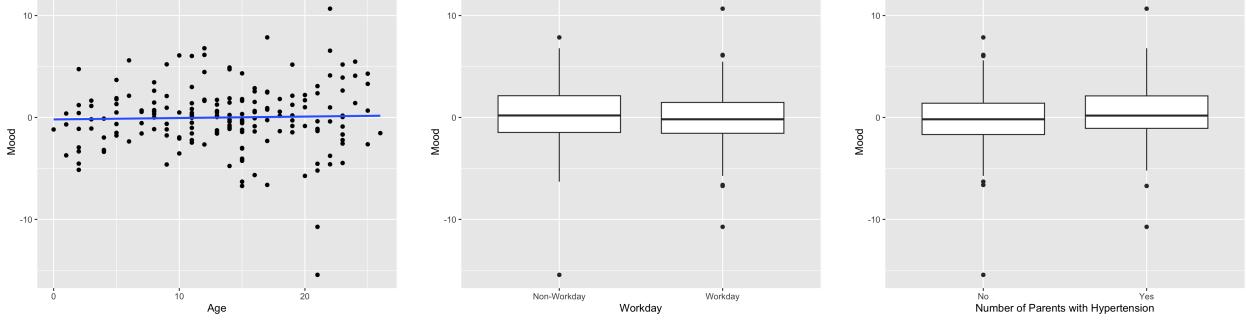


Figure 12: MLR Standing Fixed Effects by Level 2 Covariates



(a) MLR Mood by Age (b) MLR Mood by Workday (c) Mood by Family History

Figure 13: MLR Mood Slopes by Level 2 Covariates

and $j = 1, \dots, n_i$,

$$\begin{aligned} \text{Level 1 : } \text{BP}_{ij} &= a_i + \beta_1 \text{Time}_{ij} + \epsilon_{ij}, & \epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2) \\ \text{Level 2 : } a_i &= \alpha + u_i, & u_i &\stackrel{i.i.d.}{\sim} N(0, \sigma_u^2). \end{aligned} \quad (1)$$

A Likelihood Ration Test (LRT) reveals that compared to a Ordinary Least Squares (OLS) model with no random intercept, the random effect is significant ($\chi^2(0, 1) = 2044.1, p < 2.2 \times 10^{-16}$). Note that here the p -value is a mixture from a chi-square model with 0 degrees of freedom and 1 degree of freedom.

We then proceed to add in fixed effects for level 1 to investigate whether activity level, whether or not the participants were standing, and mood ratings were *associated* with elevating BP. We propose the following (Model 2) with a random intercept and all level 1 covariates:

$$\begin{aligned} \text{Level 1 : } \text{BP}_{ij} &= a_i + \beta_1 \text{Time}_{ij} + \beta_2 \text{Activity}_{ij} + \beta_3 \text{Standing}_{ij} + \\ &\quad \beta_4 \text{Mood}_{ij} + \epsilon_{ij}, & \epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\ \text{Level 2 : } a_i &= \alpha + u_i, & u_i &\stackrel{i.i.d.}{\sim} N(0, \sigma_u^2). \end{aligned} \quad (2)$$

A LRT between Model 1 and 2 reveals that the three added fixed effects are statistically significant ($\chi^2(3) = 365.37, p < 2.2 \times 10^{-16}$). Naturally, one might wonder if we need all three fixed effect. Indeed, a LRT suggests that the following Model 2' without the covariate Mood ($\beta_4 = 0$) is just as good as Model 2 ($\chi^2(1) = 0.43, p = 0.51$). Because we are interested in *whether* something is associated with elevated BP at all, we proceed the analysis with the simpler Model 2'.

$$\begin{aligned} \text{Level 1 : } \text{BP}_{ij} &= a'_i + \beta'_1 \text{Time}_{ij} + \beta'_2 \text{Activity}_{ij} + \beta'_3 \text{Standing}_{ij} + \epsilon_{ij}, \\ &\quad \epsilon_{ij} \stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\ \text{Level 2 : } a'_i &= \alpha' + u_i, & u_i &\stackrel{i.i.d.}{\sim} N(0, \sigma_u^2). \end{aligned} \quad (2')$$

Interestingly, LRT tests also suggest that compared to Model 2', a model without the **Time** term ($\beta'_1 = 0$) is also just as good ($\chi^2(1) = 0.99, p = 0.32$). However, because time is such an important aspect of the longitudinal model, we think it is important that we keep **Time** as a level 1 covariate in our model.

Next we investigate what random effects are needed in our model. The most clear evidence of random slopes from our EDA comes from **Mood**, but since LRT tests suggest that the fixed effect of **Mood** is not significant, we will not consider its random effect. For the rest of the covariates, EDA do show marginal signs of varying slopes. However, only adding a random effect for **Standing** do not raise convergence issues. This leads us to the following model with a random effect for **Standing**:

$$\begin{aligned} \text{Level 1 : } \text{BP}_{ij} &= a_i + \gamma_1 \text{Time}_{ij} + \gamma_2 \text{Activity}_{ij} + b_i \text{Standing}_{ij} + \epsilon_{ij}, \\ \epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\ \text{Level 2 : } a_i &= \alpha + u_i, \\ b_i &= \beta + v_i, \\ \begin{bmatrix} u_i \\ v_i \end{bmatrix} &\stackrel{i.i.d.}{\sim} N_2 \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_u^2 & \rho_{uv}\sigma_u\sigma_v \\ \rho_{uv}\sigma_u\sigma_v & \sigma_v^2 \end{bmatrix} \right). \end{aligned} \tag{3}$$

A LRT suggests that the random effect for **Standing** is significant, based on a mixture from a chi-square model with 1 and 2 degrees of freedom ($\chi^2(1, 2) = 377.34.1, p < 2.2 \times 10^{-16}$). Interestingly, removing the correlation term (ρ_{uv}) between the random effect for the intercept and the random effect for **Standing** causes further convergence issues, so we preserve the it in our following analysis.

We move on to consider the interaction between level 2 and level 1 covaraites. Recall that our EDA identifies **Age**, **Workday**, and **Family History** as possibly interacting with the effect for **Standing**, the effects for **Time** and **Standing**, and the effect for **Time**, respectively. We will first consider whether the intercept and the effect of **Standing** depend on **Age** (recentered at 24):

$$\begin{aligned} \text{Level 1 : } \text{BP}_{ij} &= a_i + \gamma_1 \text{Time}_{ij} + \gamma_2 \text{Activity}_{ij} + b_i \text{Standing}_{ij} + \epsilon_{ij}, \\ \epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\ \text{Level 2 : } a_i &= \alpha + \alpha_1 \text{Age}_i + u_i, \\ b_i &= \beta + \beta_1 \text{Age}_i + v_i, \\ \begin{bmatrix} u_i \\ v_i \end{bmatrix} &\stackrel{i.i.d.}{\sim} N_2 \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_u^2 & \rho_{uv}\sigma_u\sigma_v \\ \rho_{uv}\sigma_u\sigma_v & \sigma_v^2 \end{bmatrix} \right). \end{aligned} \tag{4}$$

When compared with Model 3 ($\alpha_1 = \beta_1 = 0$), a LRT suggests that the smaller model without **Age** is just as good as the full model with the **Age** term ($\chi^2(2) = 0.97, p = 0.61$). Because this project concerns *whether* a covaraite is associated with elevated BP, we will proceed with the smaller model without **Age**.³

³Note that Goldstein and Shapiro (2000) does include **Age** as a predictor because they are interested in preventative measures *controlling for* age. This is not the aim of this project, even though **Age** is a meaningful and important predictor.

Next, we consider the interaction of **Workday** between **Time** and **Standing**.

$$\begin{aligned}
\text{Level 1 : } \text{BP}_{ij} &= a_i + b_i \text{Time}_{ij} + \delta \text{Activity}_{ij} + c_i \text{Standing}_{ij} + \epsilon_{ij}, \\
\epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\
\text{Level 2 : } a_i &= \alpha_0 + \alpha_1 \text{Workday}_i + u_i, \\
b_i &= \beta_0 + \beta_1 \text{Workday}_i \\
c_i &= \gamma_0 + \gamma_1 \text{Workday}_i + v_i, \\
\begin{bmatrix} u_i \\ v_i \end{bmatrix} &\stackrel{i.i.d.}{\sim} N_2 \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_u^2 & \rho_{uv}\sigma_u\sigma_v \\ \rho_{uv}\sigma_u\sigma_v & \sigma_v^2 \end{bmatrix} \right).
\end{aligned} \tag{5}$$

A LRT suggests that, when compared to Model 3 ($\alpha_1 = \beta_1 = \gamma_1 = 0$), at least one of coefficients is statistically significantly different from zero; we have some evidence to reject the Model 3 and prefer Model 5 for better model fit ($\chi^2(3) = 8.22, p = 0.04$). However, when one removes the interaction between **Workday** and **Standing** ($\gamma_1 = 0$), a LRT test suggests that the smaller model is just as good ($\chi^2(1) = 0.45, p = 0.50$); we drop the γ_1 for the sake of simplicity, which, when compared to the simpler Model 3 ($\alpha_1 = \beta_1 = 0$), still presents better explanatory power ($\chi^2(2) = 7.77, p = 0.02$). Nevertheless, if we were to remove the interaction between **Time** and **Workday** ($\beta_1 = \gamma_1 = 0$ vs. $\gamma_1 = 0$), a LRT suggests that we have some evidence to prefer having the interaction between **Time** and **Workday** for a better model fit ($\chi^2(1) = 4.46, p = 0.03$):

$$\begin{aligned}
\text{Level 1 : } \text{BP}_{ij} &= a_i + b_i \text{Time}_{ij} + \delta \text{Activity}_{ij} + c_i \text{Standing}_{ij} + \epsilon_{ij}, \\
\epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\
\text{Level 2 : } a_i &= \alpha_0 + \alpha_1 \text{Workday}_i + u_i, \\
b_i &= \beta_0 + \beta_1 \text{Workday}_i \\
c_i &= \gamma_0 + v_i, \\
\begin{bmatrix} u_i \\ v_i \end{bmatrix} &\stackrel{i.i.d.}{\sim} N_2 \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_u^2 & \rho_{uv}\sigma_u\sigma_v \\ \rho_{uv}\sigma_u\sigma_v & \sigma_v^2 \end{bmatrix} \right).
\end{aligned} \tag{5'}$$

Lastly, we will consider the interaction between **Family History** and **Time**:

$$\begin{aligned}
\text{Level 1 : } \text{BP}_{ij} &= a_i + b_i \text{Time}_{ij} + \delta \text{Activity}_{ij} + c_i \text{Standing}_{ij} + \epsilon_{ij}, \\
\epsilon_{ij} &\stackrel{i.i.d.}{\sim} N(0, \sigma^2), \\
\text{Level 2 : } a_i &= \alpha_0 + \alpha_1 \text{Workday}_i + \alpha_2 \text{Family History}_i + u_i, \\
b_i &= \beta_0 + \beta_1 \text{Workday}_i + \beta_2 \text{Family History}_i \\
c_i &= \gamma_0 + v_i, \\
\begin{bmatrix} u_i \\ v_i \end{bmatrix} &\stackrel{i.i.d.}{\sim} N_2 \left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_u^2 & \rho_{uv}\sigma_u\sigma_v \\ \rho_{uv}\sigma_u\sigma_v & \sigma_v^2 \end{bmatrix} \right).
\end{aligned} \tag{6}$$

When compared with 5' ($\alpha_2 = \beta_2 = 0$), a LRT suggests that there is strong evidence to reject the smaller model and prefer having the interaction between **Time** and **Family History** for better model fit ($\chi^2(2) = 16.3, p = 0.00029$). As before, removing the correlation between

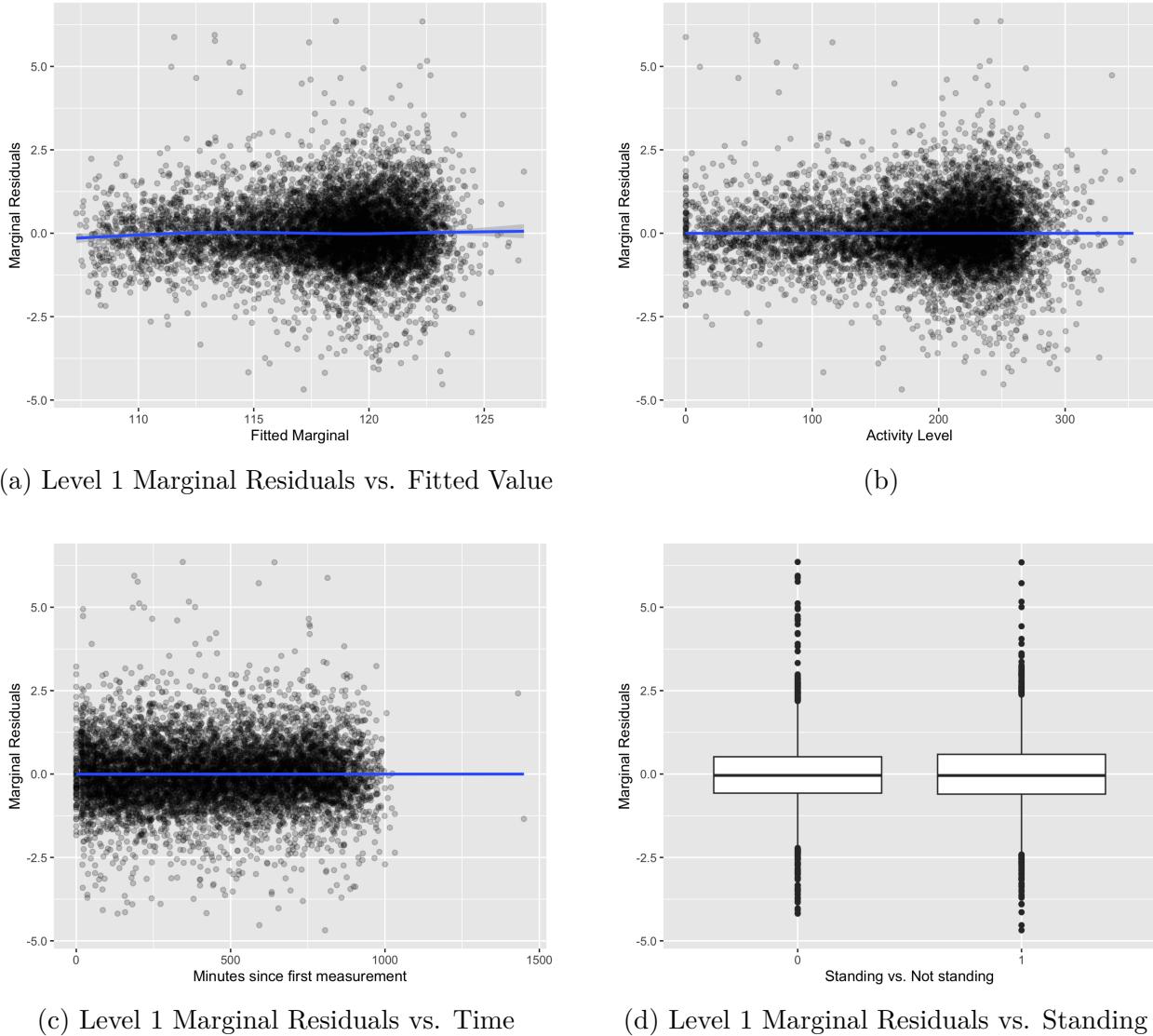
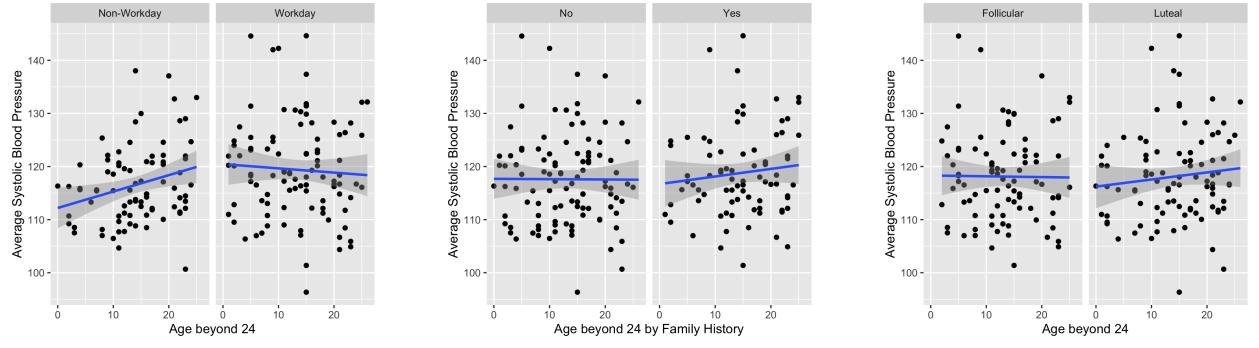


Figure 14: Level 1 Marginal Residuals vs. Predictors

random effects results in convergence issues. We will use Model 6 as our final model for interpretation.

3.1 Residual Analysis

We first consider the level 1 *marginal residuals* for each of the predictors as well as fitted values. From [Figure 14a](#), we see that



(a) BP vs. Age Level by Workday

(b) BP vs. Age by Family History

(c) BP vs. Age by Menstrual Phase

Figure 15: BP vs. Age

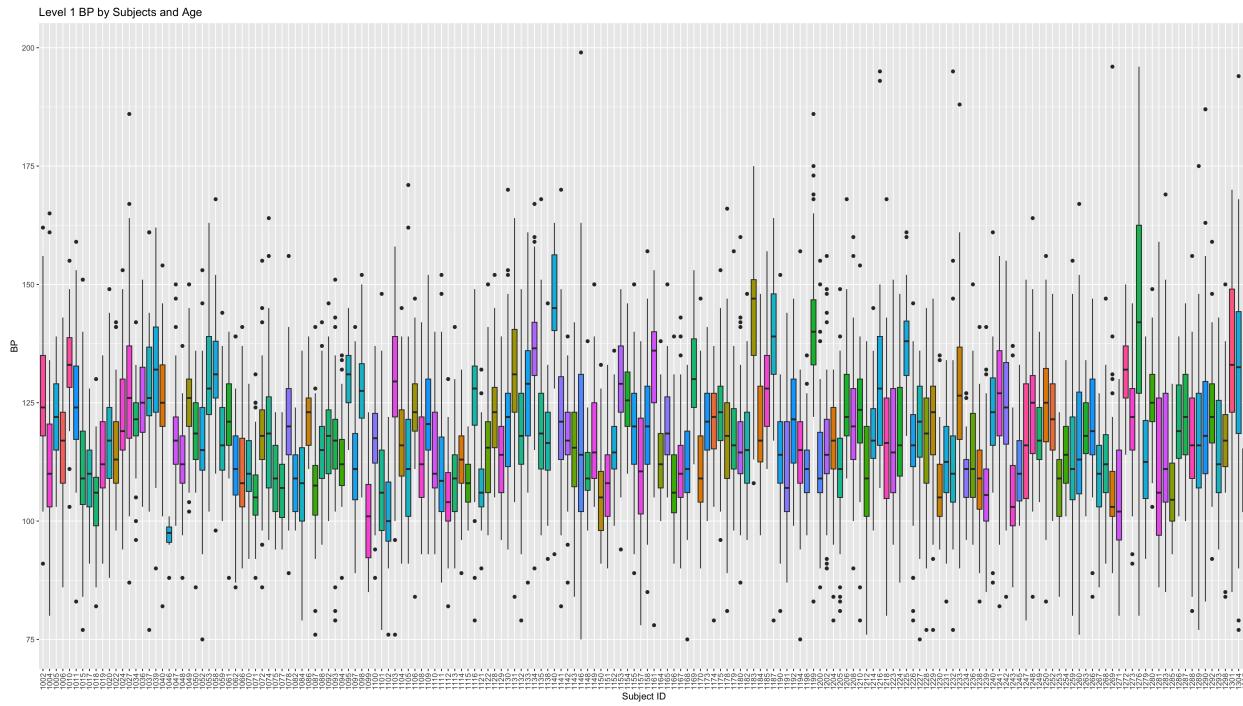
3.2 Influential Statistics

4 Results

Appendix A Additional Visualizations

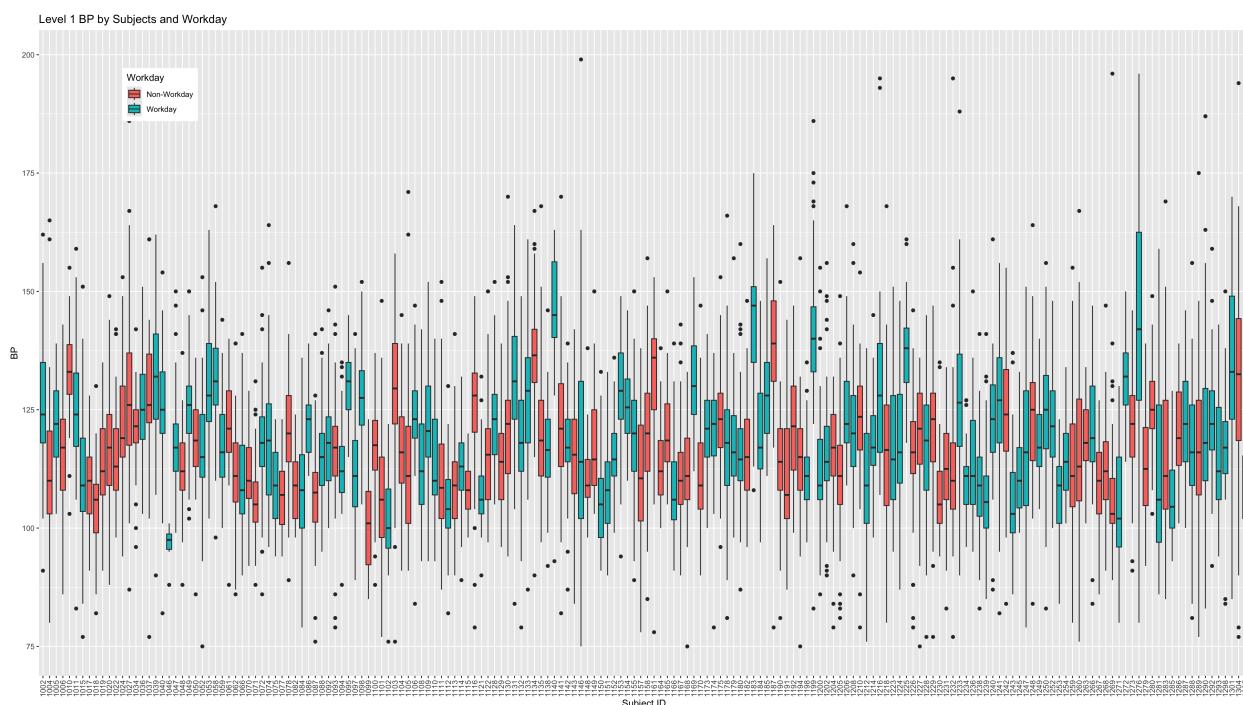
References

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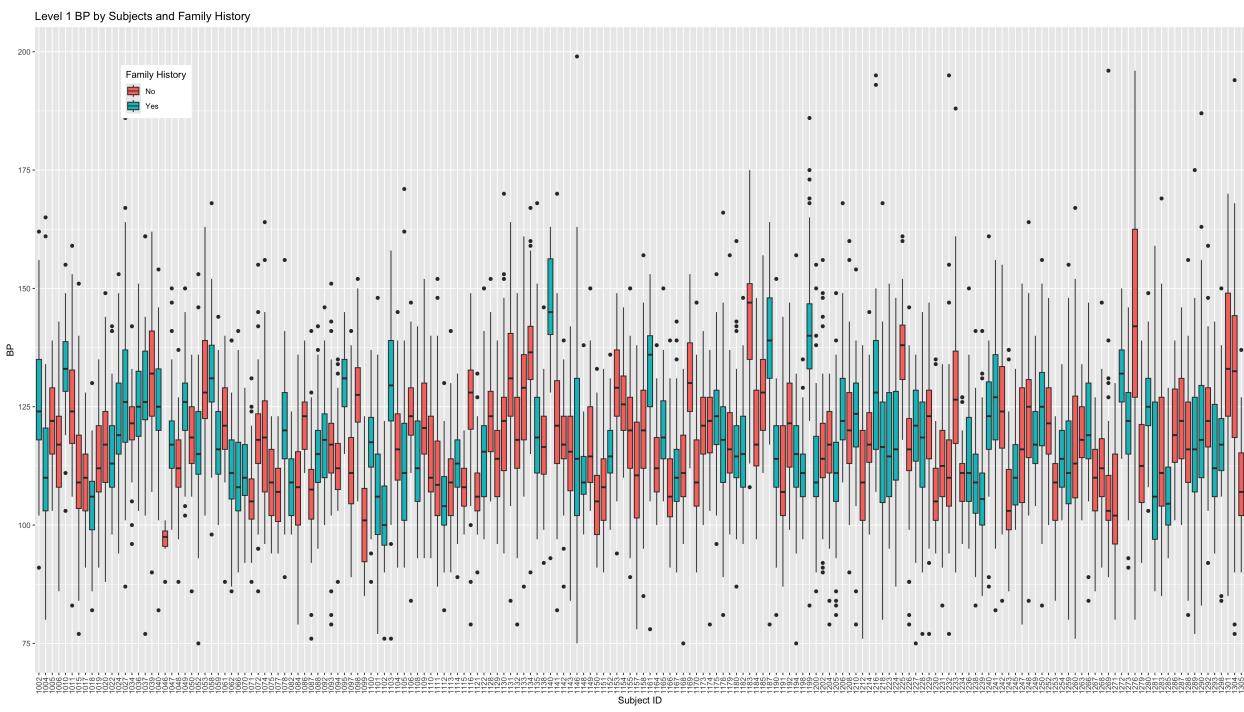
(a) BP vs. Age by Subjects

Figure 16: BP vs. Level 2



(b) BP vs. Workday by Subjects

Figure 16: BP vs. Level 2



(c) BP vs. Family History by Subjects

Figure 16: BP vs. Level 2