Introduction to R and RStudio

Part 4: Extended Inferential Statistics in R

Rob Cribbie
Department of Psychology
York University

http://www.psych.yorku.ca/cribbie/r_course_trent.html
Hypothesis #6: Is there a difference between the three treatment conditions on posttest-perfectionism?

- **Option 1:**
  - `> mod4 <- lm(perf3 ~ group, data=dat)`
  - `> anova (mod4)`

- **Option 2:**
  - `> mod4 <- aov(perf3 ~ group, data=dat)`
  - `> summary(mod4)`

- **Option 3:**
  - `> oneway.test(perf3 ~ group, var.equal=TRUE, data=dat)`
One-way Independent Groups
ANOVA

> oneway.test(perf3 ~ group, var.equal=TRUE, data=dat)

One-way analysis of means

data: perf3 and group
F = 0.2913, num df = 2, denom df = 87, p-value = 0.748

> mod1 <- lm(perf3 ~ group, data=dat)
> anova(mod1)
Analysis of Variance Table

Response: perf3

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>group</td>
<td>2</td>
<td>131.2</td>
<td>65.575</td>
<td>0.2913</td>
<td>0.748</td>
</tr>
<tr>
<td>Residuals</td>
<td>87</td>
<td>19586.0</td>
<td>225.126</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Multiple Comparisons for One-way Independent Groups ANOVA**

- Tukey’s Honestly Significant Difference (HSD) Familywise Error Controlling Procedure for Pairwise Comparisons

```r
> mod2 <- aov(perf3 ~ group, data = dat)
> TukeyHSD(mod2)
 Tukey multiple comparisons of means
  95% family-wise confidence level

Fit: aov(formula = perf3 ~ group, data = dat)
```

$group

<table>
<thead>
<tr>
<th></th>
<th>diff</th>
<th>lwr</th>
<th>upr</th>
<th>p adj</th>
</tr>
</thead>
<tbody>
<tr>
<td>control-cbt</td>
<td>0.1048851</td>
<td>-9.132747</td>
<td>9.342518</td>
<td>0.9995960</td>
</tr>
<tr>
<td>stress-cbt</td>
<td>-2.5067089</td>
<td>-11.744341</td>
<td>6.730924</td>
<td>0.7945257</td>
</tr>
<tr>
<td>stress-control</td>
<td>-2.6115940</td>
<td>-11.849227</td>
<td>6.626039</td>
<td>0.7791236</td>
</tr>
</tbody>
</table>
Multiple Comparisons for One–way Independent Groups ANOVA

- Flexible procedure for all pairwise comparisons

```r
> pairwise.t.test(perf3, group, p.adj="none")
```

Pairwise comparisons using t tests with pooled SD

data:  perf3 and group
cbt    control
control 0.98 -
stress  0.52 0.50

P value adjustment method: none

This option can be changed to any post hoc test you prefer, e.g., ‘bonf’, ‘holm’, ‘fdr’
How can we check for assumption violation?

- Variance Homogeneity Assumption

```r
> library(car)
> leveneTest(dat$perf3, dat$group)

Levene's Test for Homogeneity of Variance (center = median)

<table>
<thead>
<tr>
<th></th>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>group</td>
<td>2</td>
<td>0.5558</td>
<td>0.5756</td>
</tr>
</tbody>
</table>

87
```

Note that by default it uses the median, rather than the mean, to compute deviations.
How can we check for assumption violation?

- Normality Assumption

```r
> tapply(dat$perf3, dat$group, shapiro.test) $cbt

Shapiro-Wilk normality test
data:  x[[1L]]
w = 0.9445, p-value = 0.1203

$control

Shapiro-Wilk normality test
data:  x[[2L]]
w = 0.9631, p-value = 0.3712

$stress

Shapiro-Wilk normality test
data:  x[[3L]]
w = 0.9281, p-value = 0.04379
```

Plots are better, but I just wanted to show a different method that can be used along with plots.
Welch’s Independent Groups ANOVA

- As with the t.test function, the default for the oneway.test function is to use Welch’s heteroscedastic ANOVA

```r
> oneway.test (perf3 ~ group)
```

One-way analysis of means (not assuming equal variances)

```r
data:  perf3 and group
F = 1.8752, num df = 2.000, denom df = 55.448, p-value = 0.1629
```

Good hint that the Welch test is being reported
Multiplicity control with `pairwise.t.test`

```r
> pairwise.t.test(perf3, group, p.adjust.method = "holm", pool.sd=FALSE, data=dat)

Pairwise comparisons using t tests with non-pooled SD

data:  perf3 and group
cbt   control
control 0.57 -
stress  0.20  0.56

P value adjustment method: holm
```

`pool.sd = FALSE` indicates that you would like to use Welch’s t-test for conducting the analyses.
One-way Independent Groups
ANOVA under Nonnormality

- Kruskal–Wallis Nonparametric Test

```r
> kruskal.test (perf3 ~ group, data=dat)

Kruskal-Wallis rank sum test

data:  perf3 by group
Kruskal-Wallis chi-squared = 4.5791, df = 2, p-value = 0.1013
```
As in the two independent groups situation, we can use one of Rand Wilcox’s functions (in this case *t1way*) for computing a Welch omnibus test on trimmed means.

This test is much more reliable than a standard one-way ANOVA when the normality and variance homogeneity assumptions are violated.
One-way Independent Groups ANOVA under Nonnormality and Variance Heterogeneity

```r
> library(wRS2)
> t1way(perf3 ~ group, data=dat, tr=.2)
Call:
t1way(formula = perf3 ~ group, data = dat, tr = 0.2)

Test statistic: 2.7615
Degrees of Freedom 1: 2
Degrees of Freedom 2: 33.18
p-value: 0.07774
```
Hypothesis #7: Is there a significant difference in perfectionism scores from pretest to one-month to posttest?

- Problem: Simple methods for conducting repeated measures ANOVAs ignore the important sphericity assumption that is regularly violated with repeated measures data and inflates Type I error rates.

- Example:
  - `mod5 <- aov(perf ~ week + error (subject / week))`

- However, other functions are available in R that use adjusted df or multivariate solutions to solve the sphericity issue.
One-way Repeated Measures ANOVA with the “car” package

- library(car)
- time <- c(1,2,3)
- time <- as.factor(time)
- idat <- data.frame(time)
- mod6 <- lm(cbind(perf1, perf2, perf3) ~ 1)
- aov1 <- Anova(mod6, idata = idat, idesign = ~ time)
- summary(aov2)

Multivariate Tests: time

<table>
<thead>
<tr>
<th>Test</th>
<th>Df</th>
<th>test stat</th>
<th>approx F</th>
<th>numDf</th>
<th>denDf</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pillai</td>
<td>1</td>
<td>0.290019</td>
<td>17.973521</td>
<td>2</td>
<td>88</td>
<td>2.85e-07 ***</td>
</tr>
<tr>
<td>Wilks</td>
<td>1</td>
<td>0.709981</td>
<td>17.973521</td>
<td>2</td>
<td>88</td>
<td>2.85e-07 ***</td>
</tr>
<tr>
<td>Roy</td>
<td>1</td>
<td>0.408489</td>
<td>17.973521</td>
<td>2</td>
<td>88</td>
<td>2.85e-07 ***</td>
</tr>
</tbody>
</table>

Greenhouse–Geisser Correction for Departure from Sphericity

- GG eps   | Pr(>F[GG]) |
- time     | 0.68104     | 1.728e-07 *** |

This is the old method which lost popularity with newer functions and the emergence of mixed-models for repeated measures.
One-way Repeated Measures ANOVA with the “ez” package

- As the name implies, the `ez` package makes repeated measures ANOVA easier
  - However, one catch is that the data must be in long-form rather than wide-form
  - To do this we can use the ‘reshape’ function

```r
> head(dat,n=2)
   sex group dep1   perf1   perf2   perf3
1  m   cbt 87.59479  68.70716  62.76111  78.43853
2  m   cbt 96.39773  87.44450  75.06312  76.95246
> longdata<-reshape(dat,direction="long",varying=4:6,sep="")
> head(longdata,n=2)
   sex group dep1 time perf1 perf2 perf3 id
1.1 m   cbt 87.59479  1 68.70716  1
2.1 m   cbt 96.39773  1 87.44450  2
```

Columns in the data set that specify the repeated measures

A new variable that represents the levels of the perfectionism variable
One-way Repeated Measures ANOVA with the “ez” package

```R
> longdata$time<-factor(longdata$time)
> library(ez)
> ezANOVA(data=longdata,dv=perf,wid=id,within=time)
```

Warning: Converting "id" to factor for ANOVA.

$ANOVA

<table>
<thead>
<tr>
<th>Effect</th>
<th>DFn</th>
<th>DFd</th>
<th>F</th>
<th>p</th>
<th>p &lt; .05</th>
<th>ges</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>2</td>
<td>178</td>
<td>40.02523</td>
<td>4.422495e-15</td>
<td>*</td>
<td>0.07638647</td>
</tr>
</tbody>
</table>

$`Mauchly's Test for Sphericity`

<table>
<thead>
<tr>
<th>Effect</th>
<th>W</th>
<th>p</th>
<th>p &lt; .05</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>0.6921641</td>
<td>9.31536e-08</td>
<td>*</td>
</tr>
</tbody>
</table>

$`Sphericity Corrections`

<table>
<thead>
<tr>
<th>Effect</th>
<th>GGp</th>
<th>p [GG]</th>
<th>GGp &lt; .05</th>
<th>HFe</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>0.7646219</td>
<td>4.239785e-12</td>
<td>*</td>
<td>0.7752988</td>
</tr>
</tbody>
</table>

p [HF] | p [HF] < .05 |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3.103753e-12</td>
<td>*</td>
</tr>
</tbody>
</table>

Within Subject Variable

ID variable (automatically assigned by ‘reshape’)
Hypothesis 8: Is there a significant relationship between posttest perfectionism scores and the predictors group and sex?

Factorial ANOVA is computed using the linear model (lm) function, along with a function for computing the anova summary table.

- `anova` function in R for computing, by default, Type I SS
- `Anova` function in R for computing, by default, Type II SS
Factorial Independent Groups ANOVA with an Interaction

```r
> anova(lm(perf3 ~ group + sex, data=dat))
Analysis of Variance Table

Response: perf3
 Df Sum Sq  Mean Sq  F value Pr(>F)
group  2 138.7  69.327  0.3359 0.7156
sex    1  2.2  2.2200  0.0108 0.9176
Residuals 86 17747.1 206.362
```

```r
> anova(lm(perf3 ~ group*sex, data=dat))
Analysis of Variance Table

Response: perf3
 Df Sum Sq  Mean Sq  F value Pr(>F)
group  2 138.7  69.327  0.3374 0.7146
sex    1  2.2  2.2200  0.0108 0.9175
group:sex  2 485.3 242.652  1.1808 0.3121
Residuals 84 17261.8 205.498
```
These are equivalent specifications of the model
Factorial Independent Groups ANOVA with Type II SS

```r
> library(car)
> Anova(lm(perf3 ~ group*sex, data=dat))

Anova Table (Type II tests)

Response: perf3

<table>
<thead>
<tr>
<th></th>
<th>Sum Sq</th>
<th>Df</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>group</td>
<td>136.2</td>
<td>2</td>
<td>0.3314</td>
<td>0.7188</td>
</tr>
<tr>
<td>sex</td>
<td>2.2</td>
<td>1</td>
<td>0.0108</td>
<td>0.9175</td>
</tr>
<tr>
<td>group:sex</td>
<td>485.3</td>
<td>2</td>
<td>1.1808</td>
<td>0.3121</td>
</tr>
<tr>
<td>Residuals</td>
<td>17261.8</td>
<td>84</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
```
Factorial ANOVA: Plotting a Potential Interaction

```r
> interaction.plot(dat$group, dat$sex, dat$perf3)
```
Mixed ANOVA

- Hypothesis 9: Are perfectionism scores affected by time, group, or the interaction of time & group?

- We will again use the ez package since it makes computing repeated measures analyses very straightforward

- The only difference is that we will add a between subject variable
Mixed ANOVA

> ezANOVA(data=longdata,dv=perf,wid=id,within=time,between=group)

Warning: Converting "id" to factor for ANOVA.

$ANOVA$

<table>
<thead>
<tr>
<th>Effect</th>
<th>DFn</th>
<th>DFd</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 group</td>
<td>2</td>
<td>87</td>
<td>0.9253750</td>
<td>4.002485e-01</td>
</tr>
<tr>
<td>3 time</td>
<td>2</td>
<td>174</td>
<td>79.0046855</td>
<td>3.869946e-25</td>
</tr>
<tr>
<td>4 group:time</td>
<td>4</td>
<td>174</td>
<td>0.1125054</td>
<td>9.780010e-01</td>
</tr>
</tbody>
</table>

p<.05

$\text{Mauchly's Test for Sphericity} $

<table>
<thead>
<tr>
<th>Effect</th>
<th>W</th>
<th>p</th>
<th>p &lt;.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 time</td>
<td>0.7135874</td>
<td>4.991465e-07</td>
<td>*</td>
</tr>
<tr>
<td>4 group:time</td>
<td>0.7135874</td>
<td>4.991465e-07</td>
<td>*</td>
</tr>
</tbody>
</table>

$\text{Sphericity Correcions} $

<table>
<thead>
<tr>
<th>Effect</th>
<th>GGe</th>
<th>p[GG]</th>
<th>p[GG]&lt;.05</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 time</td>
<td>0.7773556</td>
<td>4.068395e-20</td>
<td>*</td>
</tr>
<tr>
<td>4 group:time</td>
<td>0.7773556</td>
<td>9.565367e-01</td>
<td></td>
</tr>
</tbody>
</table>
One modern approach to analyze repeated measures is to utilize a hierarchical/mixed-model approach

- A mixed model approach has the following advantages:
  - No need to assume sphericity
  - Flexible treatment of missing data (uses all available data)
  - Flexible treatment of time
    - Not every individual needs to be measured at the exact same time

Like the `ezANOVA` function, the data must be in longform
Mixed Model Analysis

Non-linear Mixed Effects package, also conducts linear analyses with the \texttt{lme} function

\begin{verbatim}
> library(nlme)
> mixmod<-lme(perf ~ time, random = ~ 1 | id, data=longdata)
> anova(mixmod)

        numDF denDF F-value  p-value
(Intercept)     1  178  4083.73  <.0001
  time          2  178   80.61  <.0001
\end{verbatim}

Specifies that ids are random, and links the ids to the repeated measures