The Distribution of Sample Means

The Logic of Hypothesis Testing

1

Single Group Analyses	Single Group Experiments
T-test Z-test	Single Sample Design
T-test	Pre-Post Designs
Mixed-effects models	Repeated Measures Designs
Multi-Group Analyses	**Multi-Group Experiments**
T-test	Two Group Design
Analysis of Variance	Multi-Group Design
Regression Analysis	Continuous Predictor Design
Mixed Analyses	**Mixed Experiments**
Mixed-effects models	Group Design with Repeated Measurements
Analysis of Covariance	Group Design also measured on a continuous variable

2

Single Group Analyses	Single Group Experiments
T-test **Z-test**	**Single Sample Design**
T-test	Pre-Post Designs
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T-test	Two Group Design
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Mixed Analyses	**Mixed Experiments**
Mixed-effects models	Group Design with Repeated Measurements
Analysis of Covariance	Group Design also measured on a continuous variable

3

FROM BEFORE

Z-Test Statistic

$$z_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{\sigma_{\bar{X}}}$$

4

Z-Test Statistic

$$z_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{\sigma_{\bar{X}}}$$

- Requires knowledge of population μ (mean before treatment)
- Requires knowledge of population σ^2

5

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6

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T-test **Z-test$_{\sigma\mu}$**	**Single Sample Design**
T-test	Pre-Post Designs
Mixed-effects models	Repeated Measures Designs
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7

Single Group Analyses	Single Group Experiments
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8

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Z-Test Statistic

$$z_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{\sigma_{\bar{X}}}$$

- Requires knowledge of population μ (mean before treatment)
- **Requires knowledge of population σ^2**

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} = \sqrt{\frac{\sigma^2}{n}}$$

$$s^2 \hat{=} \sigma^2$$

The sample variance is an unbiased estimator of the population variance.

13

Population

$$\sigma_{\bar{X}}$$

True Standard Error

Sample

$$s_{\bar{X}}$$

Estimated Standard Error

14

True Standard Error

$$\sigma_{\bar{X}} = \frac{\sigma}{\sqrt{n}} = \sqrt{\frac{\sigma^2}{n}}$$

15

$$s_{\bar{X}} = \frac{s}{\sqrt{n}} = \sqrt{\frac{s^2}{n}}$$

Estimated Standard Error

16

Z-Test Statistic

$$z_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{\sigma_{\bar{X}}}$$

- Requires knowledge of population μ (mean before treatment)
- **Requires knowledge of population σ^2**

17

T-Test Statistic

$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

- Requires knowledge of population μ (mean before treatment)

18

T-Statistic, General Form

$$t = \frac{\text{sample statistic - population parameter}}{\text{estimated standard error of statistic}}$$

19

T-Statistic, General Form

$$t = \frac{\text{sample statistic - population parameter}}{\boxed{\text{estimated standard error of statistic}}}$$

20

T-Tests

One Sample | Dependent Measures | Independent Measures

T-Tests

One Sample | Dependent Measures | Independent Measures

T-Statistic, General Form

$$t = \frac{\text{sample statistic - population parameter}}{\text{estimated standard error of statistic}}$$

T-Statistic, One Mean

$$t = \frac{\text{sample mean - population mean}}{\text{estimated standard error of mean}}$$

T-Statistic, One Mean

if H_0 is True
(if there is no effect)

$$t = \frac{\text{sample mean - population mean}}{\text{estimated standard error of mean}}$$

25

T-Statistic, One Mean

$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

- Requires knowledge of population μ (mean before treatment)

26

T-Tests

One Sample | Dependent Measures | Independent Measures

27

T-Tests

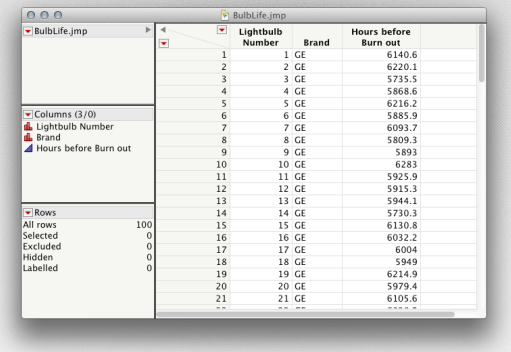
$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

One Sample | Dependent Measures | Independent Measures

28

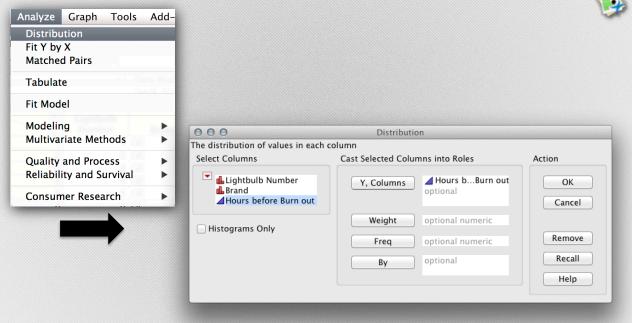
BulbLife

Life in Hours of 100 CFL Bulbs
(6000 hour Claim By Manufacturer)



	Lightbulb Number	Brand	Hours before Burn out
1	1	GE	6140.6
2	2	GE	6220.1
3	3	GE	5735.5
4	4	GE	5868.6
5	5	GE	6216.2
6	6	GE	5885.9
7	7	GE	6093.7
8	8	GE	5809.3
9	9	GE	5893
10	10	GE	6283
11	11	GE	5925.9
12	12	GE	5915.3
13	13	GE	5944.1
14	14	GE	5730.3
15	15	GE	6130.8
16	16	GE	6032.2
17	17	GE	6004
18	18	GE	5949
19	19	GE	6214.9
20	20	GE	5979.4
21	21	GE	6105.6

29



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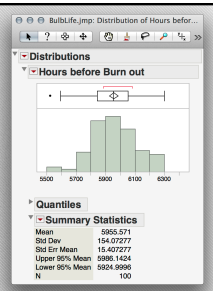
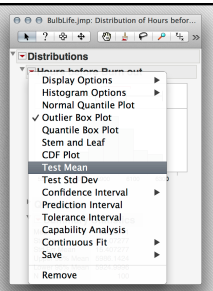
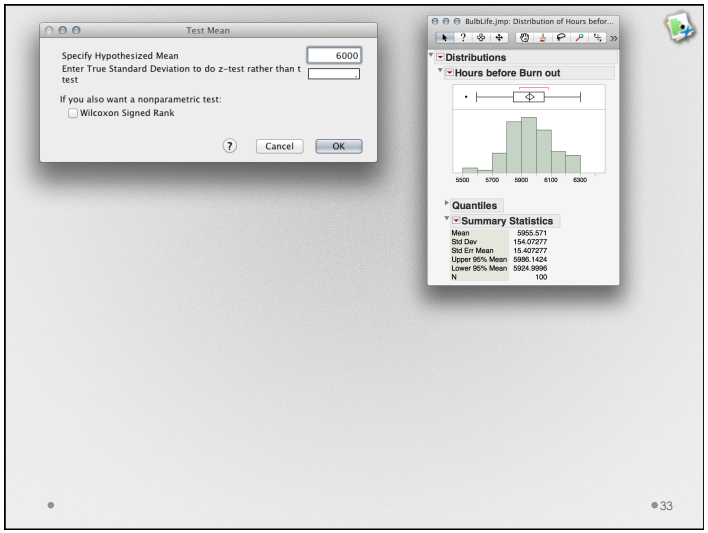
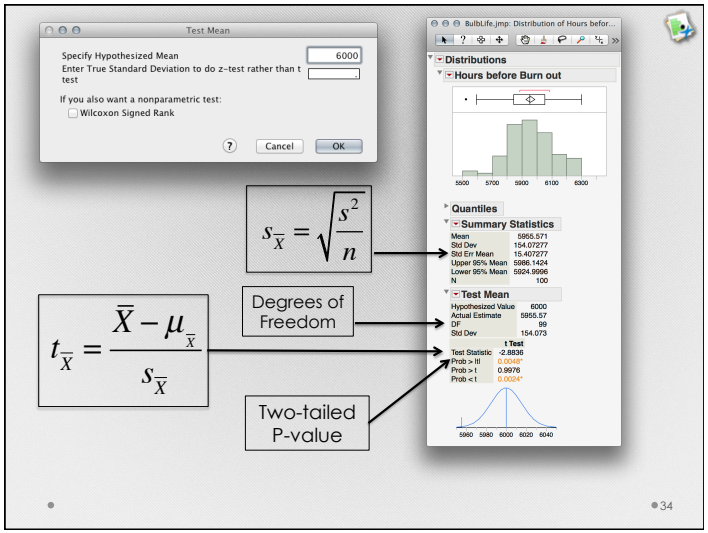


31



32


Test Mean
Specify Hypothesized Mean
6000
Enter True Standard Deviation to do z-test rather than t test
If you also want a nonparametric test:
Wilcoxon Signed Rank
Cancel
OK
Distributions
Hours before Burn out
Quantiles
Summary Statistics
Mean 5955.571
Std Dev 154.07277
Std Err Mean 15.407277
Upper 95% Mean 5986.1424
Lower 95% Mean 5924.9996
N 100
33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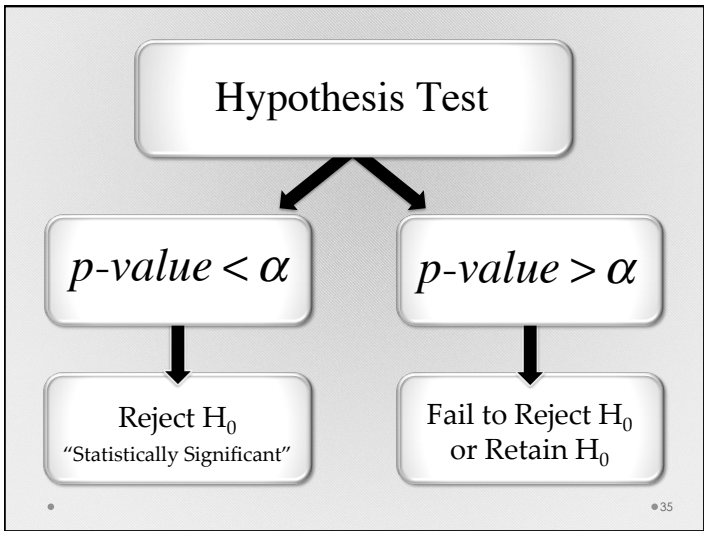
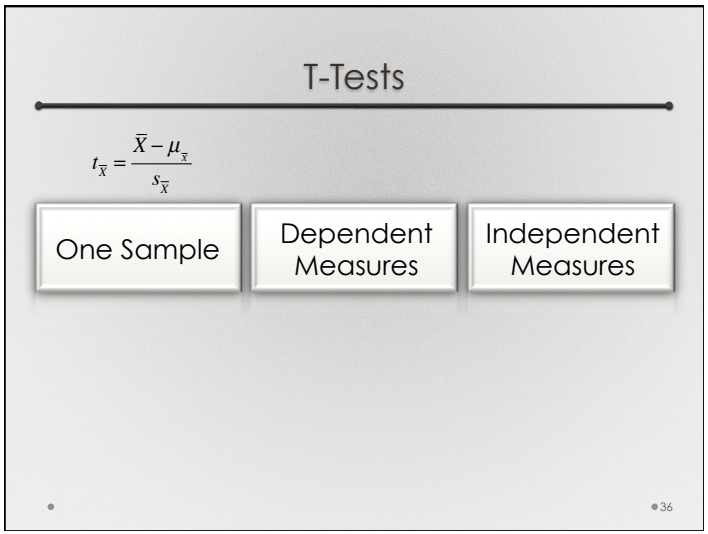
Upper 95% Mean 5986.1424
Lower 95% Mean 5924.9996
N 100
Test Mean
Hypothesized Value 6000
Actual Estimate 5955.57
DF 99
Std Dev 154.073
t Test
Test Statistic -2.8836
Prob > |t| 0.0049*
Prob > t 0.9976
Prob < t 0.0024*
$s_{\bar{X}} = \sqrt{\frac{s^2}{n}}$
$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$
Degrees of Freedom
Two-tailed P-value
34

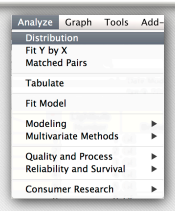

Hypothesis Test
$p\text{-value} < \alpha$
$p\text{-value} > \alpha$
Reject H_0
"Statistically Significant"
Fail to Reject H_0
or Retain H_0
35


T-Tests
$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$
One Sample
Dependent Measures
Independent Measures
36

T-Tests

$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

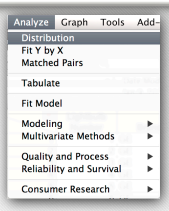
One Sample | Dependent Measures | Independent Measures



T-Tests

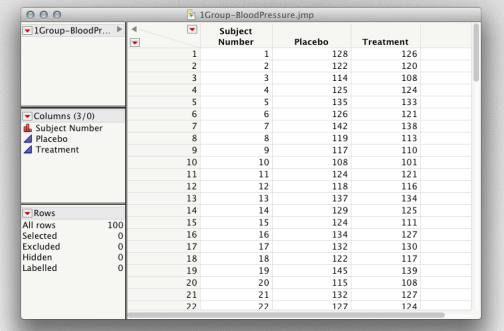
$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

One Sample | Dependent Measures | Independent Measures



1Group-BloodPressure

Effects of Blood Pressure Drug
Pre-Post, Dependent Measures



Single Sample Blood Pressure Drug

T-Statistic, General Form

$$t = \frac{\text{sample statistic - population parameter}}{\text{estimated standard error of statistic}}$$

41

T-Statistic, Dependent Measures

$$t = \frac{\text{sample difference score mean - population difference score mean}}{\text{estimated standard error of difference score mean}}$$

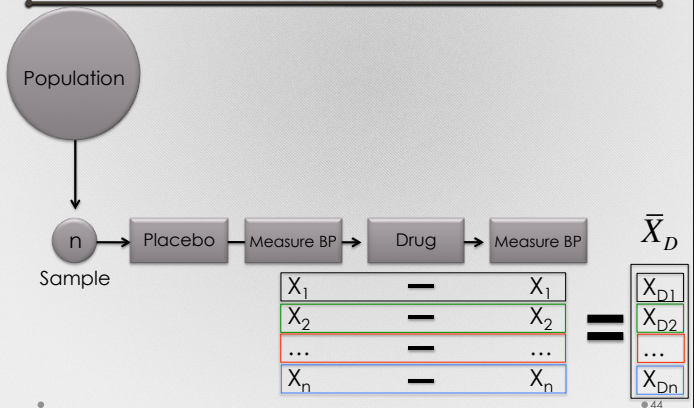
42

T-Statistic, Dependent Measures

$$t = \frac{\bar{X}_D \text{ - population difference score mean}}{\text{estimated standard error of difference score mean}}$$

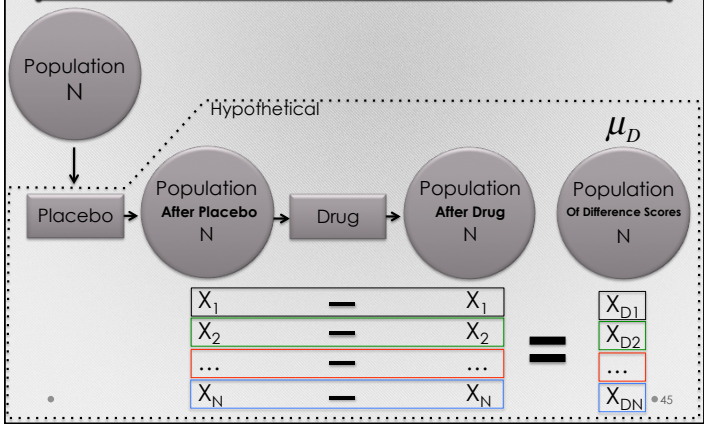
43

Single Sample Blood Pressure Drug



44

Population Representation Blood Pressure Drug



45

T-Statistic, Dependent Measures

$$t = \frac{\bar{X}_D \text{ - population difference score mean}}{\text{estimated standard error of difference score mean}}$$

46

T-Statistic, Dependent Measures

$$t = \frac{\bar{X}_D - \mu_D}{\text{estimated standard error of difference score mean}}$$

47

T-Statistic, Dependent Measures

$$t = \frac{\bar{X}_D - \mu_D}{s_{\bar{X}_D}}$$

48

T-Statistic, One Sample

$$t = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$$

T-Statistic, Dependent Measures

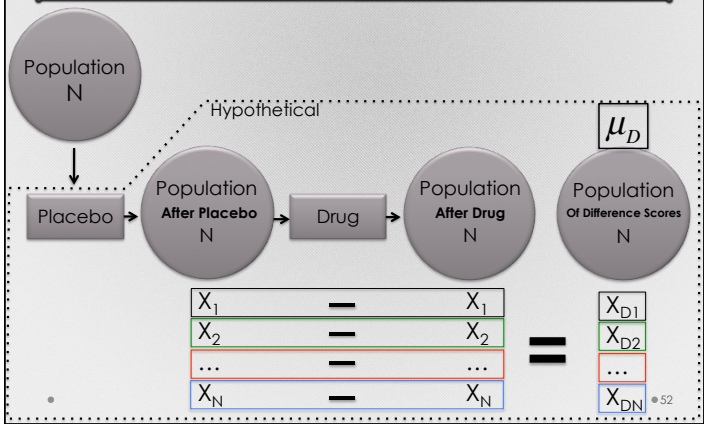
$$t = \frac{\bar{X}_D - \mu_D}{s_{\bar{X}_D}}$$

T-Statistic, Dependent Measures

if H_0 is True
(if there is no effect)

$$t = \frac{\bar{X}_D - \mu_D}{s_{\bar{X}_D}}$$

Population Representation Blood Pressure Drug



T-Statistic, Dependent Measures

if H_0 is True
(if there is no effect)

$$t = \frac{\bar{X}_D - \mu_D}{s_{\bar{X}_D}}$$

53

T-Statistic, Dependent Measures

if H_0 is True
(if there is no effect)

$$t = \frac{\bar{X}_D - 0}{s_{\bar{X}_D}}$$

54

T-Statistic, Dependent Measures

$$t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$$

55

T-Statistic, Dependent Measures

$$t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$$

$$s_{\bar{X}_D} = \sqrt{\frac{s_D^2}{n}}$$

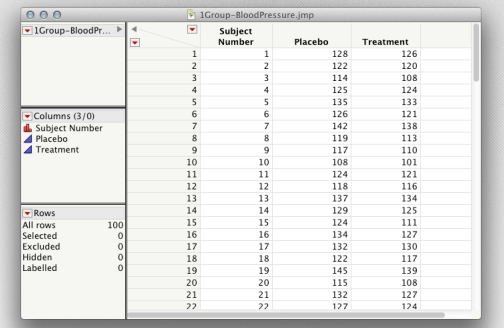
df for $t_{\bar{X}_D} = (n-1)$

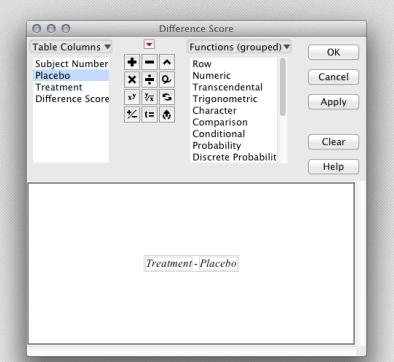
Where n is the number of **difference scores**

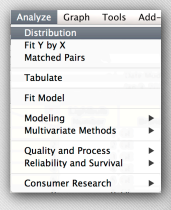
56

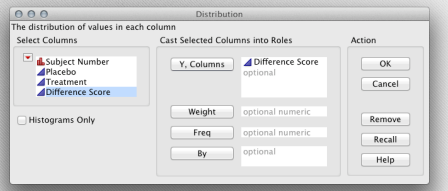
1Group-BloodPressure

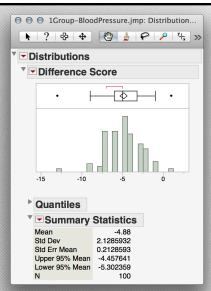
Effects of Blood Pressure Drug
Pre-Post, Dependent Measures

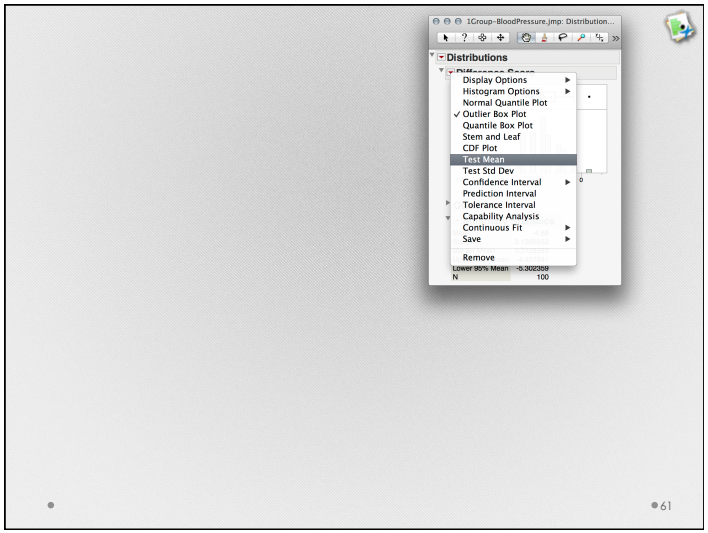


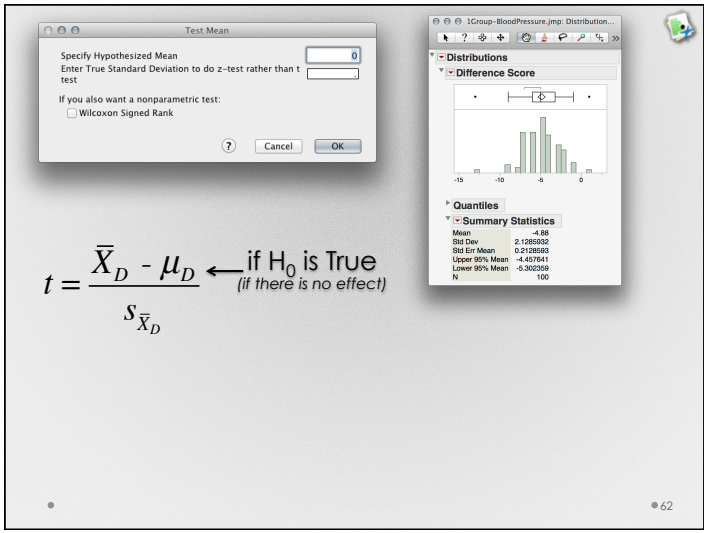


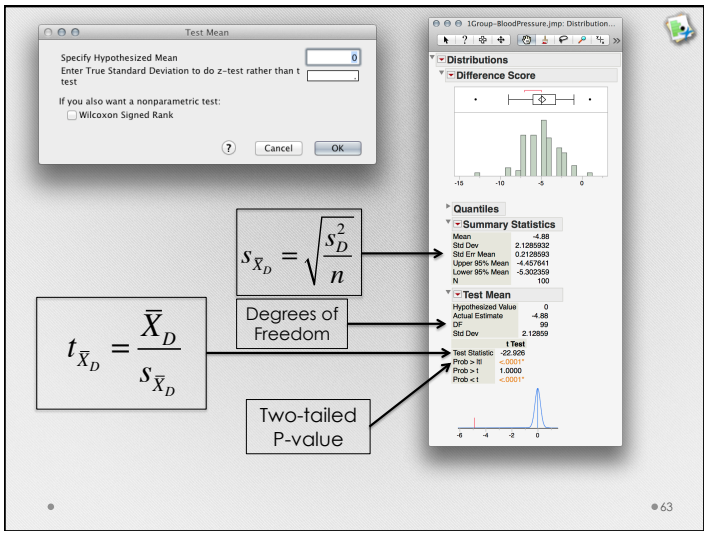







1Group-BloodPressure.jmp: Distribution...
Distributions
Display Options
Histogram Options
Normal Quantile Plot
Outlier Box Plot
Quantile Box Plot
Stem and Leaf
CDF Plot
Test Mean
Test Std Dev
Confidence Interval
Prediction Interval
Tolerance Interval
Capability Analysis
Continuous Fit
Save
Remove
Lower 95% Mean -5.302359
N 100
61


Test Mean
Specify Hypothesized Mean
0
Enter True Standard Deviation to do z-test rather than t test
If you also want a nonparametric test:
Wilcoxon Signed Rank
Cancel
OK
1Group-BloodPressure.jmp: Distribution...
Distributions
Difference Score
Quantiles
Summary Statistics
Mean -4.88
Std Dev 2.1285932
Std Err Mean 0.2128593
Upper 95% Mean -4.457641
Lower 95% Mean -5.302359
N 100
$t = \frac{\bar{X}_D - \mu_D}{s_{\bar{X}_D}}$ ← if H_0 is True (if there is no effect)
62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Wilcoxon Signed Rank
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1Group-BloodPressure.jmp: Distribution...
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Quantiles
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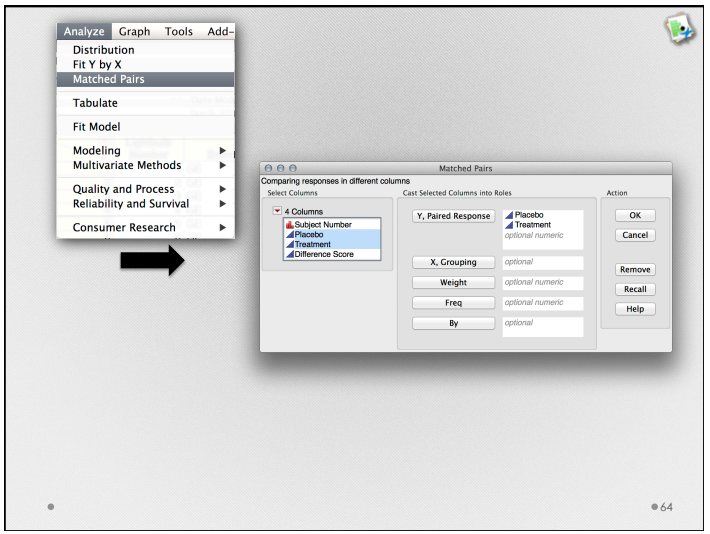
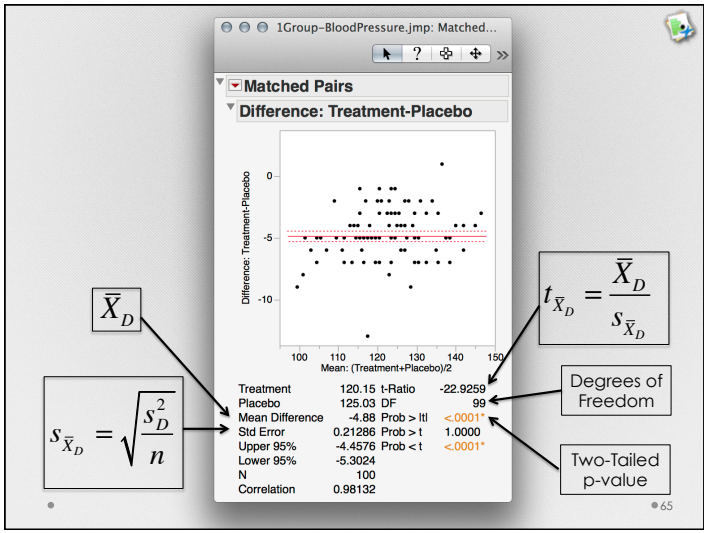
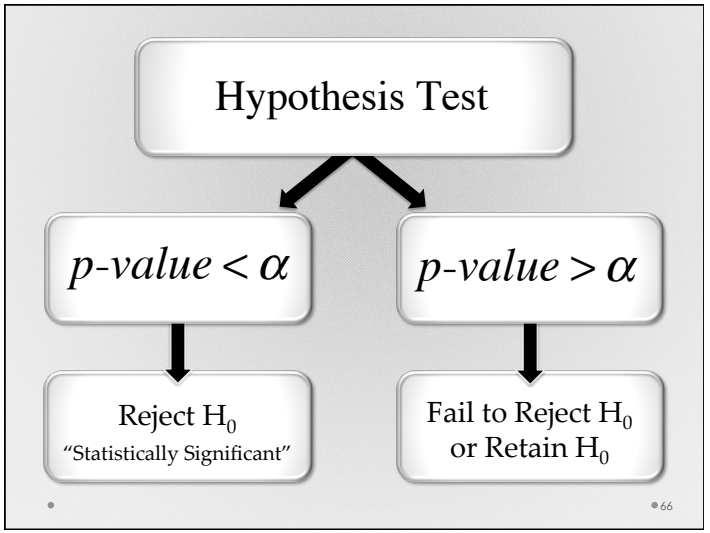
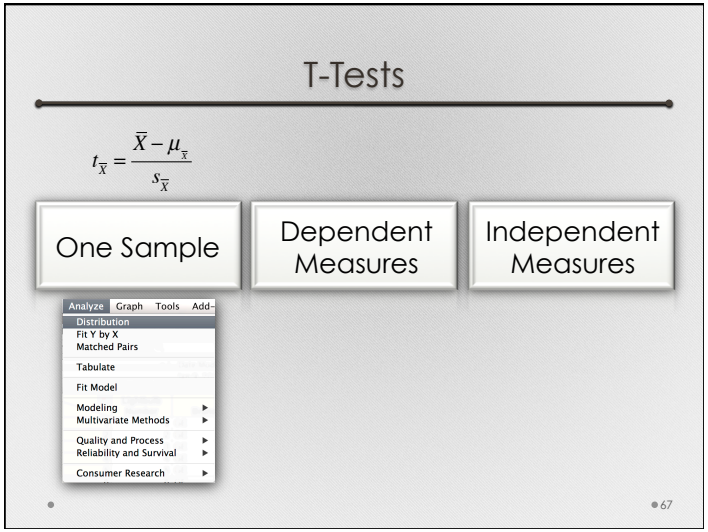
Std Dev 2.1285932
Std Err Mean 0.2128593
Upper 95% Mean -4.457641
Lower 95% Mean -5.302359
N 100
Test Mean
Hypothesized Value 0
Actual Estimate -4.88
DF 99
Std Dev 2.12859
t Test
Test Statistic -22.926
Prob > |t| <.0001*
Prob > t 1.0000
Prob < t <.0001*
$s_{\bar{X}_D} = \sqrt{\frac{s_D^2}{n}}$
Degrees of Freedom
$t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$
Two-tailed P-value
63


Analyze
Graph
Tools
Add-
Distribution
Fit Y by X
Matched Pairs
Tabulate
Fit Model
Modeling
Multivariate Methods
Quality and Process
Reliability and Survival
Consumer Research
Matched Pairs
Comparing responses in different columns
Select Columns
4 Columns
Subject Number
Placebo
Treatment
Difference Score
Cast Selected Columns into Roles
Y, Paired Response
Placebo
Treatment
optional numeric
X, Grouping
optional
Weight
optional numeric
Freq
optional numeric
By
optional
Action
OK
Cancel
Remove
Recall
Help
64


1Group-BloodPressure.jmp: Matched...
Matched Pairs
Difference: Treatment-Placebo
Difference: Treatment-Placebo
Mean: (Treatment+Placebo)/2
Treatment 120.15 t-Ratio -22.9259
Placebo 125.03 DF 99
Mean Difference -4.88 Prob > |t| <.0001*
Std Error 0.21286 Prob > t 1.0000
Upper 95% -4.4576 Prob < t <.0001*
Lower 95% -5.3024
N 100
Correlation 0.98132
$\bar{X}_D$
$s_{\bar{X}_D} = \sqrt{\frac{s_D^2}{n}}$
$t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$
Degrees of Freedom
Two-Tailed p-value
65


Hypothesis Test
$p\text{-value} < \alpha$
$p\text{-value} > \alpha$
Reject H_0
"Statistically Significant"
Fail to Reject H_0 or Retain H_0
66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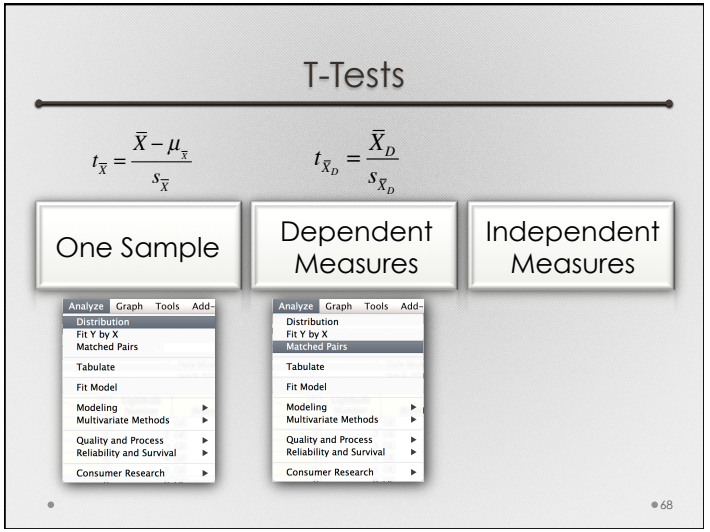
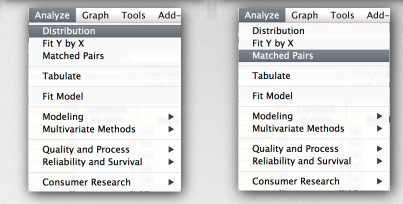
Distribution
Fit Y by X
Matched Pairs
Tabulate
Fit Model
Modeling
Multivariate Methods
Quality and Process
Reliability and Survival
Consumer Research
67


T-Tests
$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}}$
$t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$
One Sample
Dependent Measures
Independent Measures
Analyze Graph Tools Add-
Distribution
Fit Y by X
Matched Pairs
Tabulate
Fit Model
Modeling
Multivariate Methods
Quality and Process
Reliability and Survival
Consumer Research
68

T-Tests

$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}} \qquad t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$$

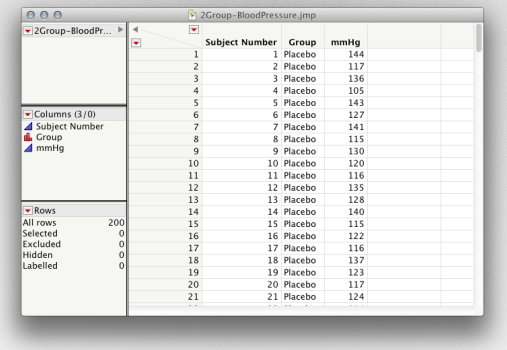
One Sample | Dependent Measures | Independent Measures



69

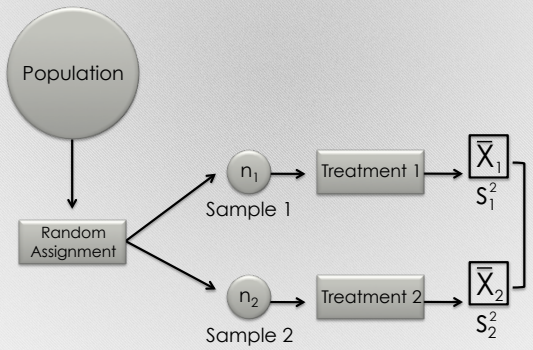
2Group-BloodPressure

Effects of Blood Pressure Drug
Two Groups, Independent Measures



70

Independent Samples Experiment



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T-Statistic, General Form

$$t = \frac{\text{sample statistic - population parameter}}{\text{estimated standard error of statistic}}$$

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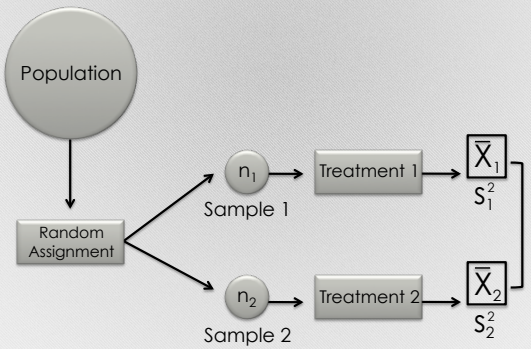
T-Statistic, Two Mean Difference

$$t = \frac{\text{sample mean difference - population mean difference}}{\text{estimated standard error of the mean difference}}$$

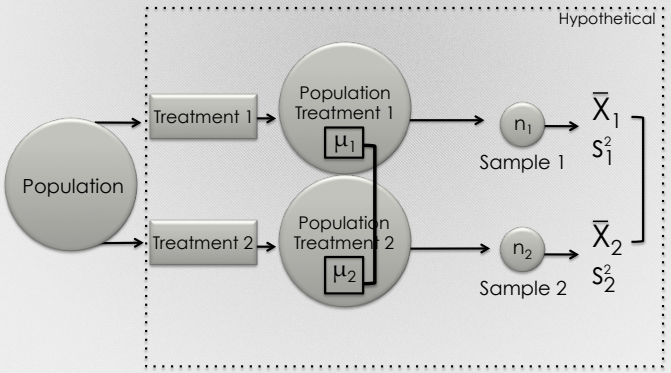
T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2) \text{ - population mean difference}}{\text{estimated standard error of the mean difference}}$$

Independent Samples Experiment



Independent Samples Experiment



T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2) \text{ - population mean difference}}{\text{estimated standard error of the mean difference}}$$

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T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\text{estimated standard error of the mean difference}}$$

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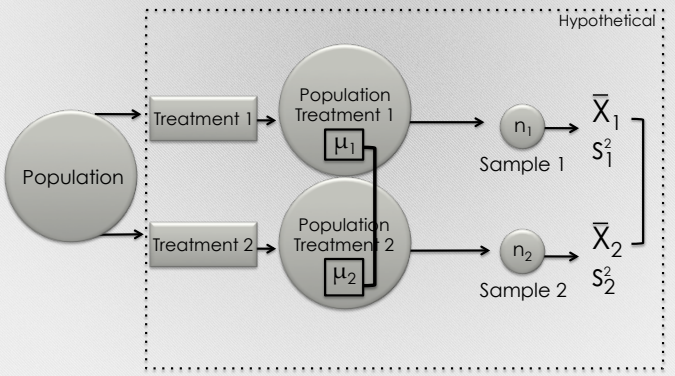
T-Statistic, Two Mean Difference

if H_0 is True
(if there is no effect)

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\text{estimated standard error of the mean difference}}$$

79

Independent Samples Experiment



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If H_0 is True

$$(\mu_1 - \mu_2) = 0$$

T-Statistic, Two Mean Difference

if H_0 is True
(if there is no effect)

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (\mu_1 - \mu_2)}{\text{estimated standard error of the mean difference}}$$

T-Statistic, Two Mean Difference

if H_0 is True
(if there is no effect)

$$t = \frac{(\bar{X}_1 - \bar{X}_2) - (0)}{\text{estimated standard error of the mean difference}}$$

T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{\text{estimated standard error of the mean difference}}$$

T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{\text{estimated standard error of the mean difference}}$$

T-Statistic, Two Mean Difference

$$t = \frac{(\bar{X}_1 - \bar{X}_2)}{s_{(\bar{X}_1 - \bar{X}_2)}}$$

T-Statistic, Two Mean Difference

$$t_{(\bar{X}_1 - \bar{X}_2)} = \frac{(\bar{X}_1 - \bar{X}_2)}{s_{(\bar{X}_1 - \bar{X}_2)}}$$

T-Statistic, Two Mean Difference

$$t_{(\bar{X}_1 - \bar{X}_2)} = \frac{(\bar{X}_1 - \bar{X}_2)}{s_{(\bar{X}_1 - \bar{X}_2)}}$$

Estimate of the Standard Deviation of the Sampling Distribution of the Sample Mean Difference

Independent Samples t-test

- Appropriate for independent-samples or independent-measures designs
  - Treatments are applied to separate groups of people; no person experiences both treatments.
  - Also called a between-subjects design
- Two Varieties
  - Equal Variance Assumed (Pooled T-Test)
  - Equal Variance Not Assumed (Behrens–Fisher problem)

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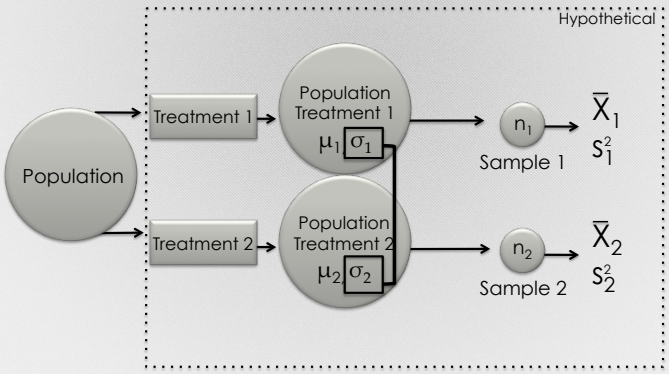
Independent Samples Experiment



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T-Statistic, Two Mean Difference

$$t_{(\bar{X}_1-\bar{X}_2)} = \frac{(\bar{X}_1-\bar{X}_2)}{s_{(\bar{X}_1-\bar{X}_2)}}$$

$$df \text{ for } t_{(\bar{X}_1-\bar{X}_2)} = (n_1-1)+(n_2-1)$$

Equal Variances Assumed

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2Group-BloodPressure

Effects of Blood Pressure Drug
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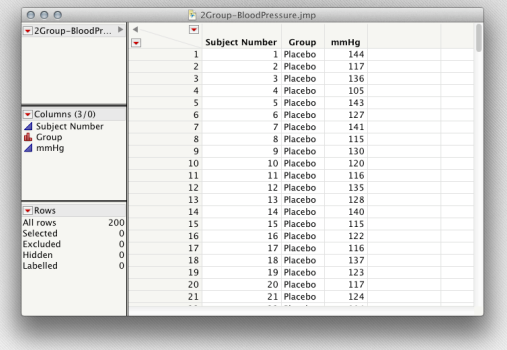
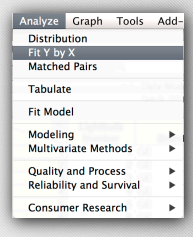
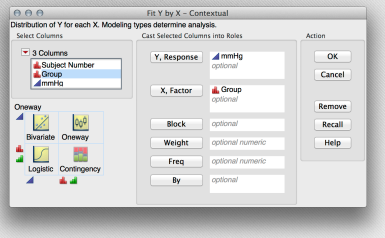
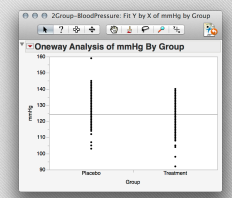
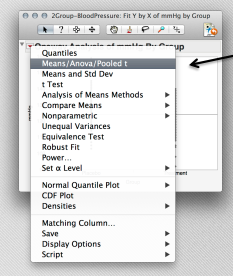


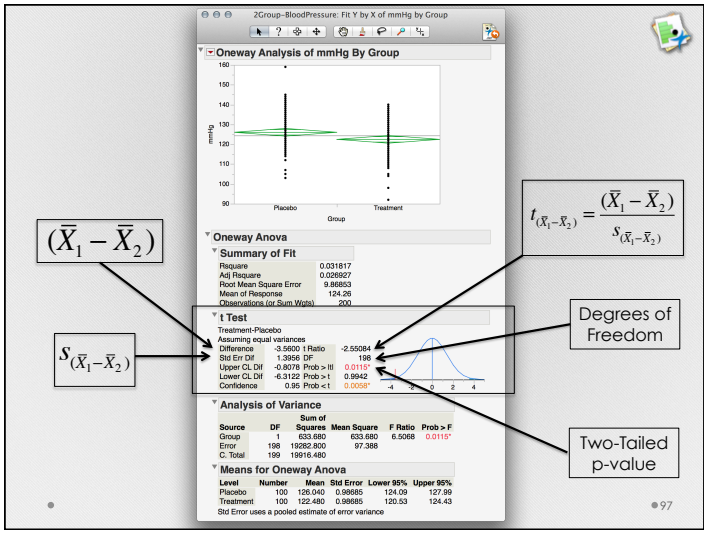


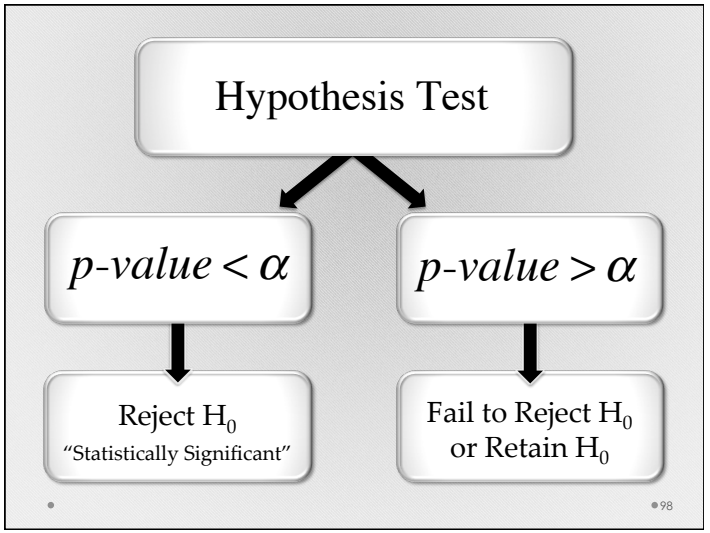






Equal Variance Assumed (Pooled T-Test)





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- Two Varieties
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99

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  - **Equal Variance Not Assumed** (Behrens–Fisher problem)

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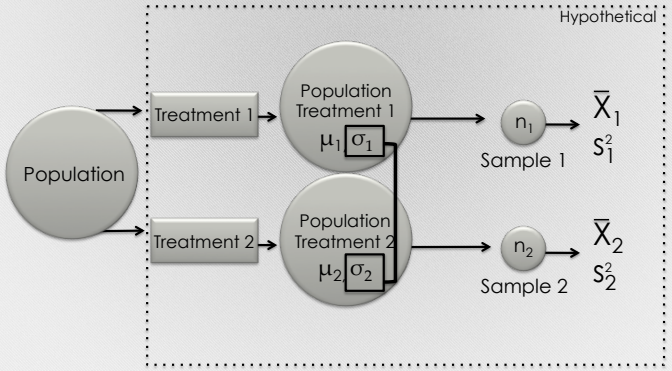
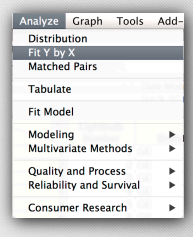
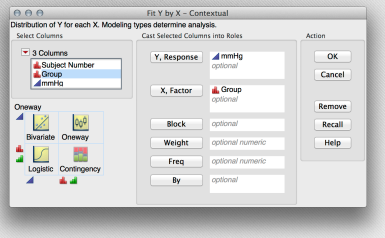
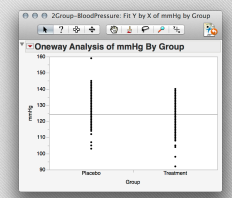
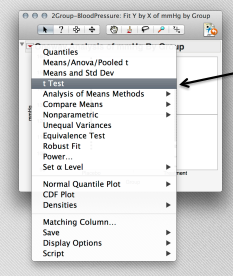
Independent Samples Experiment



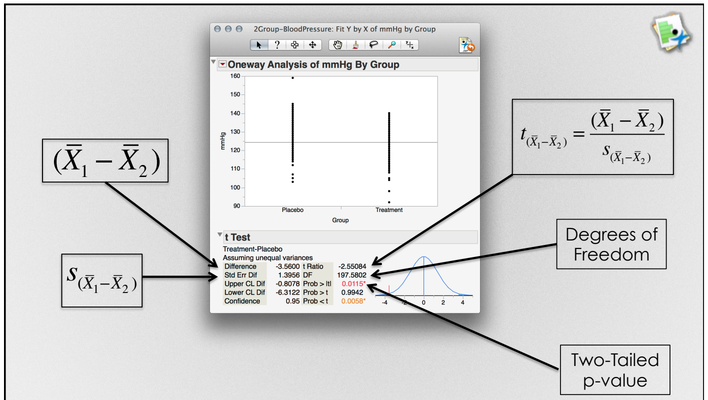








Equal Variance NOT Assumed



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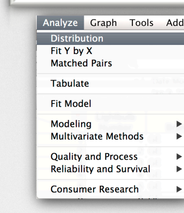
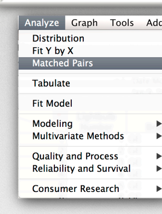
T-Tests

$$t_{\bar{X}} = \frac{\bar{X} - \mu_{\bar{X}}}{s_{\bar{X}}} \qquad t_{\bar{X}_D} = \frac{\bar{X}_D}{s_{\bar{X}_D}}$$

One Sample	Dependent Measures	Independent Measures





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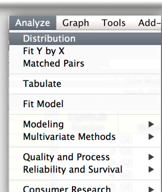

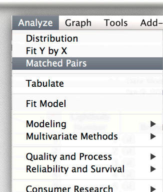

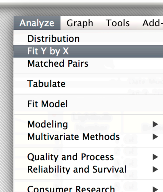

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Advantages of Repeated Measures

- Generally requires fewer subjects
  - Each person is providing two pieces of data
- Well suited for studying changes over time
  - A difference score focuses the question on individual change or growth
- Good for situations where there are large individual differences
  - Each person is their own "baseline"
  - More statistically powerful because the *difference scores* are less variable than the original scores

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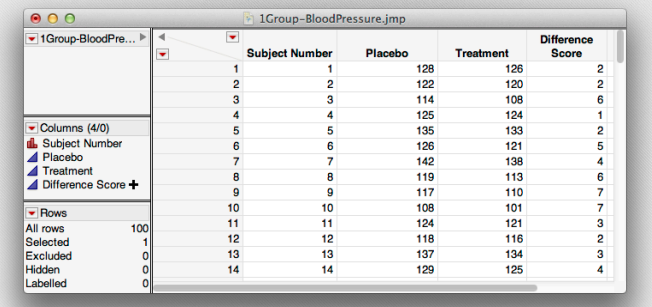

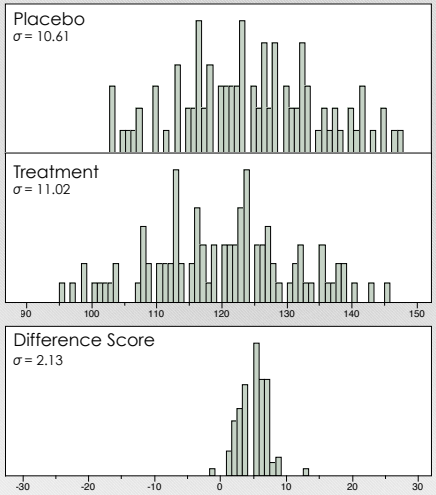

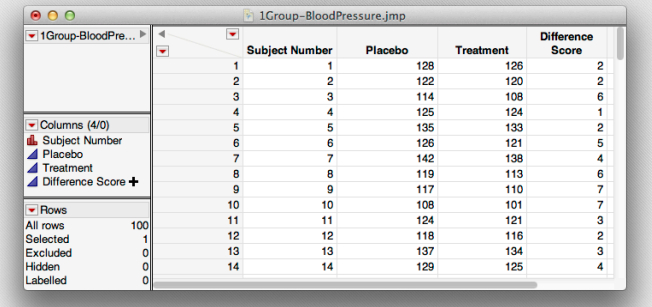

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Problems with Repeated Measures

Potential for carry-over and order effects

- Order effects: One treatment is always second, which means there could be some effect of practice, fatigue, time, etc
- Carry-over effects: One treatment can *leak* (carry-over) its effect into the other treatment

Solutions:

- *Counterbalancing:* switch the order for half of the subjects. Will wash-out small order and carryover effects
- *Use Independent or matched samples.* If order or carryover effects are very strong, cannot use repeated-measures

Questions about the Effect of Some Treatment