

## One-Way Repeated Measures ANOVA

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### Summary

The **One-Way Repeated Measures ANOVA** procedure analyzes experimental designs in which multiple measurements have been made on the same subjects. In many cases, the measurements are taken sequentially in order to examine how the effect of some treatment varies over time. The need for a special procedure stems from potential dependence between observations made on a given subject.

Included in the procedure is Mauchley’s test for *sphericity*, which is a condition requiring that the variance between any two estimated treatment means be the same. Corrections to the standard F-test are included for cases when sphericity is not present.

This procedure requires that the data be balanced: each subject must have one and only one measurement at each level of the condition that differentiates the multiple measurements.

**Sample StatFolio:** *repeat1.sgp*

## Sample Data

The file *repeat1.sgd* contains the results of an experiment reported by Milliken and Johnson (1984) in which 8 patients were given a drug that was known to affect their heart rate. Each patient's heart rate was measured 4 times at 5-minute increments after the drug was administered. The data are shown below:

<i>Patient</i>	<i>T1</i>	<i>T2</i>	<i>T3</i>	<i>T4</i>
1	72	86	81	77
2	78	83	88	81
3	71	82	81	75
4	72	83	83	69
5	66	79	77	66
6	74	83	84	77
7	62	73	78	70
8	69	75	76	70

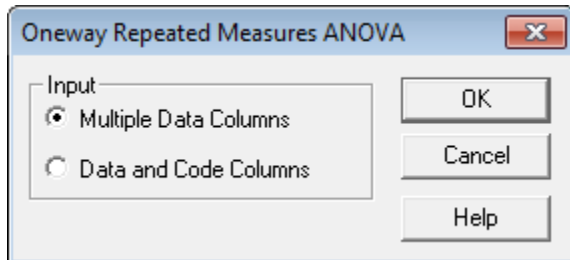
Primary interest centers on comparing the mean heart rates at different points in time.

The layout of the data above is referred to as a “multiple data column” structure. Alternatively, the data could be entered using a single column for all measurements, using a “data and code column” structure as shown below:

<i>Patient</i>	<i>Time</i>	<i>Heart Rate</i>
1	T1	72
1	T2	86
1	T3	81
1	T4	77
2	T1	78
2	T2	83
2	T3	88
2	T4	81
3	T1	71
3	T2	82
3	T3	81
3	T4	75
...	...	...

## Data Input

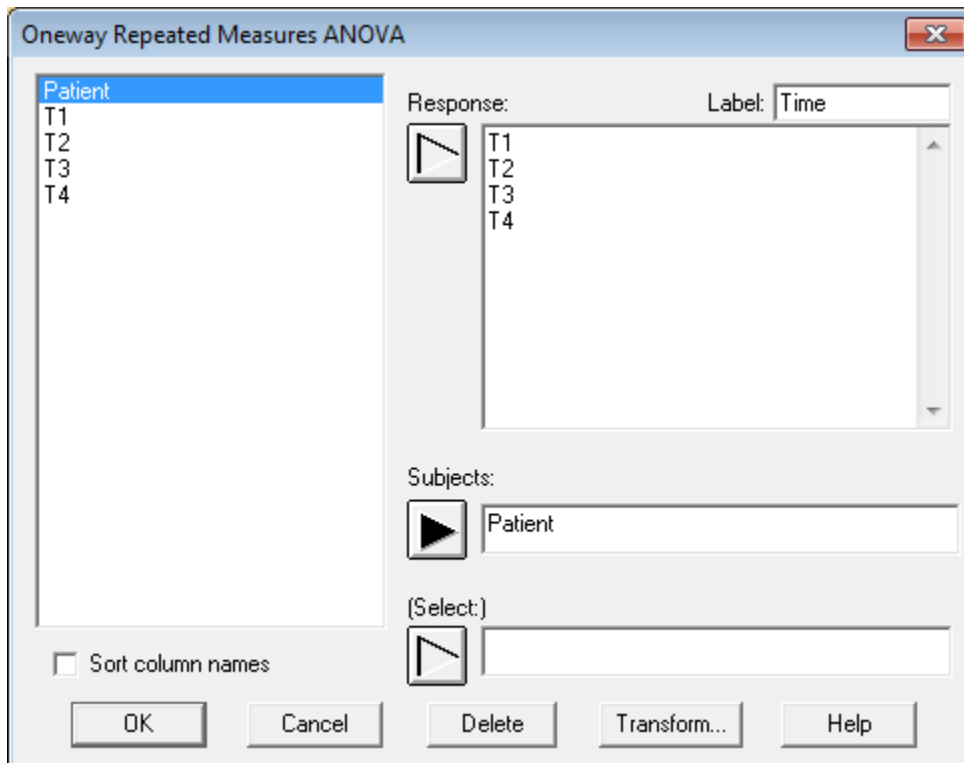
When the *Oneway Repeated Measures ANOVA* procedure is selected from the main menu, an initial dialog box is displayed on which to indicate how the data have been entered:



- **Multiple Data Columns:** indicates that each measurement taken from the same subject has been placed into a separate column.
- **Data and Code Columns:** indicates that all measurements have been placed into a single column, with a second column indicating which subject each observation comes from.

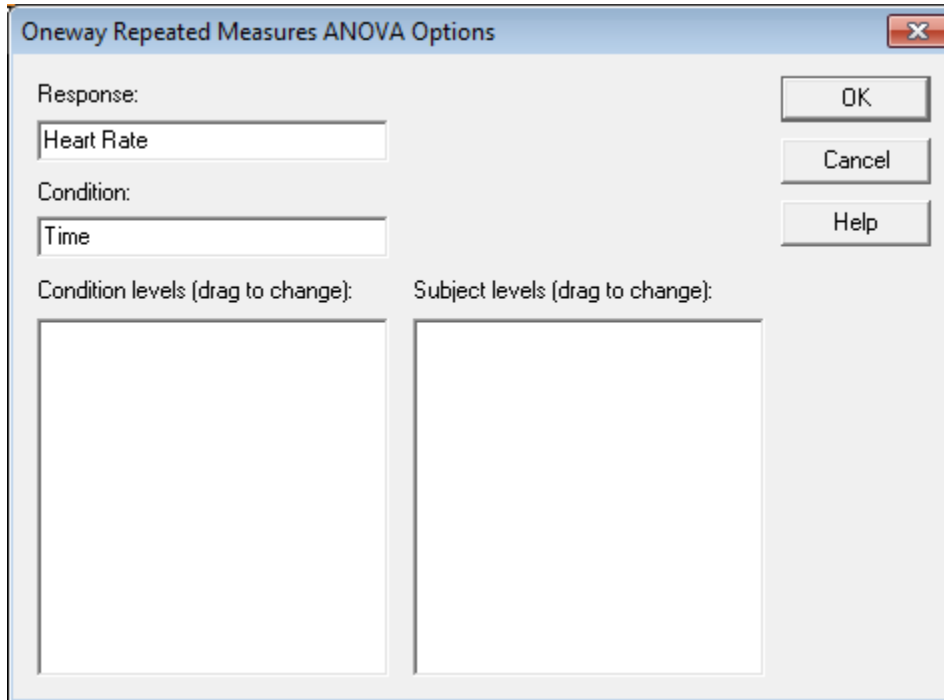
### Multiple Data Columns

If the data have been placed in separate columns for each subject, the column names must be entered on the second dialog box:



- **Response:** two or more numeric columns containing the measurements, one column for each sample.
- **Subjects:** numeric or non-numeric column identifying the subjects.
- **Select:** subset selection.

After pressing *OK*, the *Analysis Options* dialog box is displayed on which names may be entered for the response variable and the condition variable:



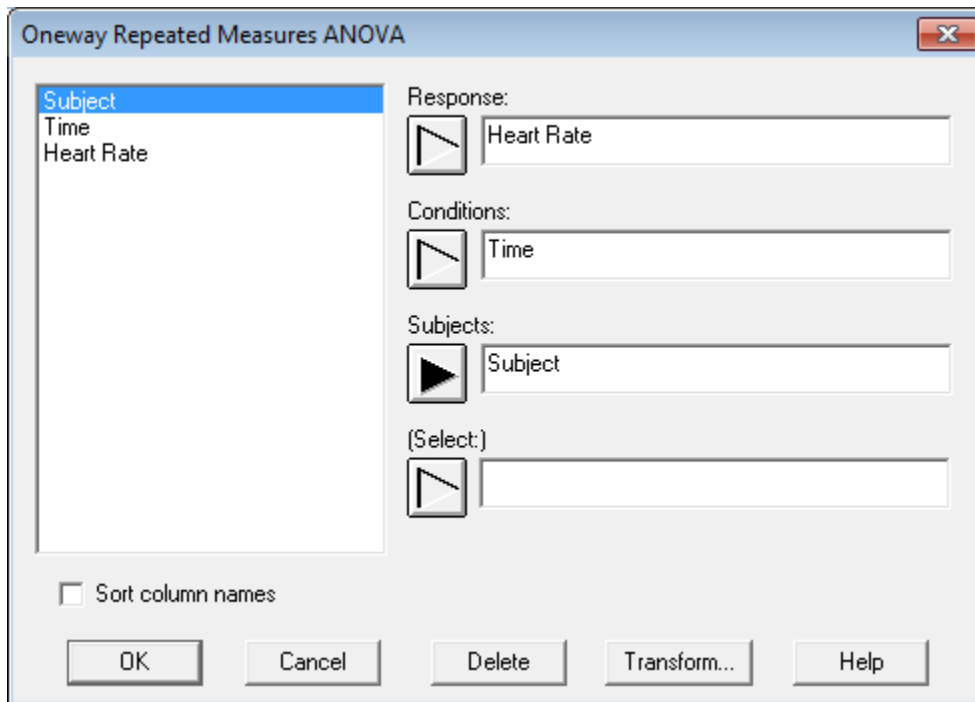
The screenshot shows a dialog box titled "Oneway Repeated Measures ANOVA Options". It has a standard Windows-style title bar with a close button (X). The dialog contains the following elements:

- Response:** A text input field containing "Heart Rate".
- Condition:** A text input field containing "Time".
- Buttons:** Three buttons are stacked vertically on the right side: "OK", "Cancel", and "Help".
- Condition levels (drag to change):** An empty rectangular box.
- Subject levels (drag to change):** An empty rectangular box.

These names will be used in the output tables and graphs. Note: the *levels* fields will be populated once the data are read.

Data and Code Columns

If the data from all subjects have been placed into a single column, enter the name of that column and the column identifying the factor levels:



- **Response:** numeric column containing the observations from all subjects.
- **Conditions:** numeric or non-numeric column containing an identifier for the condition corresponding to each data value.
- **Subjects:** numeric or non-numeric column identifying the subjects.
- **Select:** subset selection.

## Analysis Summary

The *Analysis Summary* shows the results of the analysis of variance:

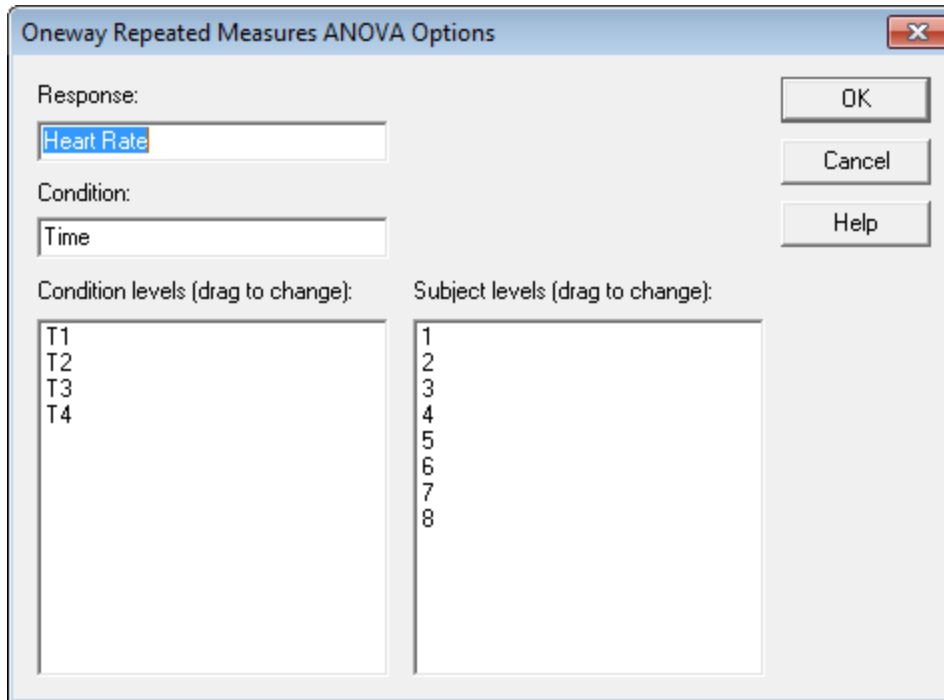
<u>Oneway Repeated Measures ANOVA</u>					
Time: T1 - T4					
Subjects: Patient					
<b>Analysis of Variance for Heart Rate</b>					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Model	1150.81	10	115.081	20.20	0.0000
Residual	119.656	21	5.69792		
Total (Corr.)	1270.47	31			
<b>Factor Sums of Squares</b>					
Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Time	667.594	3	222.531	39.05	0.0000
Patient	483.219	7	69.0312	12.12	0.0000
Error(Time)	119.656	21	5.69792		
Total (corrected)	1270.47	31			
Standard Error of Est. = 2.38703					

The most important statistic is the F-Ratio for *Time*, which equals 39.05 for the sample data. If the P-Value associated with that F statistic is small (less than 0.05 if operating at the 5% significance level), then there is a statistically significant difference between the *time* level means.

It should be noted that the P-Value for *Time* shown in this table is only appropriate if the data exhibit a property known as *sphericity*. Sphericity is present if the variance of the difference between any pair of estimated level means is the same. A later section shows how to test the assumption of sphericity and how to correct for its absence if necessary.

## Analysis Options

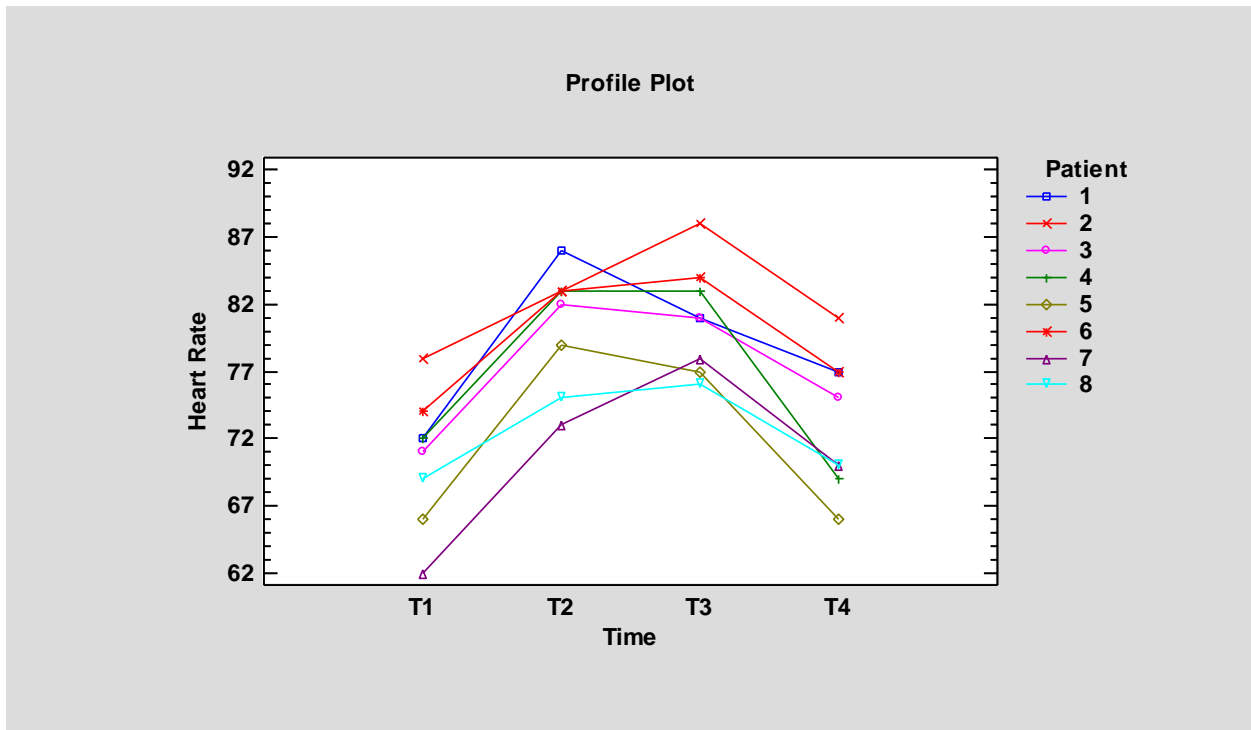
After the initial summary has been displayed, the *Analysis Options* dialog box may be used to reorder the factor levels:



To change the order of the condition or subject levels, drag them to new positions with your mouse.

## Profile Plot

The *Profile Plot* displays the data by condition level and subject:



It will be noticed that for the sample data, the heart rate rises between time T1 and T2 and falls between time T3 and T4. The difference between time T2 and T3 is less obvious.



## Sphericity Tests and Adjustments

As mentioned earlier, the F-test for treatment differences requires that a condition known as sphericity be present. This pane conducts a test known as Mauchly’s test to determine whether the assumption of sphericity is violated. It generates the following output:

<b>Sphericity Tests and Adjustments</b>						
Mauchly's Sphericity Test						
<i>W</i>	<i>Chi-square</i>	<i>D.f.</i>	<i>P-value</i>			
0.712325	1.9411	5.0	0.857233			
Epsilon						
<i>Huynh-Feldt</i>	<i>Greenhouse-Geisser</i>	<i>Lower-bound</i>				
1.0	0.804865	0.333333				
Tests of Within-Patient Effects						
<i>Source</i>	<i>Sphericity Correction</i>	<i>Sum of Squares</i>	<i>Df</i>	<i>Mean Square</i>	<i>F-Ratio</i>	<i>P-Value</i>
Time	None	667.594	3.0	222.531	39.05	0.0000
	Huynh-Feldt	667.594	3.0	222.531	39.05	0.0000
	Greenhouse-Geisser	667.594	2.41459	276.483	39.05	0.0000
	Lower-bound	667.594	1.0	667.594	39.05	0.0004
Error(Time)	None	119.656	21.0	5.69792		
	Huynh-Feldt	119.656	21.0	5.69792		
	Greenhouse-Geisser	119.656	16.9022	7.07935		
	Lower-bound	119.656	7.0	17.0937		
Multivariate Tests						
<i>Test</i>	<i>Value</i>	<i>F</i>	<i>Hypothesis D.F.</i>	<i>Error D.F.</i>	<i>P-Value</i>	
Wilks' lambda	0.0387258	41.371	3.0	5.0	0.0006	
Pillai trace	0.961274	41.371	3.0	5.0	0.0006	
Hotelling-Lawley trace	24.8226	41.371	3.0	5.0	0.0006	
Roy's largest root	24.8226	41.371	3.0	5.0	0.0006	

The top section shows the results of Mauchley’s sphericity test. Mauchley’s test calculates the test statistic  $W$  defined by:

$$W = \frac{\det(A)}{(\text{trace}(A) / d)^d} \tag{1}$$

where  $A = M^T S M$ ,  $S$  is the error sum of squares and cross product matrix, and  $M$  is an orthonormal matrix based on the within-subject effects being tested. A chi-square statistic is then calculated from

$$\chi^2 = \left( \frac{2d^2 + d + 2}{6d} - n - q \right) \log(W) \tag{2}$$

where  $q$  is the number of measurements made on each subject and  $d = q - 1$ .  $\chi^2$  is compared to a chi-square distribution with  $d(d+1)/2 - 1$  degrees of freedom. If the P-Value for Mauchley’s test is small, then the sphericity assumption is rejected. For the sample data, P is well above 0.10, so the sphericity assumption is not rejected at the 10% level of significance.

If sphericity is not present, the degrees of freedom for the F-test may be adjusted by multiplying them by an adjustment factor  $\varepsilon$ . The output shows the results of F-tests using three possible values for  $\varepsilon$  (from least conservative to most conservative):

$$\text{Huynh-Feldt: } \varepsilon_{hf} = \min\left(\frac{nd\varepsilon_{gg} - 2}{d(n-q) - d^2\varepsilon_{gg}}, 1\right) \quad (3)$$

$$\text{Greenhouse-Geisser: } \varepsilon_{gg} = \frac{(\text{trace}(A))^2}{d \times \text{trace}(A^T A)} \quad (4)$$

$$\text{Lower-Bound: } \varepsilon_{lb} = \frac{1}{d} \quad (5)$$

The lower-bound correction is the most severe, but is rarely used. The Greenhouse-Geisser correction is less conservative, but may still overcorrect the degrees of freedom when epsilon is close to 1. The Huynh-Feldt version is less conservative and may be preferable when the true epsilon is 0.75 or higher.

The bottom section shows several tests of the hypothesis that the means at each level of the within-subject factor are all the same, calculated by performing a multivariate analysis of variance (MANOVA) on differences between the level means. The tests do not assume the existence of sphericity and are thus correct regardless of whether that condition exists. If sphericity is present, however, they may not be as powerful as the usual univariate F test. For the sample data, the small P-values for the multivariate tests indicate that there are significant differences among the means at the 4 levels of *time*. Further details about the four tests may be found in the documentation for the *General Linear Models* analysis.

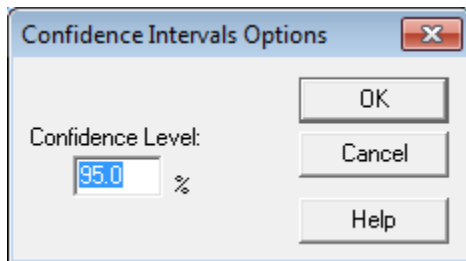
## Means Table

This pane displays the estimated means at each condition, together with estimated standard errors and confidence intervals.

			<i>Std.</i>	<i>Lower</i>	<i>Upper</i>
<i>Level</i>	<i>Count</i>	<i>Mean</i>	<i>Error</i>	<i>Limit</i>	<i>Limit</i>
GRAND MEAN	32	76.2813	0.421971	75.4037	77.1588
Time					
T1	8	70.5	0.843943	68.7449	72.2551
T2	8	80.5	0.843943	78.7449	82.2551
T3	8	81.0	0.843943	79.2449	82.7551
T4	8	73.125	0.843943	71.3699	74.8801

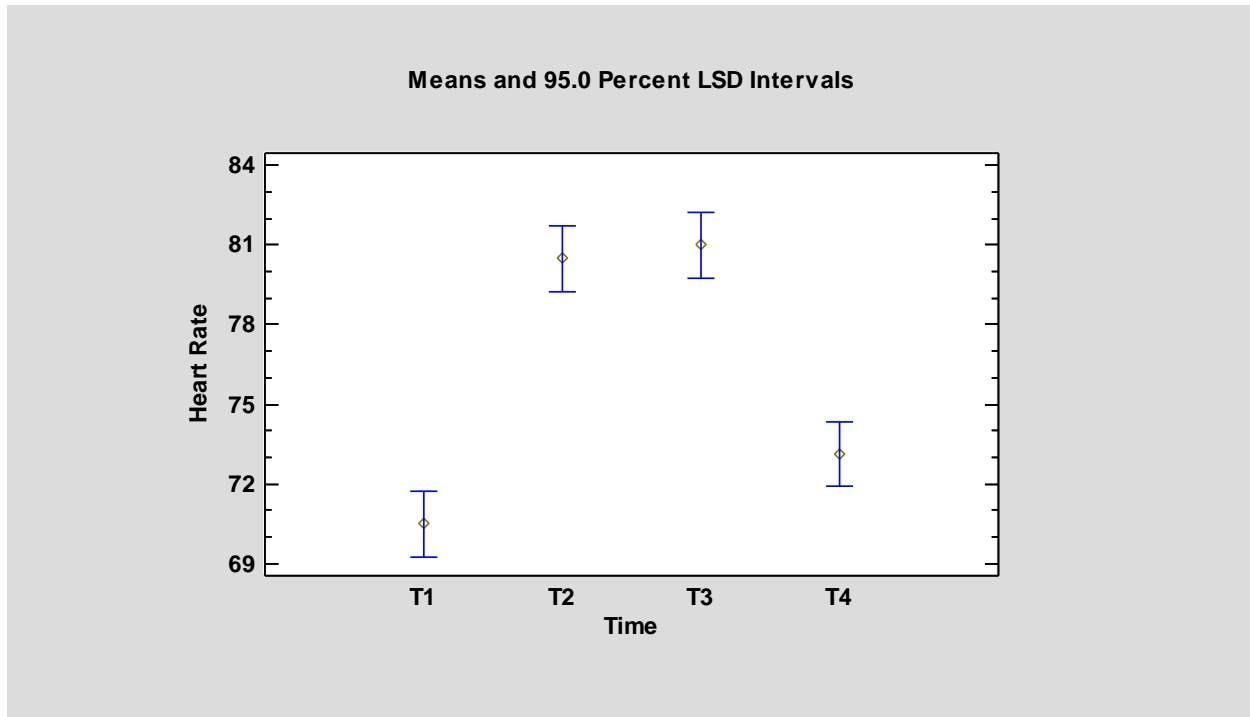
### Pane Options

You may use this dialog box to change the confidence level:



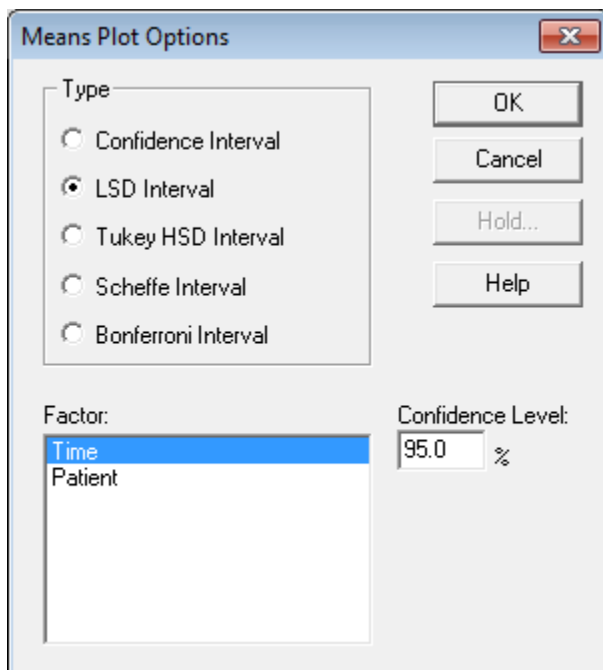
## Means Plot

The level means may be plotted together with uncertainty intervals:



The type of intervals displayed is controlled by the *Pane Options* dialog box.

### *Pane Options*



- **Type:** the method used to construct the intervals.

- **Factor:** the factor to be plotted.
- **Confidence Level:** the level of confidence associated with each interval.

The type of intervals that may be selected are:

*Confidence intervals* - displays confidence intervals for the level means using the estimated standard errors.

*LSD intervals* - designed to compare any pair of means with the stated confidence level.

*Tukey HSD Intervals* - designed for comparing all pairs of means. The stated confidence level applies to the entire family of pairwise comparisons.

*Scheffe Intervals* - designed for comparing all contrasts. Not usually relevant here.

*Bonferroni Intervals* - designed for comparing a selected number of contrasts. Tukey's intervals are usually tighter.

Each of the intervals is formed by adding a multiple of the least squares standard error to the estimated mean. The multiple depends upon the method used, as described in the *Oneway ANOVA* documentation.

## Multiple Range Tests

For factors that shows significant P-Values in the ANOVA, a further analysis can be performed by selecting the *Multiple Range Tests*.

Multiple Comparisons for Heart Rate by Time				
Method: 95.0 percent LSD				
Time	Count	LS Mean	LS Sigma	Homogeneous Groups
T1	8	70.5	0.843943	X
T4	8	73.125	0.843943	X
T2	8	80.5	0.843943	X
T3	8	81.0	0.843943	X

Contrast	Sig.	Difference	+/- Limits
T1 - T2	*	-10.0	2.48206
T1 - T3	*	-10.5	2.48206
T1 - T4	*	-2.625	2.48206
T2 - T3		-0.5	2.48206
T2 - T4	*	7.375	2.48206
T3 - T4	*	7.875	2.48206

\* denotes a statistically significant difference.

The top half of the table displays each of the estimated level means in increasing order of magnitude. It shows:

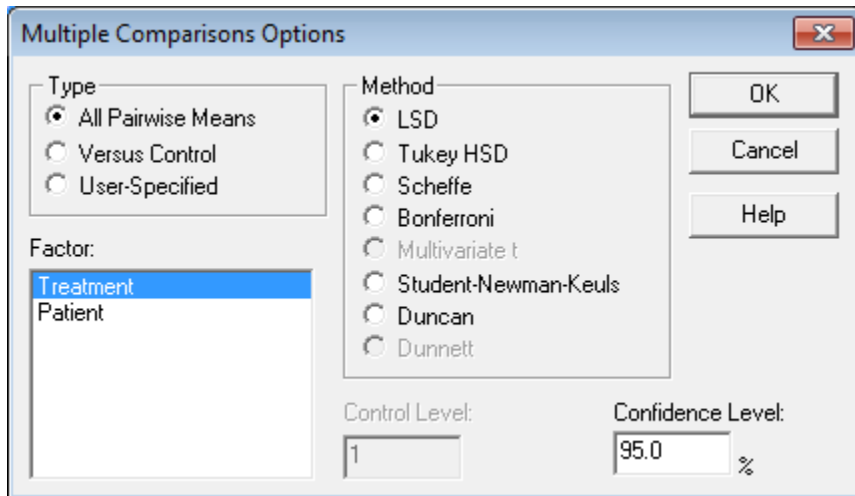
- **Count** - the number of observations at the specified level of the factor.
- **LS Mean** - the estimated least squares mean. In balanced designs such as these, the least squares mean is equivalent to the average of all observations at the indicated factor level.
- **LS Sigma** – the estimated standard error of the least squares mean.
- **Homogeneous groups** - a graphical illustration of which means are significantly different from which others, based on the contrasts displayed in the second half of the table. Each column of X's indicates a group of means within which there are no statistically significant differences. In the example, there are 3 columns of X's. The first column contains an X for time T1 only, indicating that it is significantly different than all of the other times. Time T4 is also in a column by itself, also significantly different than all of the other times. However, times T2 and T3 have an X in the same column, indicating that they are not significantly different.

The second half of the table displays a comparison between each pair of level means.

- **Difference** - the difference between the two least squares means.
- **Limits** - an interval estimate of that difference, using the currently selected multiple comparisons procedure.

- **Sig.** - An asterisk is placed next to any difference that is statistically significantly different from 0 at the currently selected significance level, i.e., any interval that does not contain 0.

### Pane Options



- **Type:** type of contrasts to be created.
- **Factor:** factor to be analyzed.
- **Method:** the method used to make the multiple comparisons.
- **Control Level:** if *Type* is set to *Versus Control*, the number of the level against which all other levels will be compared.
- **Confidence Level:** the level of confidence used by the selected multiple comparison procedure.

The available methods are:

**LSD** - forms a confidence interval for each pair of means at the selected confidence level using Student's t distribution. This procedure is due to Fisher and is called the *Least Significant Difference* procedure, since the magnitude of the limits indicates the smallest difference between any two means that can be declared to represent a statistically significant difference. It should only be used when the F-test in the ANOVA table indicates significant differences amongst the level means. The probability of making a Type I error  $\alpha$  applies to each pair of means separately. If making more than one comparison, the overall probability of calling at least one pair of means significantly different when they are not may be considerably larger than  $\alpha$ .

**Tukey HSD** - widens the intervals to allow for multiple comparisons amongst all pairs of means using Tukey's T. Tukey called his procedure the *Honestly Significant Difference* procedure since it controls the experiment-wide error rate at  $\alpha$ . If all of the means are equal, the probability of declaring *any* of the pairs to be significantly different in the entire

experiment equals  $\alpha$ . Tukey's procedure is more conservative than Fisher's LSD procedure, since it makes it harder to declare any particular pair of means to be significantly different.

**Scheffe** - designed to permit the estimation of all possible contrasts amongst the sample means (not just pairwise comparisons).

**Bonferroni** - designed to permit the estimation of any preselected number of contrasts. These limits are usually wider than Tukey's limits when all pairwise comparisons are being made.

**Multivariate  $t$**  – designed for sets of linearly independent combinations of the means.

**Student-Newman-Keuls** - Unlike the previous methods, this method does not create intervals for the pairwise differences. Instead, it sorts the means in increasing order and then begins to separate them into groups according to values of the Studentized range distribution. Eventually, the means are separated into homogeneous groups within which there are no significant differences.

**Duncan** - similar to the Student-Newman-Keuls procedure, except that it uses a different critical value of the Studentized range distribution when defining the homogeneous groups. A detailed discussion of the Duncan and Student-Newman-Keuls procedures is given by Milliken and Johnson (1992).

**Dunnett** – designed for pairwise comparisons when one level is a control.

For details on creating a user-specified contrast, refer to the *General Linear Models* procedure documentation.



## Trend Analysis

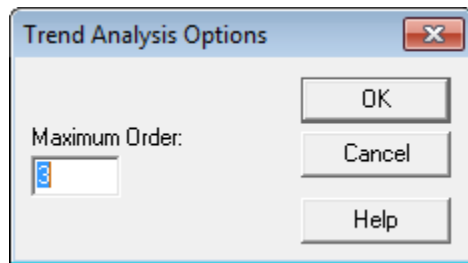
If the order of the conditions has meaning, as it does for the sample data, the pattern of the means exhibited in the *Profile Plot* can be examined using a trend analysis. A trend analysis uses orthogonal polynomials to decompose the pattern of the means into linear, quadratic, cubic and higher order components. It produces a table similar to that shown below:

Trend Analysis				
<i>Trend</i>	<i>Contrast</i>	<i>Std. error</i>	<i>t</i>	<i>P-value</i>
linear	1.87271	0.843943	2.22	0.0376
quadratic	-8.9375	0.843943	-10.59	0.0000
cubic	0.251558	0.843943	0.30	0.7686

Small P-Values suggest the need for a trend component of the order indicated.

For the sample data, both the linear and quadratic components have P-values less than 0.05. This indicates that the curvature over time evident in the *Profile Plot* is statistically significant. For the drug being studied, there is thus strong evidence that the heart rate rises and then comes back down.

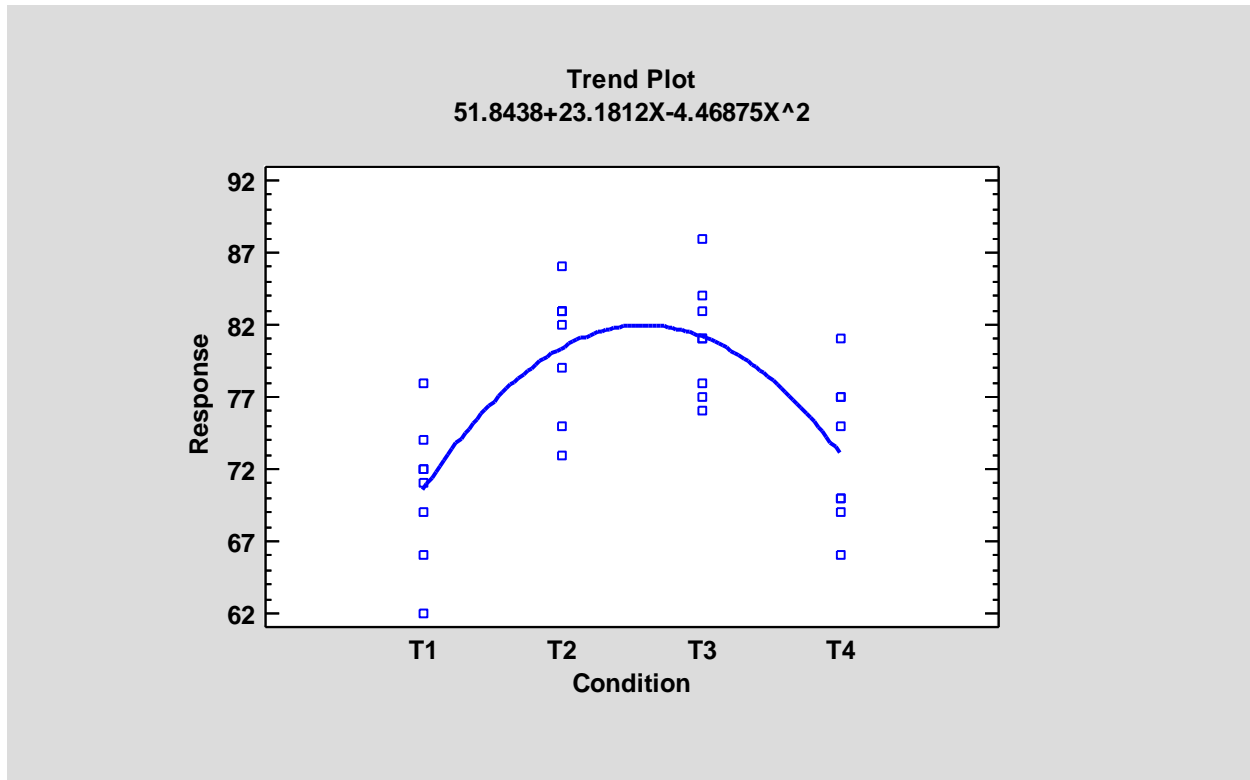
### Pane Options



*Maximum Order*: maximum order component to be included in table (cannot exceed the number of levels of the repeated measures factor minus 1).

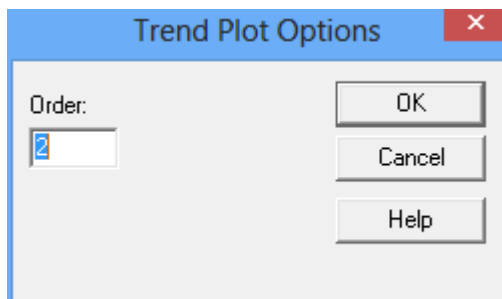
## Trend Plot

This pane plots polynomials fitted to the means at each level of the repeated measures factor. The plot below shows a quadratic model fitted to the sample data:



In fitting the equation, X is set to 1 for the first level, 2 for the second level, and so on.

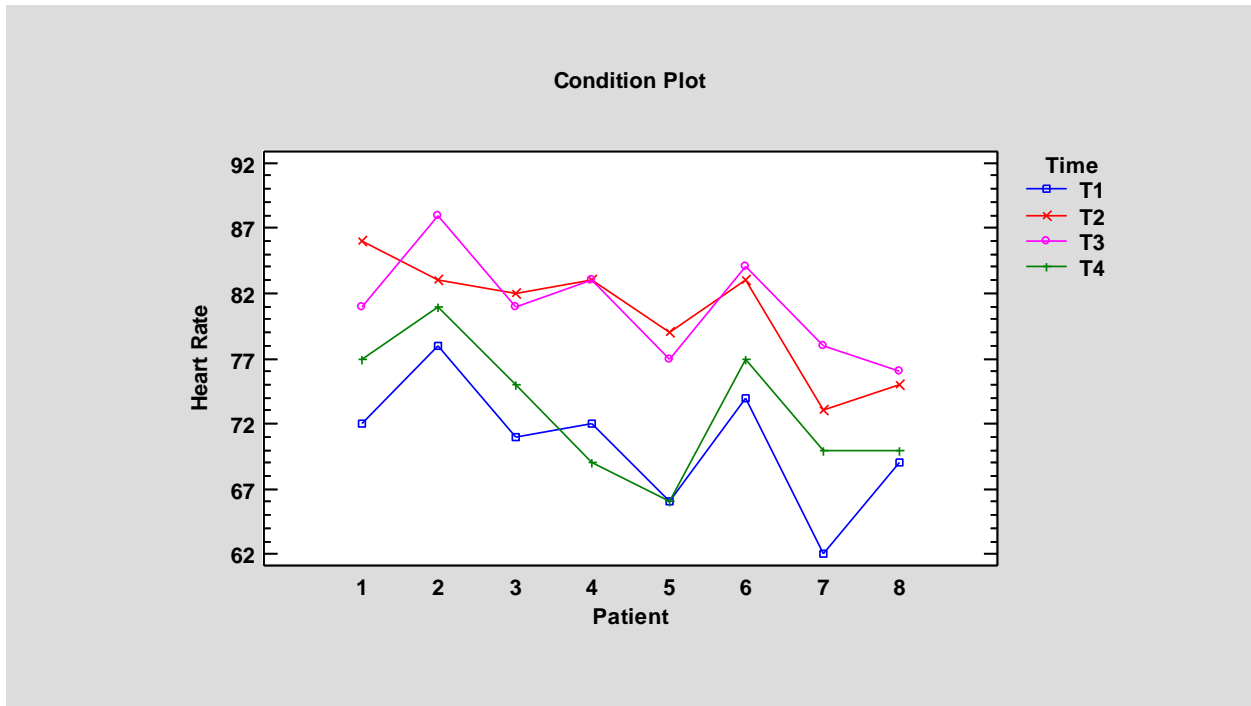
### Pane Options



*Order*: order of the fitted polynomial (cannot exceed the number of levels of the repeated measures factor minus 1).

## Condition Plot

The *Condition Plot* displays the data by condition and subject:

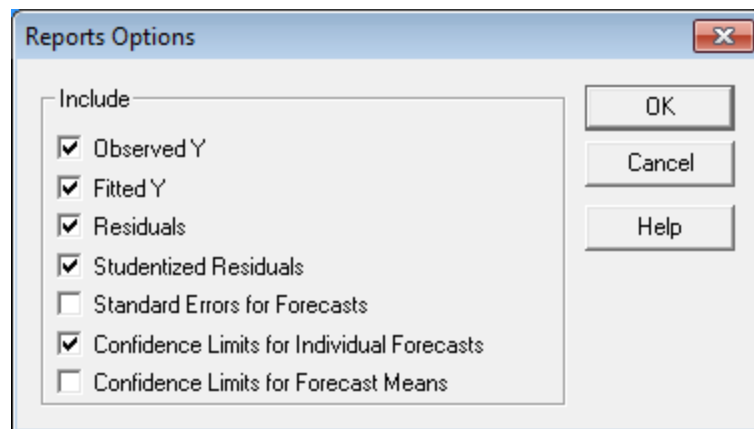


## Reports

The *Reports* pane displays information about each of the observations in the data. A section of the report is shown below:

Model Results for Heart Rate							
		Observed	Fitted		Studentized	Lower 95.0% CL	Upper 95.0% CL
Patient	Time	Value	Value	Residual	Residual	for Forecast	for Forecast
1	T1	72.0	73.2188	-1.21875	-0.620975	67.4643	78.9732
2	T1	78.0	76.7188	1.28125	0.653483	70.9643	82.4732
3	T1	71.0	71.4688	-0.46875	-0.236899	65.7143	77.2232
4	T1	72.0	70.9688	1.03125	0.524008	65.2143	76.7232
5	T1	66.0	66.2188	-0.21875	-0.110432	60.4643	71.9732
6	T1	74.0	73.7188	0.28125	0.142012	67.9643	79.4732
7	T1	62.0	64.9688	-2.96875	-1.59015	59.2143	70.7232
8	T1	69.0	66.7188	2.28125	1.19145	60.9643	72.4732
1	T2	86.0	83.2188	2.78125	1.47833	77.4643	88.9732
2	T2	83.0	86.7188	-3.71875	-2.06764	80.9643	92.4732
3	T2	82.0	81.4688	0.53125	0.268592	75.7143	87.2232
4	T2	83.0	80.9688	2.03125	1.05317	75.2143	86.7232
5	T2	79.0	76.2188	2.78125	1.47833	70.4643	81.9732
6	T2	83.0	83.7188	-0.71875	-0.363935	77.9643	89.4732
7	T2	73.0	74.9688	-1.96875	-1.01905	69.2143	80.7232
8	T2	75.0	76.7188	-1.71875	-0.884203	70.9643	82.4732

### Pane Options

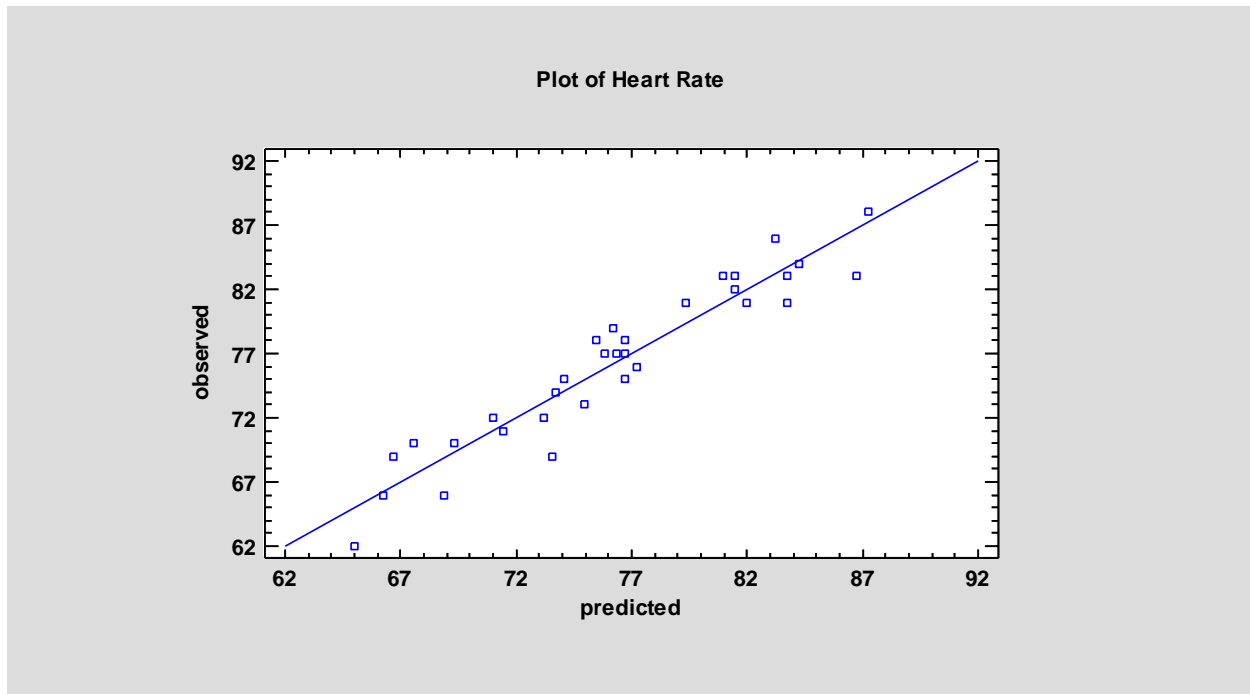


You may include:

- *Observed Y* – the observed values of the response variable.
- *Fitted Y* – the predicted values from the fitted model.
- *Residuals* – the ordinary residuals (observed minus predicted).
- *Studentized Residuals* – the Studentized deleted residuals.
- *Standard Errors for Forecasts* – the standard errors for new observations at each combination of the factors.
- *Confidence Limits for Individual Forecasts* – confidence intervals for new observations.
- *Confidence Limits for Forecast Means* – confidence intervals for the mean value of Y at each combination of the factors.

## Observed versus Predicted

The *Observed versus Predicted* plot shows the observed values of Y on the vertical axis and the predicted values  $\hat{Y}$  on the horizontal axis.



If the model fits well, the points should be randomly scattered around the diagonal line. Any change in variability from low values of Y to high values of Y might indicate the need to transform the response variable before fitting a model to the data.

## Residual Plots

As with all statistical models, it is good practice to examine the residuals. When fitting a statistical model, the residuals are defined by

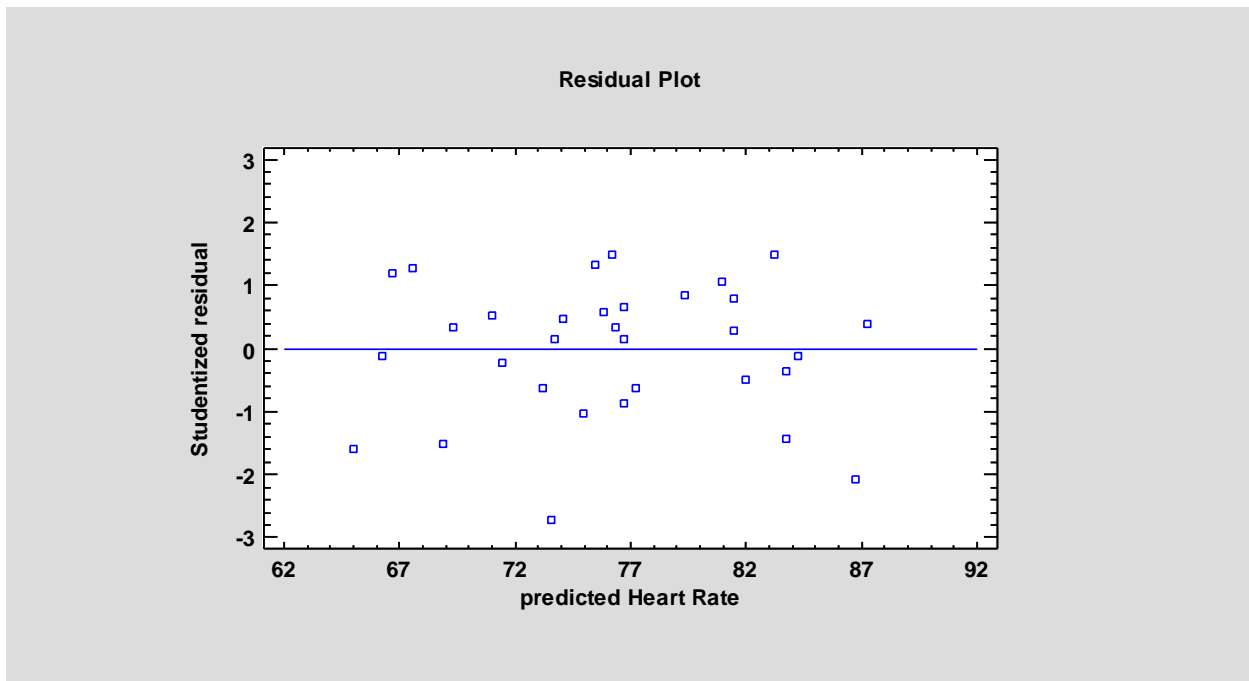
$$e_i = y_i - \hat{y}_i \quad (6)$$

i.e., the residuals are the differences between the observed data values and the fitted model.

This procedure creates various types of residual plots, depending on the settings in *Pane Options*.

### Scatterplot versus Predicted Values

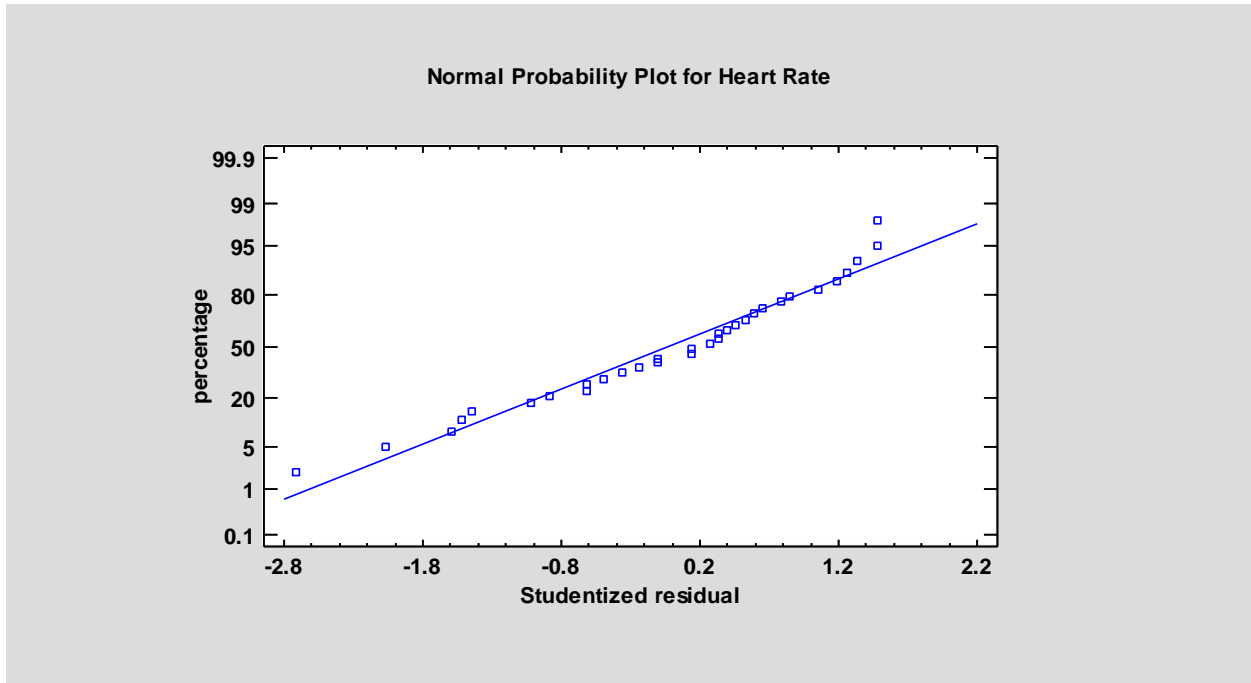
This plot is helpful in visualizing any possible dependence of the residual variance on the mean, which might necessitate a transformation of the response variable.



The above plot shows a fairly constant variance.

### Normal Probability Plot

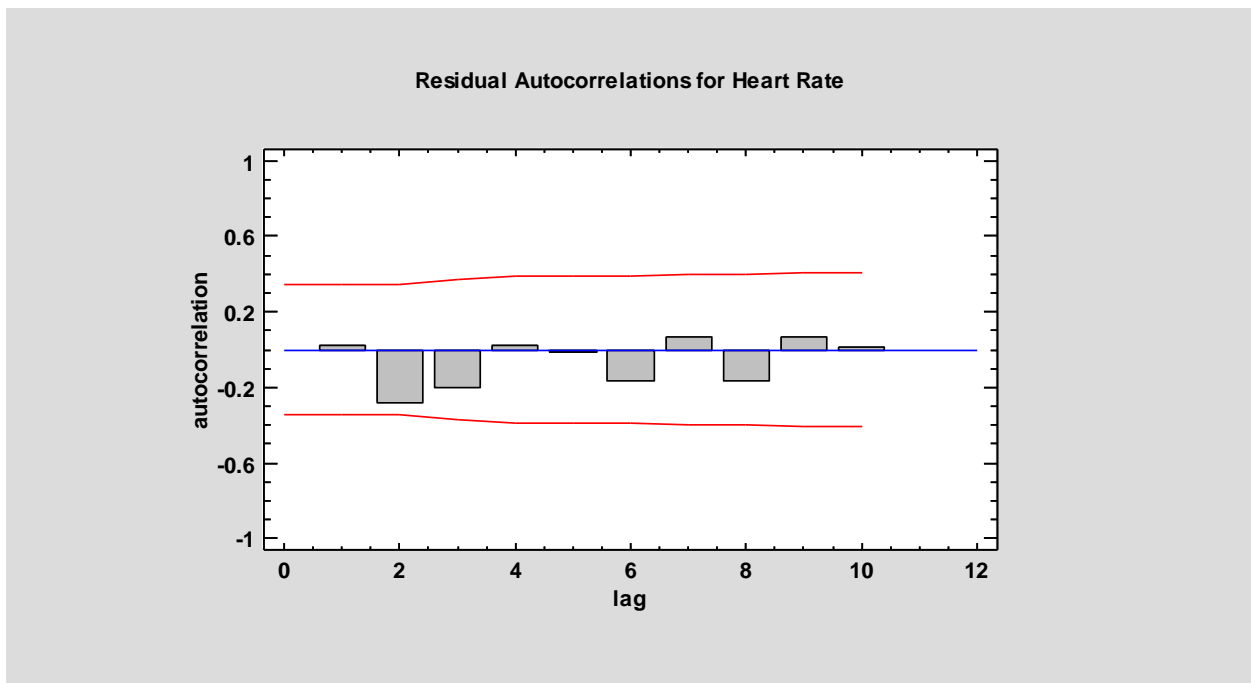
This plot can be used to determine whether or not the deviations around the line follow a normal distribution, which is the assumption used to form the prediction intervals.



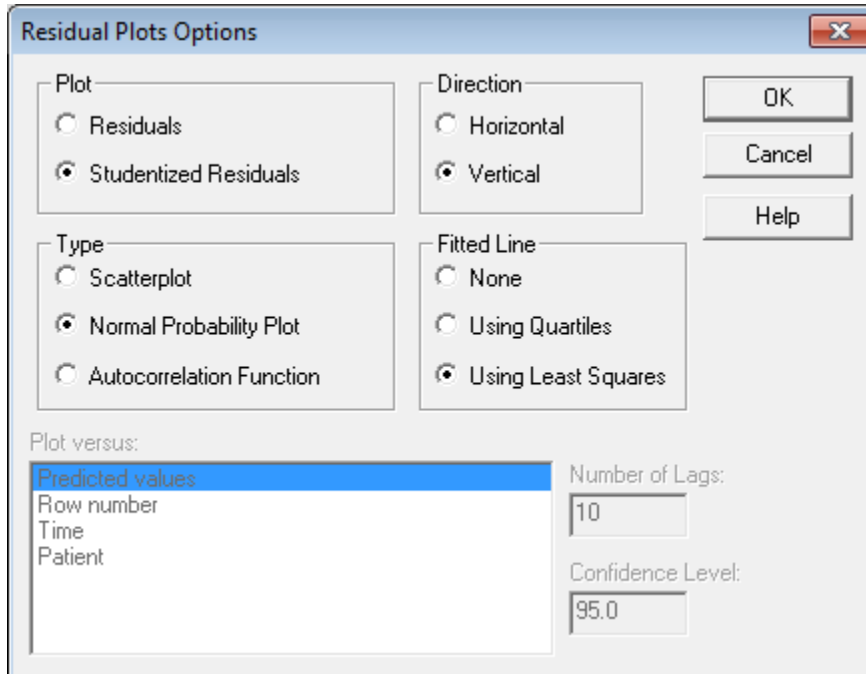
If the deviations follow a normal distribution, they should fall approximately along a straight line. In the above plot, the points fall fairly close to the line.

Residual Autocorrelations

This plot calculates the autocorrelation between residuals as a function of the number of rows between them in the datasheet.



Any bars extending beyond the probability limits would indicate significant dependence between residuals separated by the indicated “lag”, which would violate the assumption of independence made when fitting the statistical model.

*Pane Options*

- **Plot:** the type of residuals to plot:
  1. *Residuals* – the residuals from the least squares fit.
  2. *Studentized residuals* – the difference between the observed values  $y_i$  and the predicted values  $\hat{y}_i$  when the model is fit using all observations except the  $i$ -th, divided by their estimated standard error. These residuals are sometimes called *externally deleted residuals*, since they measure how far each value is from the fitted model when that model is fit using all of the data except the point being considered. This is important, since a large outlier might otherwise affect the model so much that it would not appear to be unusually far away from the line.
- **Type:** the type of plot to be created. A *Scatterplot* is used to test for curvature. A *Normal Probability Plot* is used to determine whether the model residuals come from a normal distribution. An *Autocorrelation Function* is used to test for dependence between consecutive residuals.
- **Plot Versus:** for a *Scatterplot*, the quantity to plot on the horizontal axis.
- **Number of Lags:** for an *Autocorrelation Function*, the maximum number of lags. For small data sets, the number of lags plotted may be less than this value.
- **Confidence Level:** for an *Autocorrelation Function*, the level used to create the probability limits.



## Unusual Residuals

Once the model has been fit, it is useful to study the residuals to determine whether any outliers exist that should be removed from the data. The *Unusual Residuals* pane lists all observations that have Studentized residuals of 2.0 or greater in absolute value.

Unusual Residuals for Heart Rate						
			Predicted		Studentized	
Row	Patient	Time	Y	Y	Residual	Residual
10	2	T2	83.0	86.7188	-3.71875	-2.07
28	4	T4	69.0	73.5938	-4.59375	-2.71

Studentized residuals greater than 3 in absolute value correspond to points more than 3 standard deviations from the fitted model, which is a rare event for a normal distribution. For the sample data, there are two unusual Studentized residuals.

## Friedman Test

If the data to be analyzed are unlikely to follow a normal distribution, the *Friedman Test* provides a nonparametric alternative to the F-test described earlier. In this test, the observations from each subject are ranked from 1 to  $q$ . The average rank for each condition is then computed, and a test statistic is calculated to test the hypothesis that the mean ranks are all the same.

The test produces output similar to that shown below:

Friedman Test		
	Sample Size	Average Rank
T1	8	1.1875
T2	8	3.4375
T3	8	3.5625
T4	8	1.8125

Test statistic = 20.6923 P-value = 0.000121958

95.0 percent Bonferroni intervals

Contrast	Sig.	Difference	+/- Limits
T1 - T2	*	-2.25	1.70299
T1 - T3	*	-2.375	1.70299
T1 - T4		-0.625	1.70299
T2 - T3		-0.125	1.70299
T2 - T4		1.625	1.70299
T3 - T4	*	1.75	1.70299

\* denotes a statistically significant difference.

The top section of the output shows the calculated test statistic. Small P-Values (less than 0.05 if operating at the 5% significance level) indicate that there are significant differences amongst the mean ranks.

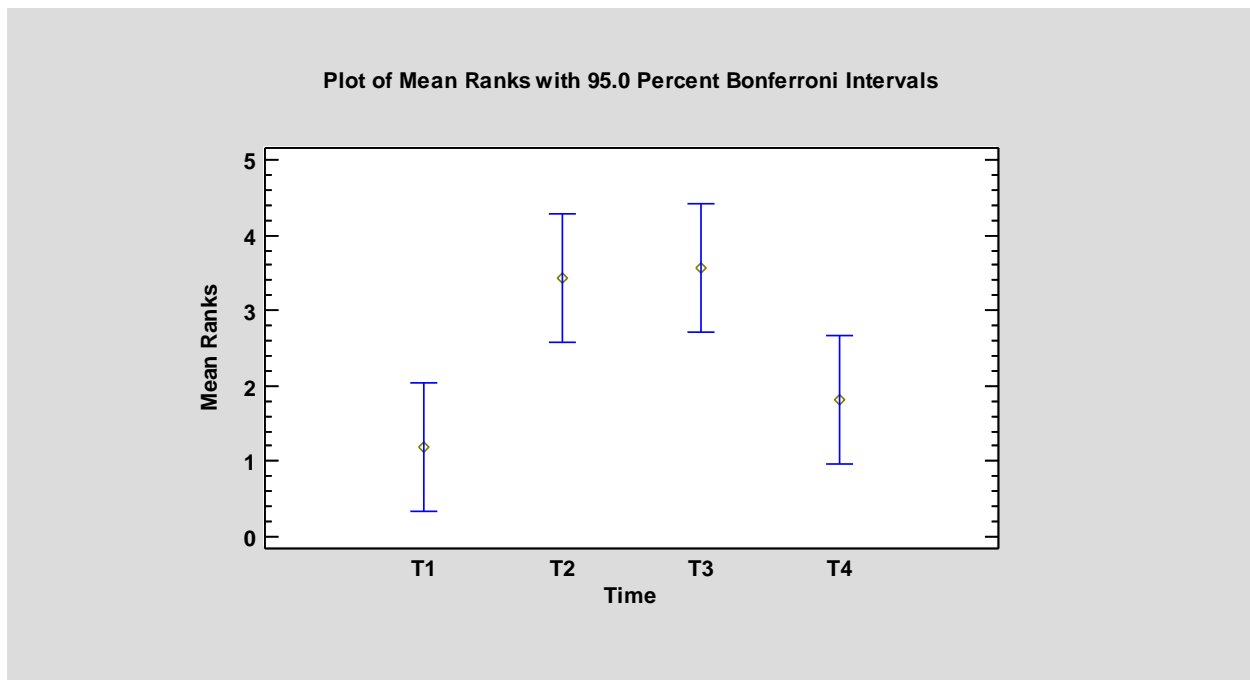
The bottom section of the output shows a comparison of the average rank for each pair of conditions. It shows the difference between the two average ranks, together with the width of a

Bonferroni interval for the difference. Any pair of groups for which the difference exceeds the “+/- Limits” value is statistically significant at the stated confidence level.

For the sample data, the results indicate a significant difference between times T1 and T2, T1 and T3, and T3 and T4.

## Mean Rank Plots

This plot displays the average ranks calculated when performing the Friedman test, together with the Bonferroni intervals:



Intervals that do not overlap indicate statistically significant differences between that pair of conditions at the family confidence level indicated.