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Comparing the Statistical Tests for Homogeneity of Variances

A thesis

presented to

the faculty of the Department of Mathematics

East Tennessee State University

In partial fulfillment

of the requirements for the degree

Master of Science in Mathematical Sciences

by

Zhiqiang Mu

August, 2006

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Key words: Equality of Variances, Robust, ANOVA, Resampling, Bootstrap Test,

Permutation Test

ABSTRACT

Comparing the Statistical Tests for Homogeneity of Variances

by

Zhiqiang Mu

Testing the homogeneity of variances is an important problem in many applications since statistical methods of frequent use, such as ANOVA, assume equal variances for two or more groups of data. However, testing the equality of variances is a difficult problem due to the fact that many of the tests are not robust against non-normality. It is known that the kurtosis of the distribution of the source data can affect the performance of the tests for variance. We review the classical tests and their latest, more robust modifications, some other tests that have recently appeared in the literature, and use bootstrap and permutation techniques to test for equal variances. We compare the performance of these tests under different types of distributions, sample sizes and true variance ratios of the populations. Monte-Carlo methods are used in this study to calculate empirical powers and type I errors under different settings.

DEDICATION

This thesis is dedicated to all of those people who have supported me throughout my educational journey at East Tennessee State University.

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The writer of this dissertation strongly feels indebted to those who provided assistance and encouragement with this work.

My first appreciation goes to Dr. Seier, my committee chairperson: Your invaluable suggestions that helped to improve my performance, your deep sense of caring for your students, and your willingness to be available at any time will be long remembered.

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1 INTRODUCTION

Testing equality of variances is a fundamentally harder problem than comparing means or measures of location. There are two reasons for this. First, the standard test statistics for mean comparisons are naturally standardized to be robust to non-normality due to the central limit theorem. In contrast, normal-theory test statistics for comparing variances are not suitably standardized to be insensitive to non-normality. Asymptotically, these statistics are not distribution-free, but depend on the kurtosis of the parent distributions. Second, for comparing means, a null hypothesis of identical populations is often appropriate. For variance comparisons, a null hypothesis of identical populations is rarely reasonable. [2]

As stated in [2], there are three basic approaches that have been used to obtain procedures robust to non-normality:

- “ 1. Adjust the normal theory test procedure using an estimate of kurtosis [5, 18].
2. Perform an analysis of variance (ANOVA) on a data set in which each observation is replaced by a scale variable such as the absolute deviation from the mean or median [6, 13].
3. Use resampling to obtain p -values for a given test statistic [3, 5].”

A new simple test, Count Five [15], recently appeared in the literature. It is also interesting to apply and compare computer intensive technology such as the bootstrap test and the permutation test. Through this study, we will compare all those tests for powers and type I errors obtained by simulations. In chapter one, the tests to be compared will be discussed. The distributions and experimental details will be discussed in chapter two and in chapter three. The results and conclusions of this study will be reported in chapter four.

2 TESTS FOR EQUAL VARIABILITY

In this chapter, we will briefly introduce tests for equality of variances, including the F test, (and its modified version,) Levene's tests, Barlett's test, (and its modified version) Count-five test, and computer intensive tests (Bootstrap test and Permutation test).

2.1 F Test

An F-test is a statistical test in which the test statistic has an F-distribution if the null hypothesis is true. Great varieties of hypotheses in applied statistics are tested by F-tests. Examples are given below: [10]

- The hypothesis that the means of multiple normally distributed populations, all having the same standard deviation, are equal. This is the simplest problem in the analysis of variance.
- The hypothesis that the standard deviations of two normally distributed populations are equal, and thus that they are of comparable origin.

We know that $F = \frac{\frac{U}{r_1}}{\frac{V}{r_2}}$, where U and V are independent Chi-square variables with

r_1 and r_2 degrees of freedom, respectively, has an F distribution with degrees of freedom r_1 and r_2 .

In the F test for equal variances, the null and alternative hypotheses are

$$H_0: \sigma_1^2 = \sigma_2^2$$

$$H_1: \sigma_1^2 < \sigma_2^2 \text{ for a lower one-tailed test}$$

$$\sigma_1^2 > \sigma_2^2 \text{ for an upper one-tailed test}$$

$$\sigma_1^2 \neq \sigma_2^2 \text{ for a two-tailed test}$$

The test statistic:

$$F = \frac{s_1^2}{s_2^2}$$

where s_1^2 and s_2^2 are the sample variances of two equal-sized samples from the same population. The more this ratio deviates from 1, the stronger the evidence for unequal population variances.

Notice that if the equality of variances (or standard deviations) is being tested, the F-test is extremely non-robust to non-normality. That is, even if the data display only modest departures from the normal distribution, the test is unreliable and should not be used. This is discussed further in chapter 4.

2.2 F-Test Improved Version – Shoemaker's Adjustment

One of the desirable features of the F test is that it has a natural measure of spread, the sample variance. In addition, confidence interval estimates can be calculated for the ratio of population variances. Shoemaker [18] proposed two adjustments to the F test that improve its robustness properties and that have superior power as compared to the Levene/Brown-Forsythe test for light-tailed distributions and heavy-tailed distributions. We implemented the Shoemaker's adjustment about degrees of freedom in our study.

If one takes samples of size n_1 and n_2 from two independent normal populations having variances σ_1^2 and σ_2^2 that $F = \frac{\sigma_2^2 s_1^2}{\sigma_1^2 s_2^2}$, has F distribution with $r_1 = n_1 - 1$, $r_2 = n_2 - 1$ degrees of freedom.

Shoemaker [18] used the matching-of-moments technique to approximate the degrees of freedom. The sample variance s^2 is approximately the average of independent and identically distributed random variables. By central limit theorem, it should approximate a normal random variable for large n . However, due to the skewness of the exact distribution of s^2 , n would have to be quite large. "By using a log transformation for s^2 , much of the asymmetry can be removed." [18]

Let $\ln F = \ln s_1^2 - \ln s_2^2 - \ln \sigma_1^2 + \ln \sigma_2^2$. Under assumption of normality, $\ln F$ is approximately normally distributed with $Var(\ln F) \cong \frac{2}{r_1} + \frac{2}{r_2}$.

More generally, if one samples from two independent distributions which are similarly distributed with possible different locations and spreads, $\ln F$ will behave approximately as a normal random variable. $Var(\ln F) \approx Var(s_1^2) + Var(s_2^2)$. Set $\frac{2}{r_i} = Var(\ln s_i^2)$ and

solve for s_i to get:
$$r_i = \frac{2n_i}{\frac{\mu_4}{\sigma^4} - \frac{(n_i - 3)}{(n_i - 1)}}$$

where μ_4 is the 4th moment about the population mean and σ is the standard deviation. Hence, the term μ_4/σ^4 is associated with the kurtosis of the distribution.

2.3 Levene Test

Levene [13] proposed using the one-way ANOVA F statistic on new variables

$$Z_{ij} = |Y_{ij} - Y_{i.}|.$$

where $Y_{i.}$ could be mean, median or trimmed mean of i^{th} subgroup.

The statistic is defined as:

$$W = \frac{(N - k) \sum_{i=1}^k N_i (\bar{Z}_i - \bar{Z}_{..})^2}{(k - 1) \sum_{i=1}^k \sum_{j=1}^{N_i} (Z_{ij} - \bar{Z}_{i.})^2}$$

where \bar{Z}_i are the group means of Z_{ij} and $\bar{Z}_{..}$ is the pooled mean of Z_{ij} .

Levene's original paper only proposed using the mean as the center. Brown and Forsythe [6] extended Levene's test to use either the median or the trimmed mean to substitute for the mean. They performed Monte Carlo studies that indicated that using the trimmed mean performed best when the underlying data followed a Cauchy distribution (i.e. symmetric heavy-tailed) and the median performed best when the underlying data followed a Chi-Square(4) (i.e. skewed) distribution. Using the mean as the center provided the best power for symmetric, moderate-tailed, distributions. [16]

Levene's test is an alternative to the Bartlett test. The Levene test is less sensitive to departures from normality than the Bartlett test. Generally, if strong evidence presents that the data do in fact come from a normal, or nearly normal, distribution, Bartlett's test performs better since it gives higher power than Levene's.

2.4 Bartlett's Test

Bartlett's statistic is designed to test for equality of variances across groups against the alternative that variances are unequal for at least two groups, assuming the populations are normally distributed. Bartlett's test is sensitive to departures from normality. That is, if the samples come from non-normal distributions, then Bartlett's test may simply be testing for non-normality. [16]

Some statistical tests, for example the analysis of variance, assume that variances are equal across groups or samples. Bartlett's test can be used to verify that assumption.

Bartlett's test and Levene's test are the only tests considered in this study that are able to test homogeneity of variances for more than two groups. The other tests could be adapted by working with the two groups that have the maximum and minimum variances.

In Bartlett's test, the n_i 's in each of the treatment classes need not be equal. However, no n_i 's should be smaller than 3, and most n_i 's should be larger than 5. This is discussed in [20].

The test statistic is defined as:

$$T = \frac{(N - k) \ln s_p^2 - \sum_{i=1}^k (N_i - 1) \ln s_i^2}{1 + \frac{1}{3(k-1)} \left(\sum_{i=1}^k \left(\frac{1}{N_i - 1} \right) - \frac{1}{N - k} \right)}$$

where: $s_p^2 = \sum_{i=1}^k (N_i - 1) s_i^2 / (N - k)$

$s_i^2 =$ Sample variance of the i^{th} group.

2.5 Bhat's Version of Bartlett's Test

Bhat proposed a simple test based on Gini's mean difference to test the hypothesis of equality of population variances. Bhat claims "the test compares favorably with Bartlett's and Levene's test for the normal population. Also, it is more powerful than Bartlett's and Levene's tests for some alternative hypotheses for some non-normal distributions and more robust than the other two tests for large sample sizes under some alternative hypotheses". [1]

The mean difference as proposed by Gini is given by

$$G = \frac{2}{n(n-1)} \sum_{j < l} (x_{(j)} - x_{(l)}) \quad \text{for a sample } \{x_j\} \text{ of size } n.$$

The null hypothesis is $H_0 : \sigma_1^2 = \sigma_2^2$. The test statistic proposed is

$$T_G = \frac{T_g E(T_g)}{\text{Var}(T_g)} \left(\frac{\text{Var}(T_w)}{T_w E(T_w)} \right) \frac{p_2}{p_1}$$

Under H_0 , the mean of T_w reduces to σ and $\text{Var}(T_w) = \sigma^2 \sum n_i D_i / N^2$. Hence,

$T_G = \frac{\sigma T_g}{T_w E(T_g)}$. The definition of T_g and T_w could be found in [1]. When compared to

Bartlett's test, one got

$$T = \frac{(N-k) \ln s_p^2 - \sum_{i=1}^k (N_i - 1) \ln s_i^2}{\left(1 + \frac{1}{3(k-1)} \left(\sum_{i=1}^k \left(\frac{1}{N_i - 1} \right) - \frac{1}{N-k} \right) \right) \left(1 + \frac{v}{2} \right)}$$

v is the adjustment for kurtosis, and

$$v = \frac{N \sum_i \sum_j \left(x_{ij} - \tilde{x}_i \right)^4}{\left[\sum_i (n_i - 1) s_i^2 \right]^2} - 3$$

2.6 Count Five Test

McGrath and Yeh [15] proposed a simple compact dispersion test, Count Five. This test compares absolute deviations of one sample to another.

Let $X_1 \dots X_n$ and $Y_1 \dots Y_n$ be independent random samples with $E(X_i) = \mu_x$, $Var(X_i) = \sigma_x^2$, $E(Y_i) = \mu_y$ and $Var(Y_i) = \sigma_y^2$. Assume X_i and Y_i are similarly distributed, with μ_x and μ_y known. The absolute deviations $|X_i - \mu_x|$ and $|Y_i - \mu_y|$ are independent and identically distributed (i.i.d.) random variables under $H_0: \sigma_x^2 = \sigma_y^2$. Let C_x be the extreme count for the X sample, i.e. the number of $|X_i - \mu_x|$ that exceeds the maximum $|Y_i - \mu_y|$ with C_y being defined analogously:

$$C_x = \text{Number of } \{i : |X_i - \mu_x| > \max |Y_i - \mu_y|\}$$

To find appropriate tail probabilities under H_0 , an application of the hypergeometric distribution is used. Let $P(C_x > m | H_0)$ be the probability given H_0 that a random sample of m observations from $n_x + n_y$ observations all come from the n_x observations:

$$P(C_x > m | H_0) = \prod_{k=0}^{m-1} \frac{n_x - k}{n_x + n_y - k}$$

if $n_x = n_y = n = N/2$, then:

$$P(C_x > m | H_0) = \frac{1}{2^m} \prod_{k=1}^{m-1} \frac{N - 2k}{N - k}$$

Thus, a two-sided test could have critical value of $m = 5$ and have significance level $< .0625$ for finite n regardless of distribution.

2.7 Introduction to Randomization Test

A randomization test is defined in [14] as “A procedure that involves comparing an observed test statistic with a distribution that is generated by randomly reordering the data value in some sense”. Many hypotheses of interest in science can be regarded as alternatives to null hypotheses of randomness. That is, the hypothesis suggests that there will be a tendency for a certain type of pattern to appear in data. Randomization test is an option for determining whether the null hypothesis is reasonable in this type of situation.

A statistic S is chosen to measure the extent to which data show the pattern in question. The value s of S for the observed data is then compared with the distribution of S that is obtained by randomly reordering the data. The claim made is that if the null hypothesis is true, then the probability of possible orders for the data was equally likely to occur. The observed data are just one of the equally likely outcomes and s should appear as a typical value from the randomization distribution of S . If this does not seem to be the case, then the alternative hypothesis is regarded reasonable. The significance level of s is the proportion or percentage of values that are as extreme as, or more extreme than this value (s) in the randomization distribution.

In comparison with more standard statistical methods, randomization tests have two advantages. First, they are valid even with non-random samples. Second, it is relatively easy to take into account the peculiarities of the situation of interest and use non-standard test statistics. The disadvantage of the randomization test is that it is not always possible to generalize the conclusion from a randomization test to a population of interest. What a randomization test tells us is that a certain pattern in data is or is not likely to happen by chance. This is less serious than it might seem at first sight since the generalization that is often made with conventional statistical procedures is based upon the unverifiable assumption that non-random samples are equivalent to random samples.

2.8 The Bootstrap Test

Bootstrapping is a statistical method for estimating the sampling distribution of an estimator by sampling with replacement from the original sample, most often with the purpose of deriving robust estimates of standard errors and confidence intervals of a population parameter like a mean, median, proportion, odds ratio, correlation coefficient or regression coefficient [14]. It may also be used for constructing hypothesis tests. Bootstrapping is often used as a robust alternative to inference based on parametric assumptions when those assumptions are in doubt, or where parametric inference is impossible or requires very complicated formulas for the calculation of standard errors.

The technique of bootstrapping was first considered in a systematic manner by Efron. [7] The essence of bootstrapping is the idea that, in the absence of any other knowledge about a population, the distribution of the values found in a random sample of size n from the population is the best guide to the distribution in the population. Therefore, in order to approximate what could happen if the population was resampled, it is logical to resample the sample. The sampling is with replacement, which is one of the differences between bootstrap and permutation.

Much of the research on bootstrapping confidence has been aimed at developing reliable methods for constructing confidence limits for population parameters. However, recently bootstrap tests of significance have been attracting more interest.

The standard bootstrapping confidence limits are calculated as the estimate $\pm Z_{\alpha/2}$ (bootstrap standard deviation), where the standard deviation is estimated by resampling the original data values.

The Standard bootstrap confidence interval:

With the standard bootstrap confidence interval σ is estimated by the standard deviation of estimates of a parameter θ that are found by bootstrap resampling of the values in the original sample of data. The interval is

$$\text{Estimate} \pm Z_{\alpha/2} (\text{bootstrap standard deviation})$$

Using $Z_{.025} = 1.96$ gives the standard 95% bootstrap interval.

The requirements for this method to work are that:

1. $\hat{\theta}$ has an approximately normal distribution;
2. $\hat{\theta}$ is unbiased so that its mean value for repeated samples from the population of interest is θ ;
3. Bootstrap resampling gives a good approximation to σ .

The first percentile method (Efron [8]):

Bootstrap resampling of the original sample is used to generate the empirical sampling (bootstrap) distribution of the parameter of interest. (It is σ in our study.) The $100(1 - \alpha) \%$ (95% by default) confidence interval of the true value of the parameter is then given by the two values that encompass the central $100(1 - \alpha)\%$ of this distribution.

Hall [9] suggested that the percentile confidence interval is analogous to looking up the wrong statistical table backwards. The reasoning was based upon the concept that a bootstrap distribution should imitate the particular distribution of interest. This implies that the distribution of error in $\hat{\theta}$, $\varepsilon = \hat{\theta} - \theta$, should be approximated by the error in the bootstrap distribution, $\varepsilon_B = \hat{\theta}_B - \hat{\theta}$. Thus, a bootstrap distribution of ε_B can be generated to find two errors ε_L and ε_H such that:

$$\text{Prob}(\varepsilon_L < \hat{\theta}_B - \hat{\theta} < \varepsilon_H) = 1 - \alpha,$$

The second percentile method (Hall [9]):

Bootstrap resampling is used to generate a distribution of estimates $\hat{\theta}_B$ for a parameter θ . The bootstrap distribution of difference between the bootstrap estimate and estimate of θ in the original sample $\varepsilon_B = \hat{\theta}_B - \hat{\theta}$ is then assumed to approximate the distribution of errors for $\hat{\theta}$ itself. On this basis, the bootstrap distribution of ε_B is used to find limits ε_L and ε_H for the sampling error such that $100(1-\alpha)$ % of errors are contained by the interval of these limits. The $100(1-\alpha)$ % confidence interval for θ is $(\hat{\theta} - \varepsilon_H, \hat{\theta} - \varepsilon_L)$.

The number of bootstrap samples: Manly [14] recommended that 1000 is the minimum number of bootstrap samples. We used 5000 bootstrap samples in this study.

We applied the first percentile method in this study and could implement the second percentile method for further investigation. Bootstrap resamplings of the original data of two groups are used to generate the bootstrap distributions of σ^2 . The $100(1 - \alpha)\%$ (95% by default) confidence interval of the true value of the parameter is then given by the two values that encompass the central $100(1 - \alpha)\%$ of this distribution.

Initial experiments showed strong evidence that the bootstrap test of individual resampling of two groups of original observed data points had bad power under all conditions. (sample size, ratio of variance) Therefore, a pooled data set was incorporated. That is, we mixed the observed data points from two groups into one group, then bootstrap resampled from the pool and re-constructed two groups with corresponding sample sizes. We are going to compare both methods. The former bootstrap method is named the Bootstrap, and the latter bootstrap method is named the Bootstrap2 through the simulations of this study.

2.9 The Permutation Test

Statistical tests use observed data to calculate a test statistic, which (in well-constructed tests) assesses a hypothesis of interest. The value of the test statistic is compared to a reference distribution, the distribution of the test statistic assuming the null hypothesis is true. The p-value is the proportion of the distribution that is at least as extreme as the observed statistic. If the p-value is too small, then the null hypothesis is rejected and an alternative hypothesis is rendered more plausible. Contrary to intuition, the alternative is not said to be accepted when the null is rejected, except in trivial examples.

A permutation test (also called a randomization test, re-randomization test, or an exact test) is a type of statistical significance test in which a reference distribution is obtained by calculating all possible values of the test statistics. This is done by permuting the observed data points across all possible outcomes, given a set of conditions consistent with the null hypothesis.

Boos and Brownie [3] implemented the permutation approach implied by Box and Andersen [5]. They used the permutation distribution based on drawing samples without replacement from $S = \{e_{ij} = X_{ij} - \hat{\eta}_i, j = 1, \dots, n_i, i = 1, \dots, k\}$, where the $\hat{\eta}_i$ are location estimates such as the sample mean or trimmed mean. They implemented the approach in the two-sample ANOVA ($F = \frac{s_1^2}{s_2^2}$) and for a ratio of robust scale estimators.

Note that because the residuals $X_{ij} - \hat{\eta}_i$ from different samples are not exchangeable, such a permutation procedure is not exact.

Instead of using a permutation distribution based on S defined above, we randomly permuted observed data points (not residuals) between two groups, since the total permutation may take too long to execute. We did 5000 random permutations.

3 EXPERIMENTAL CONDITIONS/DESIGN

3.1 Introduction to Distributions

First we introduce a few moments and ratios of moments to describe a statistical distribution.

Variance: For a single variate X having a distribution $P(x)$ with known population mean μ , the population variance $Var(x)$, commonly also written σ^2 , is defined as

$$\sigma^2 \equiv \langle (X - \mu)^2 \rangle,$$

Where μ is the population mean and $\langle X \rangle$ denotes the expectation value of X . For a continuous distribution, it is given by

$$\sigma^2 = \int P(x)(x - \mu)^2 dx$$

Skewness: A measure of the degree of asymmetry of a distribution. If the left tail (tail at the small end of the distribution) is more pronounced than the right tail (tail at the large end of the distribution), the function is said to have negative skewness. If the reverse is true, it has positive skewness. If the two are equal, it has zero skewness.

The skewness of a distribution is defined to be

$$\gamma_1 = \frac{\mu_3}{\mu_2^{3/2}}$$

where μ_i is the i^{th} central moment.

Kurtosis: The degree of peakedness of a distribution, defined as a normalized form of the fourth central moment μ_4 of a distribution. There are several measures of kurtosis commonly encountered, β_2 defined by Pearson in 1905 or α_4

$$\beta \equiv \frac{\mu_4}{\mu_2^2}$$

where μ_i denotes the i^{th} central moment (and in particular, μ_2 is the variance).

3.2 Systems of Distributions

Some families of distributions have been constructed to provide approximations to as wide a variety of observed distributions as possible. Such families are often called systems of distributions (or system of frequency curves) [12].

Pearson system

Pearson designed a system such that, for every member, the probability density function $p(x)$ satisfies a differential equation of form:

$$\frac{dp}{dx} = -\frac{p(a+x)}{c_0 + c_1x + c_2x^2} \quad (3.1)$$

The shape of the distribution depends on the values of the parameters a , c_0 , c_1 and c_2 [12]. The form of solution of (3.1) evidently depends on the nature of the roots of the equation

$$c_0 + c_1x + c_2x^2 = 0$$

Note that if $c_1 = c_2 = 0$, equation (3.1) becomes

$$\frac{d \log p(x)}{dx} = -\frac{x+a}{c_0}.$$

Whence

$$p(x) = C \exp\left[-\frac{(x+a)^2}{2c_0}\right]$$

where C is a constant, which makes $\int_{-\infty}^{+\infty} p(x)dx = 1$.

As a result, the corresponding distribution is normal with mean $-a$ and variance c_0 .

Pearson classified the different shapes into a number of types. A brief summary is listed here, see details in [12].

0. Normal distribution.

I. Beta distribution.

III. Gamma distribution. This case is intermediate to cases I and VI.

V. Intermediate to cases IV and VI.

VI. Beta prime distribution.

VII. Student's t -distribution.

3.3 Transformed Distributions

If the distribution of a random variable X is such that a simple explicit function $f(x)$ has a well-known distribution, it becomes possible to use the results of research of the well-known distribution in studying the distribution of X . A well-known example is the lognormal distribution where $\log(X - \mu)$ has a normal distribution. Other widely used families of distributions in this case include $(X - \xi)^c$ or $\exp-(X - \xi)$ have exponential distributions.

Johnson [11] described the following transformations:

$$Z = \gamma + \delta \log\left(\frac{Y}{1-Y}\right), \quad \text{This is } S_B$$

$$Z = \gamma + \delta \sinh^{-1}(Y), \quad \text{This is } S_U$$

where Z has a normal distribution. The subindex B and U denote whether the domain of x is bounded or unbounded.

Some typical probability density functions (pdfs) belonging to S_B and S_U families are shown in figure 1 and 2.

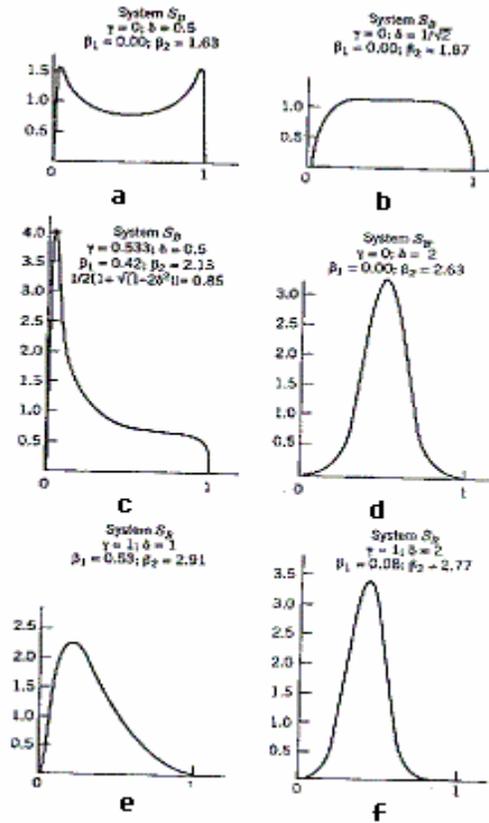


Figure 1 Sample pdfs of S_B Distributions

Adapted from [11]

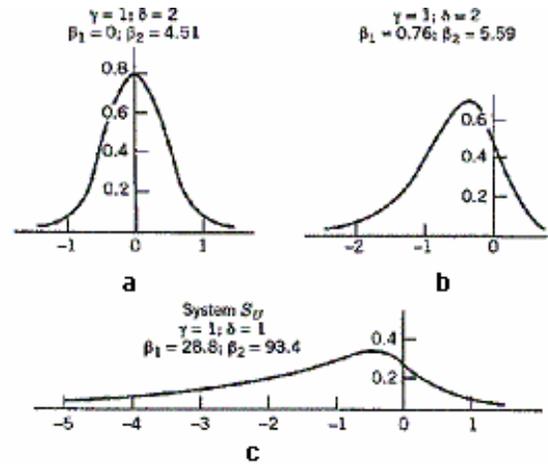


Figure 2 Sample pdfs of S_U Distributions

Adapted from [11]

All S_U curves are unimodal; S_B may be unimodal or bimodal, with an antimode between two modes. For all lognormal, S_B and S_U distributions, not only does the probability density function tend to zero as the extremity is approached, but also do all the derivatives. This applies as $Y \rightarrow \infty$, as well as when the extremities are finite. This property is not shared by all person system distributions.

Next, we introduce the distributions involved in our experiments. Figures of distributions are adapted from [16].

3.4 Laplace Distribution

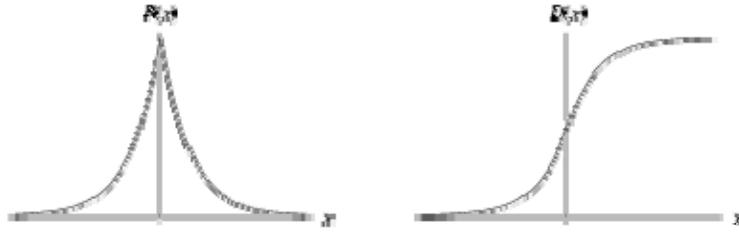


Figure 3 pdf and cdf of Laplace Distribution. Adapted from [16]

The Laplace Distribution [12] is also called the double exponential distribution. It is the distribution of differences between two independent variates with identical exponential distributions.

$$P(x) = \frac{1}{2b} e^{-|x-\eta|/b}$$
$$D(x) = \frac{1}{2} \left[1 + \operatorname{sgn}(x - \mu)(1 - e^{-|x-\eta|/b}) \right]$$

The mean, variance, skewness, and kurtosis excess are

$$\mu = \mu$$

$$\sigma^2 = 2b^2$$

$$\gamma_1 = 0$$

$$\gamma_2 = 3$$

3.5 Extreme Value Type I Distribution/Gumbel

The extreme value type I distribution has two forms. One is based on the smallest extreme and the other is based on the largest extreme. [16] We call these the minimum

and maximum cases, respectively. Formulas and plots for both cases are given. The extreme value type I distribution is also referred to as the Gumbel distribution.

The general formula for the probability density function of the Gumbel (minimum) distribution is

$$f(x) = \frac{1}{\beta} e^{\frac{x-\mu}{\beta}} e^{-e^{\frac{x-\mu}{\beta}}}$$

where μ is the location parameter and β is the scale parameter. The case where $\mu = 0$ and $\beta = 1$ is called the standard Gumbel distribution. The equation for the standard Gumbel distribution (minimum) reduces to

$$f(x) = e^x e^{-e^x}$$

The following is the plot of the Gumbel probability density function for the minimum case.

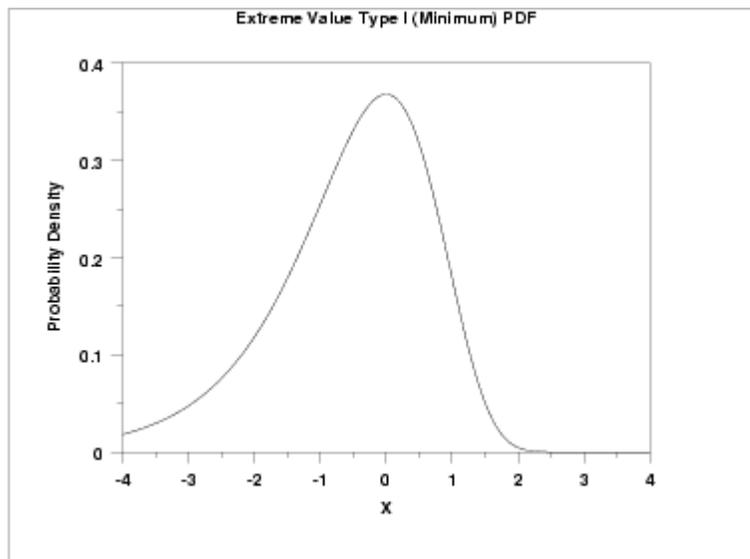


Figure 4 pdf of Extreme Value Type 1 Minimum Distribution. Adapted from [16]

The general formula for the probability density function of the Gumbel (maximum) distribution is

$$f(x) = \frac{1}{\beta} e^{-\frac{x-\mu}{\beta}} e^{-e^{-\frac{x-\mu}{\beta}}}$$

where μ is the location parameter and β is the scale parameter. The case where $\mu = 0$ and $\beta = 1$ is called the standard Gumbel distribution. The equation for the standard Gumbel distribution (maximum) reduces to

$$f(x) = e^{-x} e^{-e^{-x}}$$

The following is the plot of the Gumbel probability density function for the maximum case.

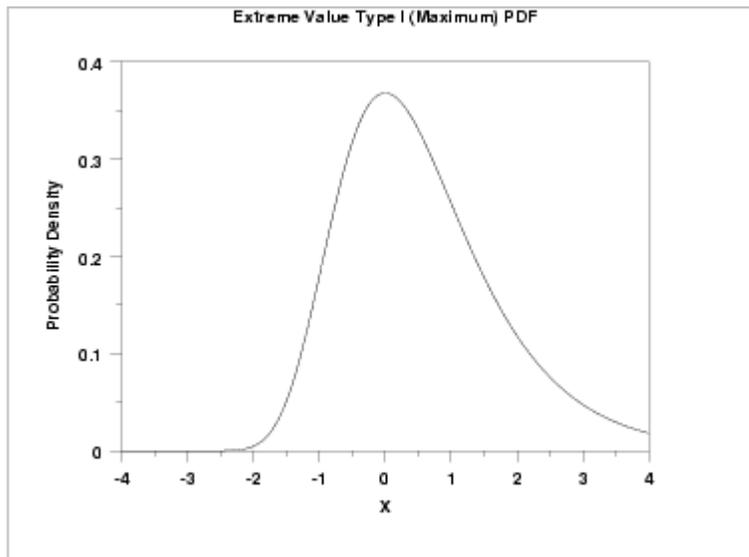


Figure 5 pdf of Extreme Value Type 1 Maximum Distribution. Adapted from [16]

The variance, skewness, and kurtosis are

$$\sigma^2 = \frac{1}{6} \pi^2 \beta^2$$

$$\gamma_1 = 1.13955$$

$$\gamma_2 = 2.4$$

3.6 Chi-Square Distribution

If $Y_i, i=1, \dots, n$, has normal independent distributions with mean 0 and variance 1, then

$$\chi^2 \equiv \sum_{i=1}^r Y_i^2$$

is distributed as χ^2 with r degrees of freedom. [10] It makes a χ^2 distribution a gamma distribution with $\theta = 2$ and $\alpha = r/2$.

More generally, if χ_i^2 are independently distributed according to a χ^2 distribution with $r_1,$

r_2, \dots, r_k degrees of freedom, then $\sum_{j=1}^k \chi_j^2$

is distributed according to χ^2 with $r = \sum_{j=1}^k r_j$ degrees of freedom.

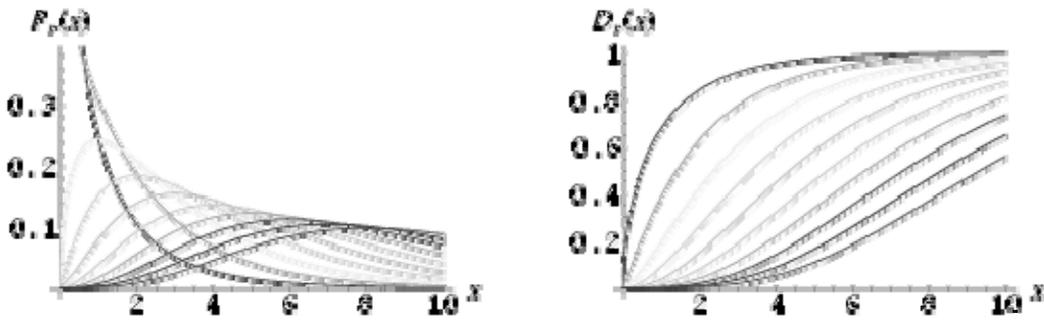


Figure 6 pdfs and cdfs of χ^2 Distribution. Adapted from [16]

The variance, skewness, and kurtosis of χ^2 are

$$\sigma^2 = 2r$$

$$\gamma_1 = 2\sqrt{2/r}$$

$$\gamma_2 = 3 + 12/r$$

3.7 Weibull Distribution

The Weibull distribution is given by

$$P(x) = \frac{\gamma}{\alpha} \left(\frac{x-\eta}{\alpha} \right)^{(\gamma-1)} e^{-\left(\frac{x-\eta}{\alpha} \right)^\gamma}$$

$$D(x) = 1 - e^{-(x^\gamma)}$$

$$x \geq \mu, \alpha, \gamma > 0.$$

Where γ is the shape parameter, μ is the location parameter and α is the scale parameter. The case where $\mu = 0$ and $\alpha = 1$ is called the standard Weibull distribution. [12]

The following is the plot of the Weibull probability density function.

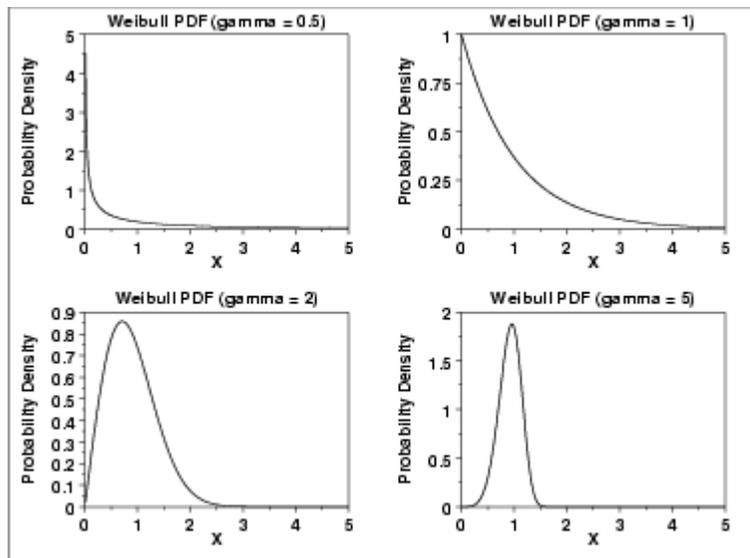


Figure 7 pdfs of Weibull Distribution. Adapted from [16]

3.8 Tukey-Lambda Distribution

The Tukey-Lambda density function does not have a simple, closed form. It is computed numerically. [16]

The Tukey-Lambda distribution has the shape parameter λ . As with other probability distributions, the Tukey-Lambda distribution can be transformed with a location parameter, μ , and a scale parameter, σ .

The following is the plot of the Tukey-Lambda pdfs for four values of λ .

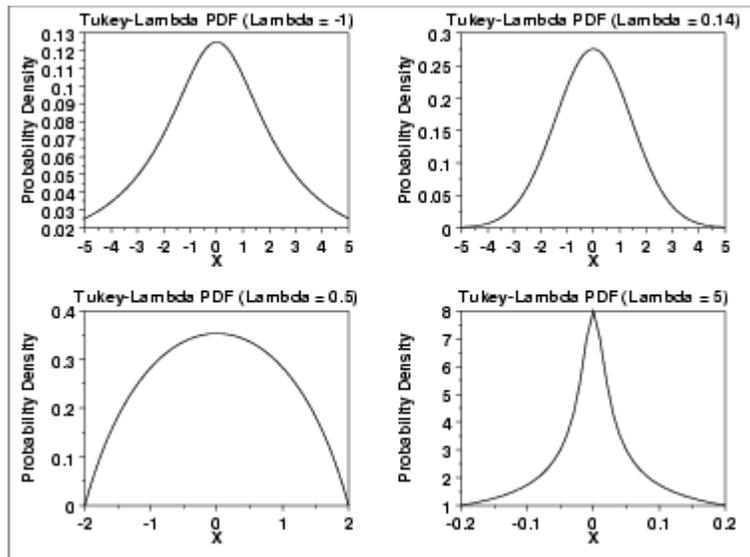


Figure 8 pdfs of Tukey-Lambda Distribution. Adapted from [16]

The formula for the percent point function of the standard form of the Tukey-Lambda distribution is

$$G(p) = \frac{p^\lambda - (1-p)^\lambda}{\lambda}$$

The Tukey-Lambda distribution is actually a family of distributions that can approximate a number of common distributions. For example,

- $\lambda = -1$ approximately Cauchy
- $\lambda = 0$ exactly logistic
- $\lambda = 0.14$ approximately normal
- $\lambda = 0.5$ U-shaped
- $\lambda = 1$ exactly uniform (from -1 to +1)

The most common use of this distribution is to generate a Tukey-Lambda Probability Plot Correlation Coefficient (PPCC) plot of a data set. Based on the PPCC plot, an appropriate model for the data is suggested. For example, if the maximum correlation occurs for a value of λ at or near 0.14, then the data can be modeled with a normal distribution. Values of λ less than this imply a heavy-tailed distribution (with -1 approximating a Cauchy). That is, as the optimal value of λ goes from 0.14 to -1, increasingly heavy tails are implied. Similarly, as the optimal value of λ becomes greater than 0.14, shorter tails are implied.

3.9 Logistic Distribution



Figure 9 pdf and cdf of Logistic Distribution. Adapted from [16]

The Logistic distribution [12] with parameters m and $b > 0$ has probability and distribution functions

$$P(x) = \frac{e^{-(x-m)/b}}{b[1 + e^{-(x-m)/b}]^2}$$

$$D(x) = \frac{1}{1 + e^{-(x-m)/b}}$$

The mean, variance, skewness, and kurtosis are

$$\mu = m$$

$$\sigma^2 = \frac{1}{3} \pi^2 b^2$$

$$\gamma_1 = 0$$

$$\gamma_2 = 1.2$$

3.10 Student's T-Distribution



Figure 10 pdf and cdf of Student's T-Distribution. Adapted from [16]

The Student's T (A.K.A. student t) is a statistical distribution published by William Gosset in 1908. His employer, Guinness Breweries, required him to publish under a pseudonym, so he chose "Student." [10] Given N independent measurements x_i , let

$$t \equiv \frac{\bar{x} - \mu}{s/\sqrt{N}}$$

The mean, variance, skewness, and kurtosis of Student's t -distribution are

$$\mu = 0$$

$$\sigma^2 = \frac{r}{r-2}$$

$$\gamma_1 = 0$$

$$\gamma_2 = \frac{6}{r-4}$$

3.11 Half-Normal Distribution

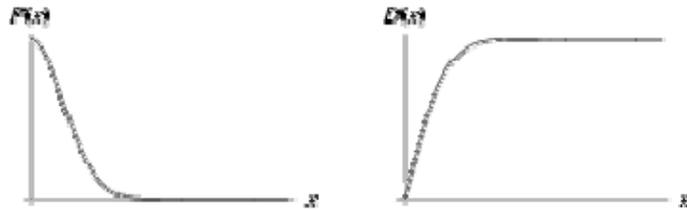


Figure 11 pdf and cdf of Half-Normal Distribution. Adapted from [16]

The half-normal distribution is a normal distribution with mean 0 and parameter θ limited to the domain $x \in [0, \infty)$. [16] It has probability and distribution functions given by

$$P(x) = \frac{2\theta}{\pi} e^{-x^2\theta^2/\pi}$$

$$D(x) = \text{erf}\left(\frac{\theta x}{\sqrt{\pi}}\right)$$

where $erf(x)$ is the error function $erf(x) = (2/\pi) \int_0^x e^{-t^2} dt$.

Giving the mean, variance, skewness, and kurtosis excess as

$$\mu = \frac{1}{\theta}$$

$$\sigma^2 = \frac{\pi - 2}{2\theta^2}$$

$$\gamma_1 = \frac{\sqrt{2}(4 - \pi)}{(\pi - 2)^{3/2}}$$

$$\gamma_2 = \frac{8(\pi - 3)}{(\pi - 2)^2}$$

3.12 Log Normal Distribution

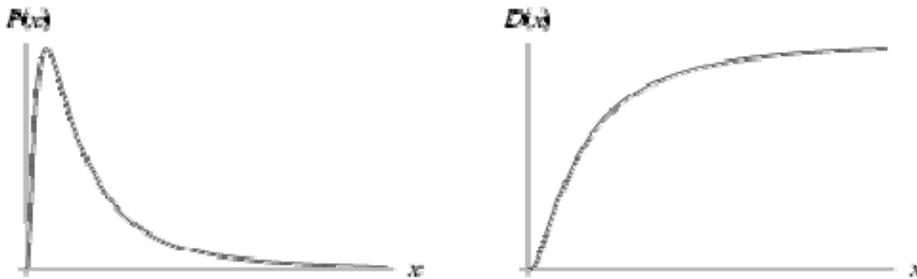


Figure 12 pdf and cdf of Log Normal Distribution. Adapted from [16]

The Log Normal Distribution is a continuous distribution in which the logarithm of a variable has a normal distribution. [12] A log normal distribution results if the variable is the product of a large number of independent, identically-distributed variables in the same way that a normal distribution results if the variable is the sum of a large number of independent, identically-distributed variables.

The probability density and cumulative distribution functions for the log normal distribution are

$$P(x) = \frac{1}{S\sqrt{2\pi}} e^{-(\ln x - M)^2 / (2S^2)}$$

$$D(x) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\ln x - M}{S\sqrt{2}} \right) \right]$$

The mean, variance, skewness, and kurtosis are given by

$$\mu = e^{M + S^2/2}$$

$$\sigma^2 = e^{S^2 + 2M} (e^{S^2} - 1)$$

$$\gamma_1 = \sqrt{e^{S^2} - 1} (2 + e^{S^2})$$

$$\gamma_2 = e^{4S^2} + 2e^{3S^2} + 3e^{2S^2} - 6$$

3.13 The Experimental Design/Simulations

An empirical experiment was conducted in order to compare the powers and type I errors of the tests for equality of variances under various conditions. Each simulation was conducted as many as 10,000 iterations. Two samples of various sizes from a particular distribution were taken in each iteration. The Levene's test, Levene/Med test, Count Five, Bartlett's test, Bhat's modification of Bartlett's test, F test, Shoemaker's modification of F test, two bootstrap tests, and permutations test statistics were calculated and equality of variances were tested at significance level $\alpha = 0.05$. When the two samples from a population have the same variance, the type I error of tests were produced. Each simulation was conducted under one combination of sample size and ratio of variances. Four ratios of population variances were used in this study: 1:1, 1:2, 1:3, and 1:4. The last three cases simulate samples from the populations with different variances. The sample sizes used in this experiment were $n_1 = n_2 = 20, 40, 60$.

The distributions considered in this experiment are:

Table 1 The Experiment Design

		Distributions	Kurtosis
Symmetric	Low Kurtosis	Normal	3.00
		logistic	4.20
		Student T3 (0,1)	N/A
		Lambda(0, .55, .2, .2)	
	High Kurtosis	Tukey(10)	5.38
		Laplace	6.00
Skewed	Low Kurtosis	$S_U (.9)$	82.9
		$S_B (.533, .5)$	2.13
		Half Normal()	3.78
		Extreme	5.40
	High Kurtosis	Location Contaminated (.05, 7)	10.40
		$\chi^2 (1)$	15.00
		Weibull(.5)	87.70
		Log Normal	113.90

There are two criteria that we are concerned with in this study in order to compare the performances of the tests for equality of variances – power and capability to control type I error. Type I error in our experiment is the probability of false rejection of equality of variance. This is calculated by counting the number of rejections of H_0 when the underlying populations have equal variances. The power of a statistical test is the probability of rejecting the null hypothesis when H_1 is true, therefore H_0 should be rejected. The power of the test is calculated by counting the number of rejections of H_0 when the underlying populations have unequal variances.

3.14 The Computations

The computation of probability of type I error and power of 10 statistics under 12 different configurations (3 sample sizes and 4 ratios of variances) were completed using Gauss. The structure of the program is as follows:

1. Population distribution from underlying distributions

Every distribution of population was created in our Gauss program either by implementing its built-in functions (normal distribution) or by utilizing the transformed distribution technique that was discussed in chapter 3. Two equal-sized random samples were drawn following the distribution.

2. Proportion of sample variance

The sample variances of two groups sampled from two populations were in ratio 1:1 (H_0 is true); 1:2, 1:3 and 1:4 (H_1 is true). This is implemented by multiplying the second sample with a scalar (1.414, 1.732 and 2).

3. The test statistics and power

The ten test statistics (Levene’s test, Levene/Med test, Count Five, Bartlett’s test, Bhat’s modification of Bartlett’s test, F test, Shoemaker’s modification of F test, two bootstrap tests and permutations) were calculated using the definitions in chapter one. We conducted 10,000 iterations under each configuration. The proportion of rejection of H_0 among a total of 10,000 iterations is the power of the test when H_1 is true, otherwise it is the type I error.

Table 2 the Experiment Plan

Population Distributions	Sample Size n_1 n_2	Population variances ratio	H_0	H_1	Result
Normal	20, 20	1:1	$\sigma_1^2 : \sigma_2^2 = 1:1$	$\sigma_1^2 : \sigma_2^2 \neq 1:1$	Type I error
		1:2			Power
		1:3			Power
		1:4			Power
	40, 40	1:1	$\sigma_1^2 : \sigma_2^2 = 1:1$	$\sigma_1^2 : \sigma_2^2 \neq 1:1$	Type I error
		1:2			Power
		1:3			Power
	60, 60	1:1	$\sigma_1^2 : \sigma_2^2 = 1:1$	$\sigma_1^2 : \sigma_2^2 \neq 1:1$	Type I error
		1:2			Power
1:3		Power			
Other Distributions

4 SIMULATION RESULTS

Figure 13 – Figure 26 show the type I errors and powers when various distributions were studied under different sample sizes and variances. The parameters of the distributions were listed in chapter three.

χ^2 Distribution (Figure 13)

When the underlying population distribution is the χ^2 distribution, most tests do not work well under smaller sample sizes (< 40) and smaller variance ratios (1:2, 1:3). Lev/Med and Bootstrap2 give slightly higher powers than other tests. When sample size is small (≤ 20), Lev and Bootstrap2 are recommended since they are more powerful than all others. Bootstrap2 has slightly higher type I error and power than Lev/Med. The modified tests lost power compared to original tests. Permutation has higher power than Count Five. Lev/Med works better when larger sample size is considered.

S_U Johnson Distribution (Figure 14)

When the underlying population distribution is the S_U Johnson distribution, Levenes, Bootstrap2 and Permutation perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4). The F test shows type I error above 0.25; in the mean time, Count Five gives much less than average power. Bootstrap2 shows slightly higher power than the other tests when the sample size is small (≤ 20). When the sample size is large (> 20), Levene and Lev/Med are recommended since they are powerful and control type I error better than Bootstrap2. The modified tests lose power again compared to original tests. Permutation has better performance (power) than Bhat, F-Shoemaker and Count Five.

Extreme Value Distribution (Figure 15)

When the underlying population distribution is the extreme value distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4). The F test, Levene and Bootstrap2 are the most powerful tests among them. However, the F test

has larger type I error, 0.14 – 0.17, than Lev and Bootstrap2. Lev/Med, Bhat and F-Shoemaker lose power against their original version, which could be considered as a tradeoff between type I error and power of tests. All modified editions – Lev/Med, Bhat and F-Shoemaker – have lower type I error than their original versions. Permutation has low type I error (0.05) and relatively high power. When type I error is considered, the Permutation test is preferred. Count Five has the lowest power among all tests, thus it is not recommended.

Half Normal Distribution (Figure 16)

When the underlying population distribution is the Half Normal distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4). The F test, Levene and Bootstrap2 give slightly higher powers than other tests, however they produce higher type I error (0.05 vs. 0.1). When sample size is small (≤ 20), the F test, Levene and Bootstrap2 are recommended since they are 10% more powerful than all others. The modified tests lost power again compared to original tests. Permutation has the best balance between power and type I error when sample size is less than 40. Lev/Med works better when larger sample size is considered. Count Five works almost identically as other common tests. It presents slightly lower power when the sample size is small.

Lambda Distribution (Figure 17)

When the underlying population distribution is the Lambda distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4) except the F test and Count Five. The F test shows type I error above 0.25; in the meantime, Count Five gives much less than average power. Bootstrap2 shows slightly higher power than other tests but produces a higher type I error (0.1 vs. 0.05) when sample size is small. When the sample size is large (> 20), Lev and Lev/Med are recommended since they are 10% more powerful than all others and control type I error better than Bootstrap2. The modified tests lose power again compared to original tests. Permutation has better performance (power) than Bhat and F-Shoemaker.

Laplace Distribution (Figure 18)

When the underlying population distribution is the Laplace Distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4) except the F test and Count Five. The F test shows type I error about 0.2; in the mean time, Count Five gives much less than average power. Bootstrap2 shows slightly higher power than other tests but produces a higher type I error (0.1 vs. 0.05) when sample size is less than 40. When sample size is greater than 40, Lev, Lev/Med and permutation tests are preferred.

Location Contaminated Distribution (Figure 19)

When the underlying population distribution is the Location Contaminated Distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4) except Count Five, since this distribution is pretty much normal. Bootstrap2 delivers the most power especially when sample size is small, but its type I error is still larger than 5%. When type I error is considered, Permutation and Lev are recommended.

Logistic Distribution (Figure 20)

The simulation result of Logistic Distribution is similar to that of Location Contaminated Distribution. The F test is as powerful as Bootstrap2 and all other tests perform almost identically except Count Five. The Count Five test is far less powerful than others. The modified versions of tests lose power compared to their original ones.

Log Normal Distribution (Figure 21)

When the underlying population distribution is the Log Normal Distribution, the F test and Lev failed to control type I error. Bootstrap2 has better power when sample size is less than 40. Lev/Med is preferred when type I error should be seriously controlled. Lev/Med gains power faster than Bootstrap2 as sample size increases. All other tests control type I error well but lack power. This distribution has an extremely large kurtosis.

S_B Johnson Distribution (Figure 22)

When the underlying population distribution is the S_B Johnson Distribution, most tests perform well under larger sample sizes (> 20) and larger variance ratios (1:3, 1:4). Bhat and F-Shoemaker tests are conservative and have relatively low power. The F test, Lev, Bootstrap2 and Count Five show the best performance when sample size is small. We were surprised to see the F test controls type I error well and Count Five test shows high power also under this distribution. The S_B distribution under these parameters is skewed with low kurtosis.

Student T Distribution (Figure 23)

When the underlying population distribution is the Student T Distribution, once again Lev, Lev/Med and Bootstrap2 show the best performance. Type I error is under control and high power is presented. Bhat and Permutation give moderate results; they show moderate power under all situations. F-shoemaker and Count Five give the lowest power and they are not preferred. The F test presents much higher type I error than all other tests. (0.25 vs. 0.05)

Tukey Distribution (Figure 24)

When the underlying population distribution is the Tukey T Distribution, Bootstrap2 shows the best performance. The F test shows highest power and also the highest type I error. Bootstrap2 has a slightly higher type I error and higher power than the others.

Weibull (0.5) (Figure 25)

When the underlying population distribution is the Weibull(0.5) distribution, the F test, Lev and Bootstrap2 are the most powerful tests among ten tests under all situations. However, the F test and Lev have larger type I errors (0.25 – 0.6) than Bootstrap2. All other tests show low power in this simulation. Lev/Med, Bhat and F-Shoemaker lose power against their original versions. No test provides a satisfactory performance under this high kurtosis distribution.

Normal (Figure 26)

Simulation result of Normal distribution is provided as a reference to all distributions.

Type I Error and Power of tests. X axis shows variance ratios and sample sizes.

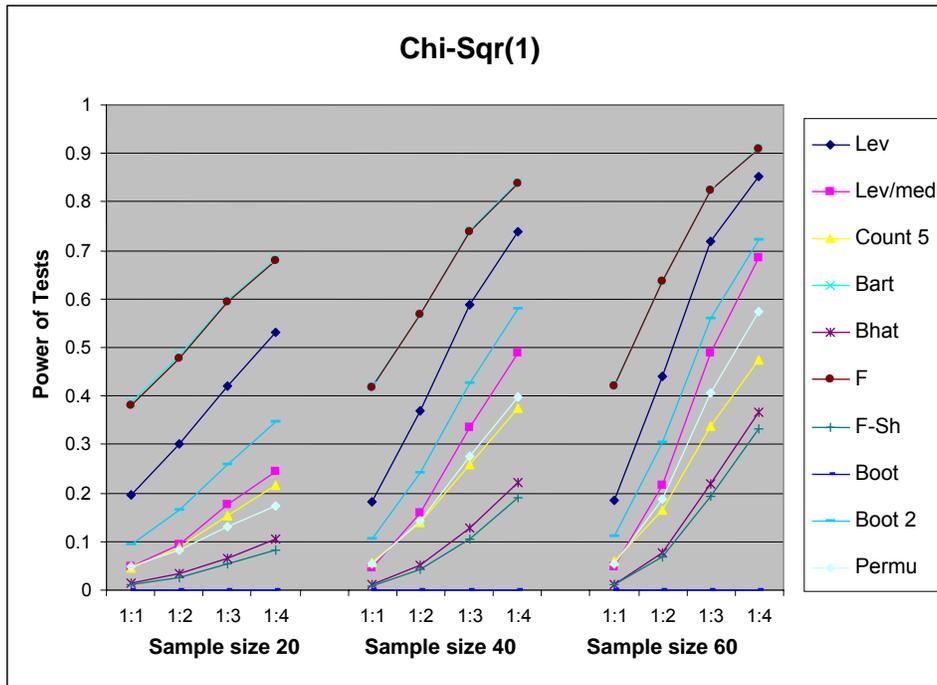


Figure 13 Simulation Result χ^2 Distribution

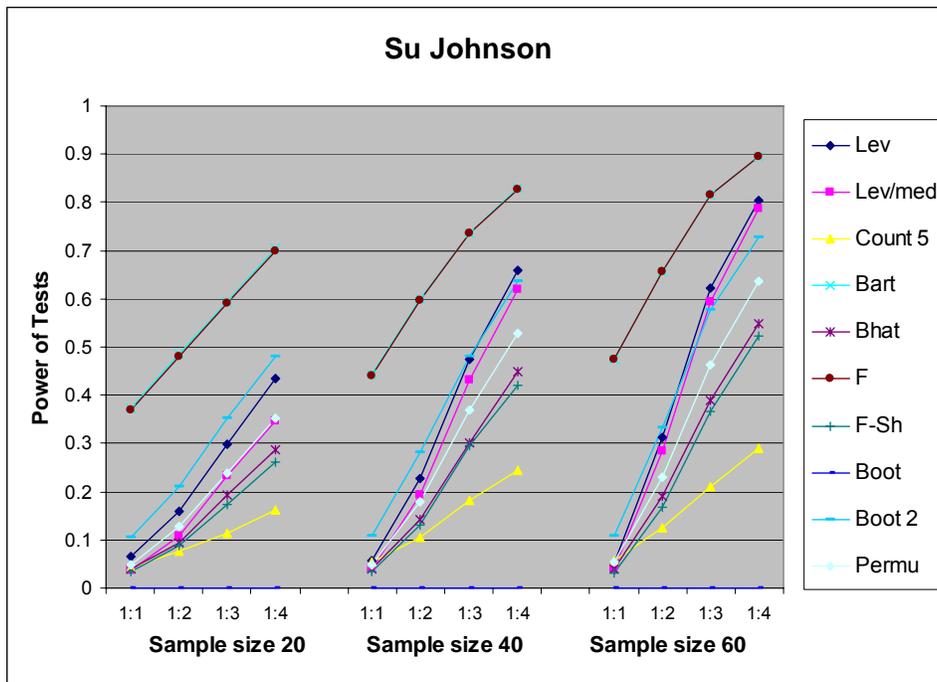


Figure 14 Simulation Result S_U Distribution

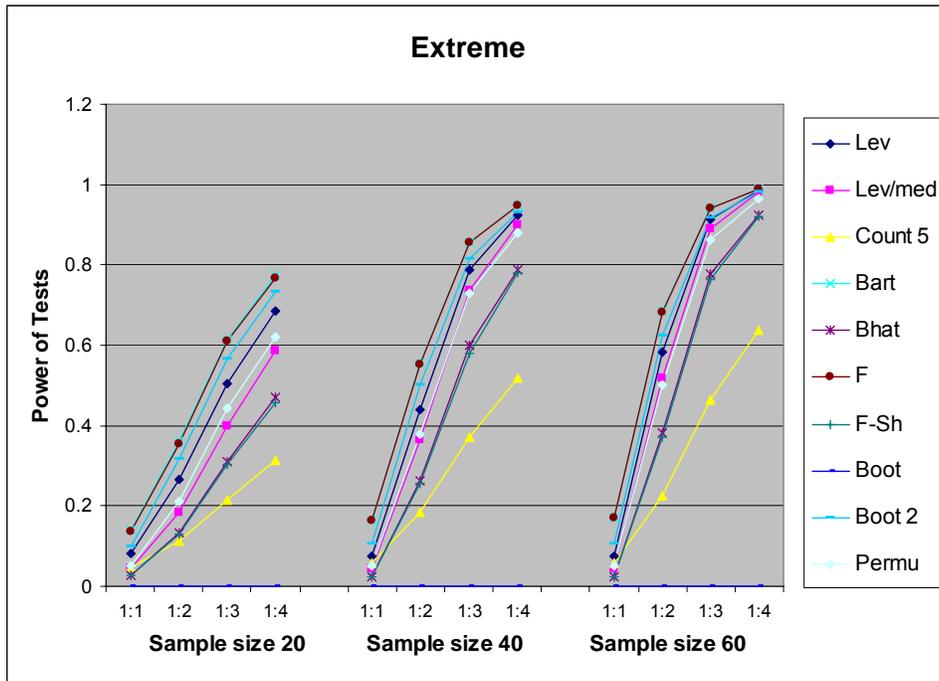


Figure 15 Simulation Result Extreme Distribution

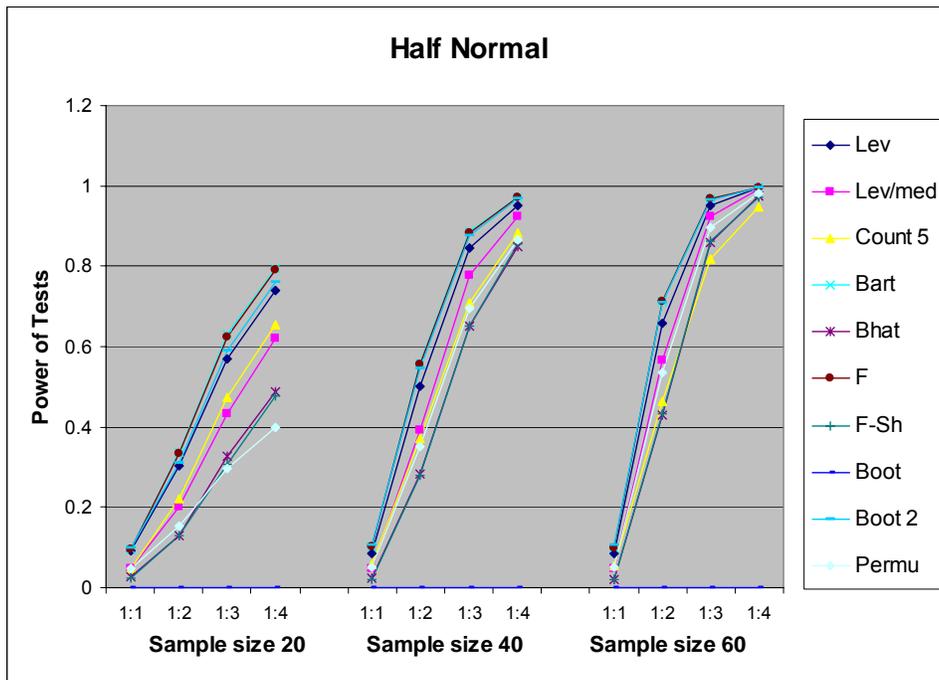


Figure 16 Simulation Result Half Normal Distribution

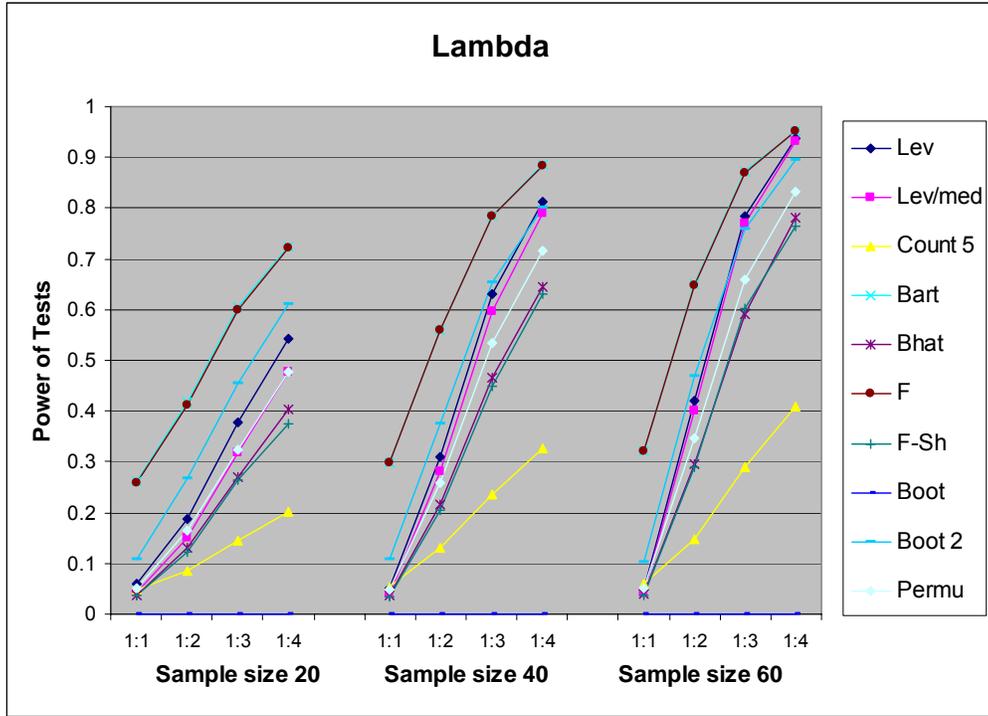


Figure 17 Simulation Result Lambda Distribution

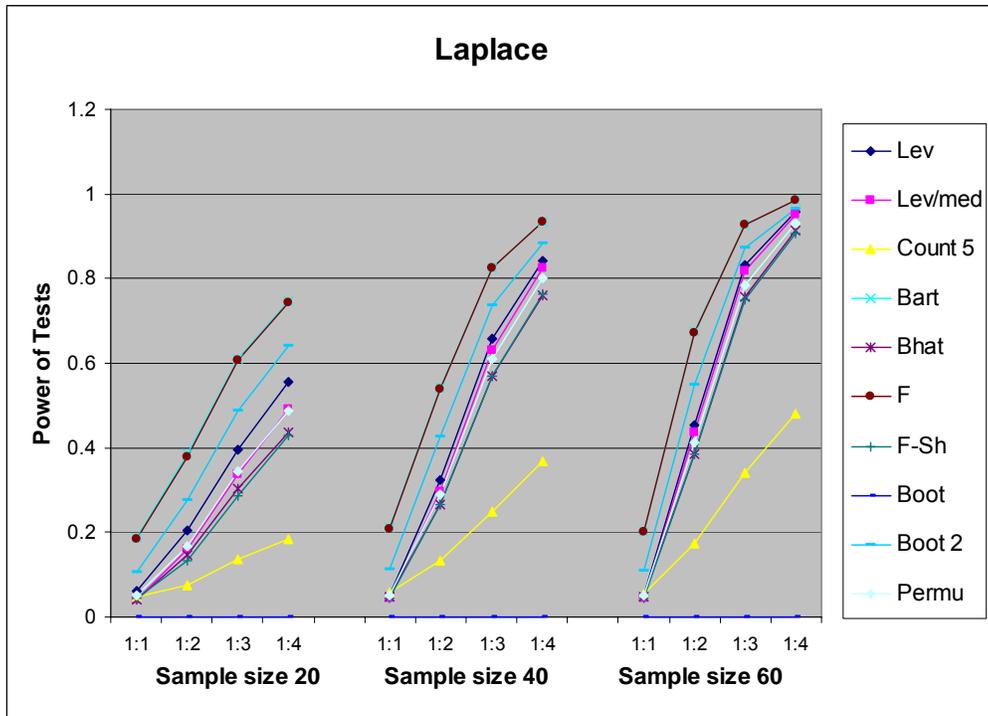


Figure 18 Simulation Result Laplace Distribution

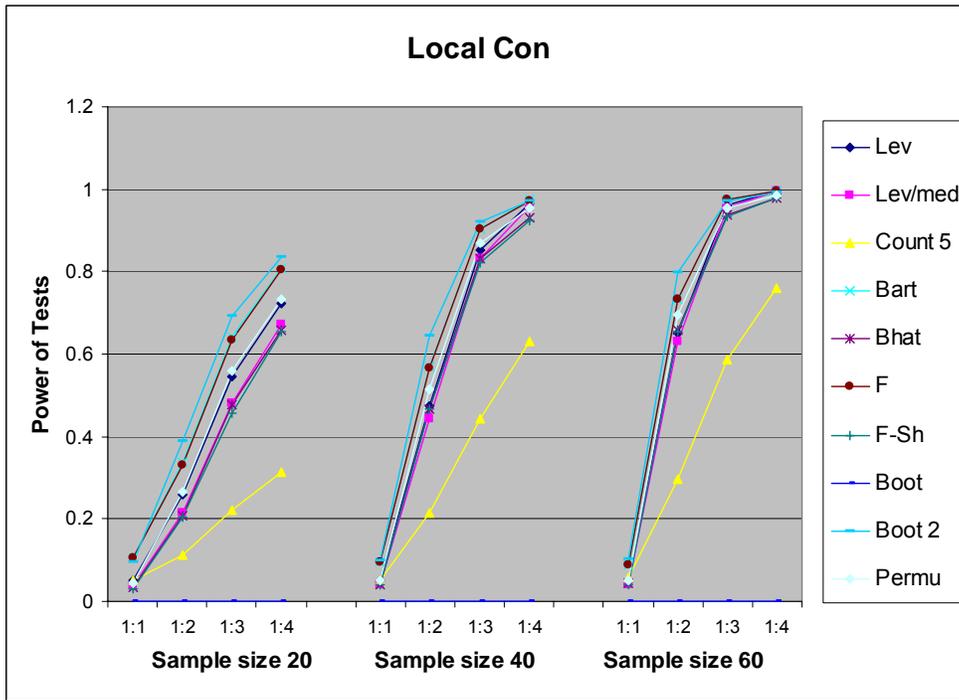


Figure 19 Simulation Result Location Contaminated Distribution

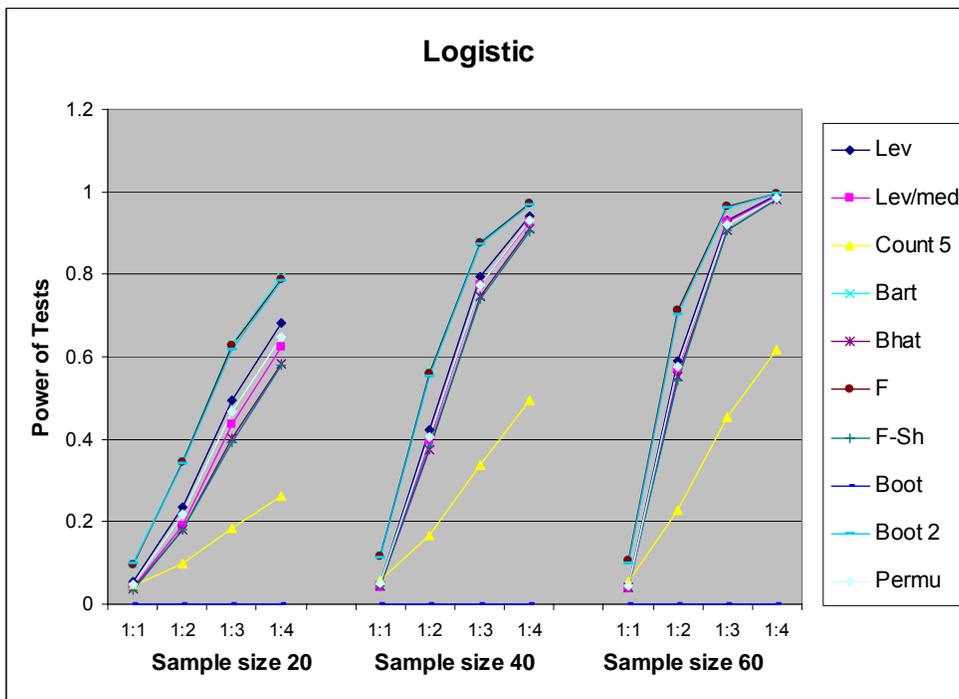


Figure 20 Simulation Result Logistic Distribution

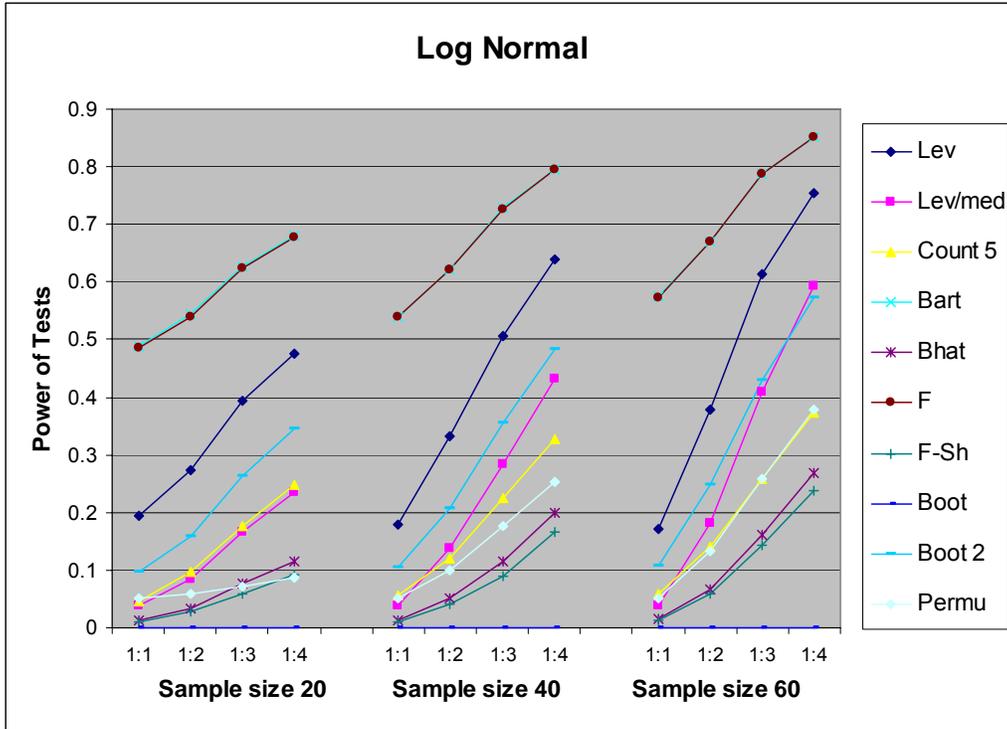


Figure 21 Simulation Result Log Normal Distribution

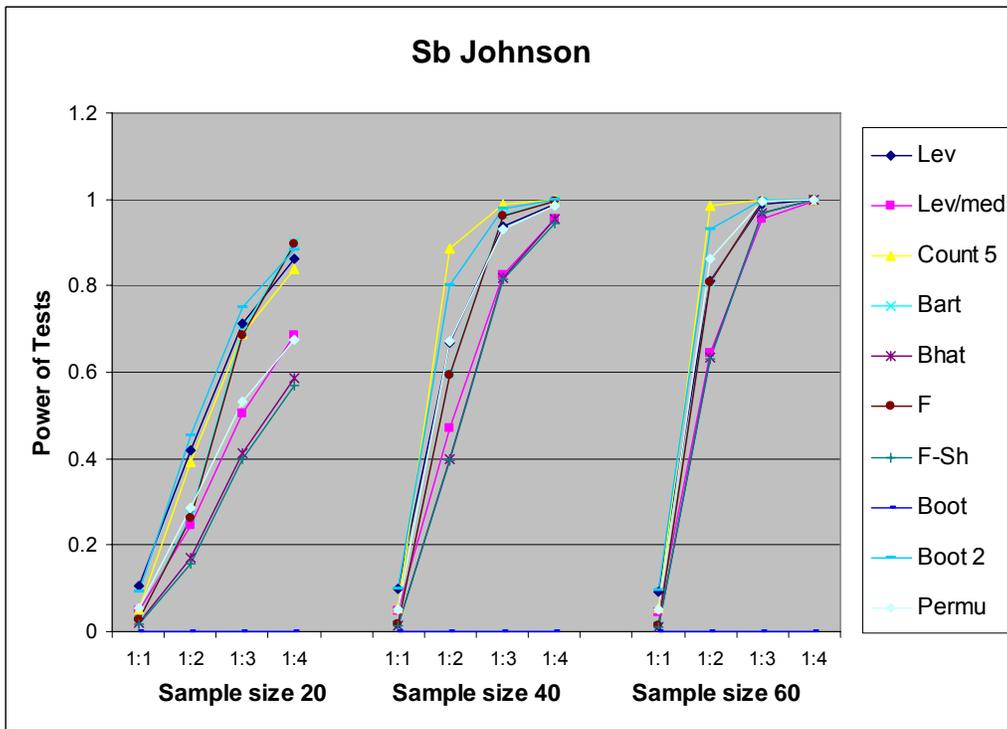


Figure 22 Simulation Result S_B Distribution

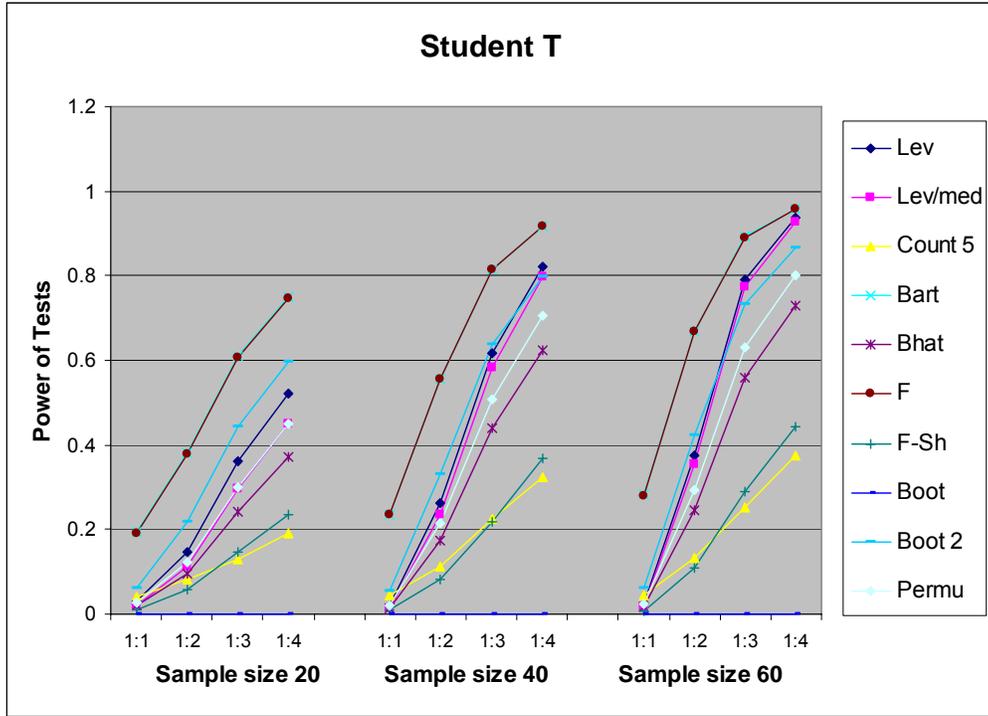


Figure 23 Simulation Result Student T Distribution

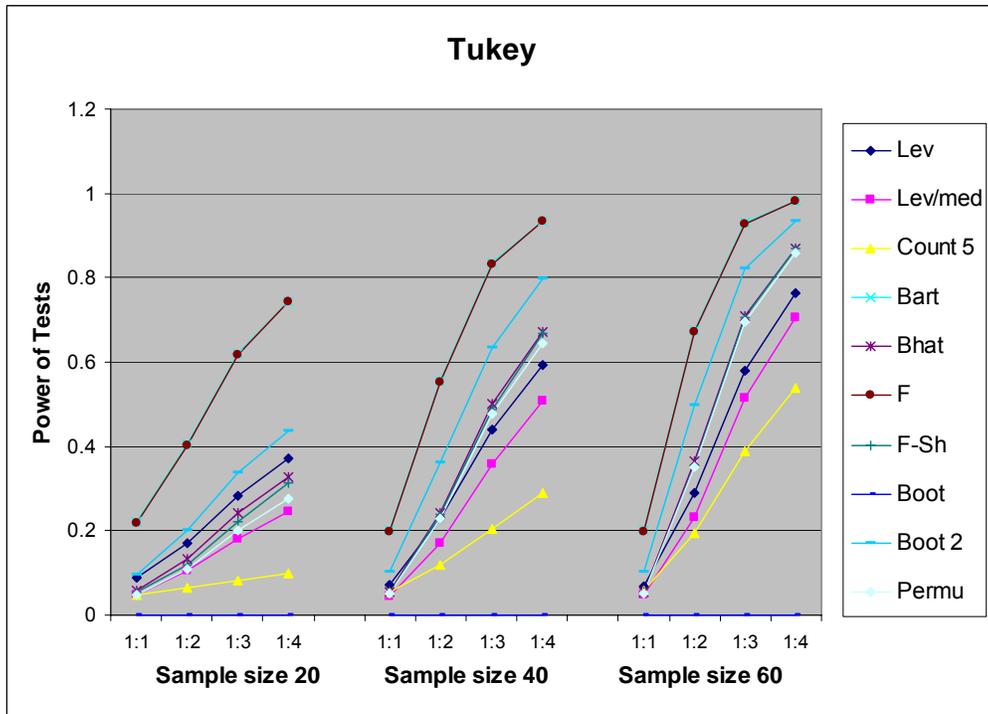


Figure 24 Simulation Result Tukey Distribution

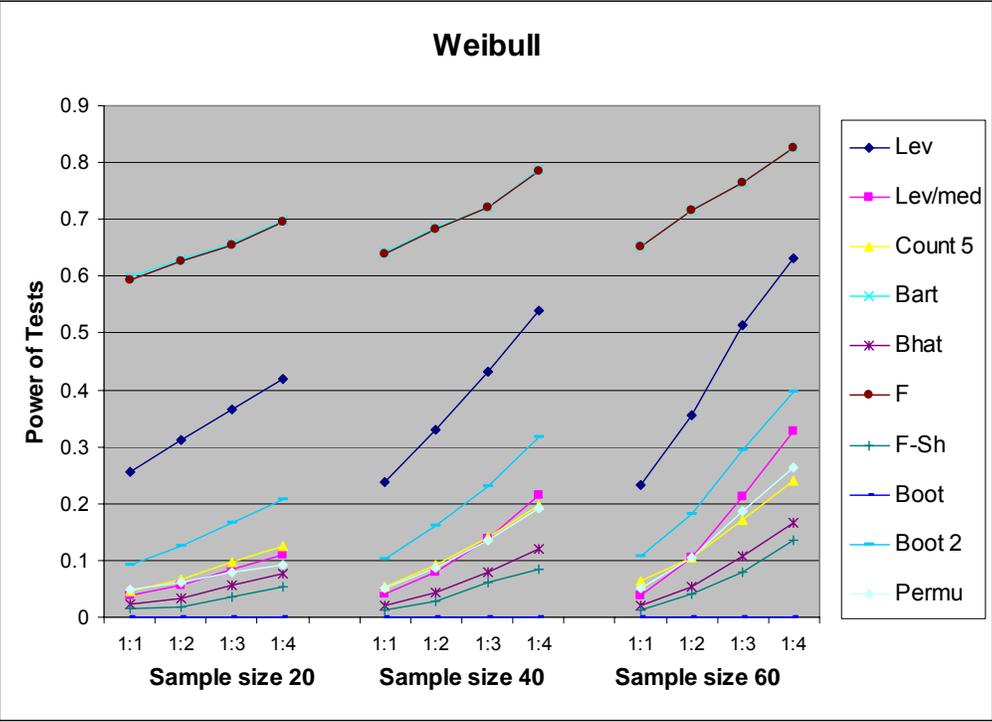


Figure 25 Simulation Result Weibull Distribution

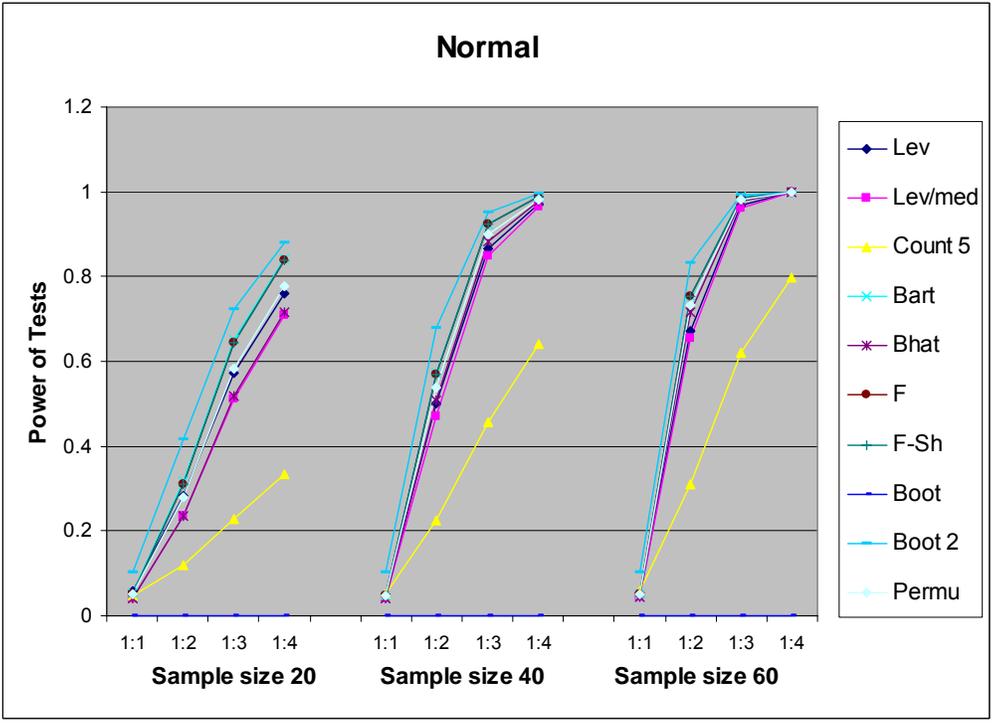


Figure 26 Simulation Result Normal Distribution

5 CONCLUSIONS

- The Bootstrap method shows a consistent performance. For the nominal type I errors of 0.05 in the simulation, the empirical type I errors are at most 0.1 and its power is always among the highest.
- Levene's test achieves its best performance when the underlying distribution has low kurtosis.
- All modified editions – Lev/Med, Bhat and F-Shoemaker – have lower type I error than their original versions.
- Except F test and Bartlett's test, all other tests control type I error pretty well. In the meantime, the F test and Bartlett's test present exceptionally high power in simulations. However, they cannot be compared with the others because of their poor control of type I error. Considering their high probability of type I error, these two tests actually reject most situations.
- Bootstrap and Lev/Med keep the best balance between type I error and power of the test. Bootstrap works slightly better at smaller sample sizes (≤ 20), Lev/Med has a better control of type I error (4% vs. 10%).
- The Permutation test and Lev/Med are the two best choices when strict control of type I error is required. Lev/Med has a slightly higher power than the Permutation test.
- No tests work well under high kurtosis distribution.
- The Count Five method is simple but its performance is very poor when kurtosis of distribution is not very small (< 3.0).

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