

A nonparametric maximum test for the Behrens-Fisher problem

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Abstract: Non-normality and heteroscedasticity are common in applications. For the comparison of two samples in the nonparametric Behrens-Fisher problem, different tests have been proposed, but no single test can be recommended for all situations. Here, we propose combining two tests, the Welch t test based on ranks and the Brunner-Munzel test, within a maximum test. Simulation studies indicate that this maximum test, performed as a permutation test, controls the type I error rate and stabilizes the power. That is, it has good power characteristics for a variety of distributions, and also for unbalanced sample sizes. Compared to the single tests, the maximum test shows acceptable type I error control.

Key words: Behrens-Fisher problem; Brunner-Munzel test; maximum test; Welch t test

1. Introduction

Comparing two groups with regard to their location is a widespread statistical challenge.

Often, the assumptions required for classical parametric tests, i.e. normality and homogeneity of variances, are violated. Nonparametric tests were developed for non-normal data, but heteroscedasticity can still distort these tests. The Welch t test and other more robust tests can

be superior to traditional tests, but “no one robust method is ideal for all situations” (Grissom, 2000). Fagerland and Sandvik (2009a, 2009b) investigated several tests for skewed distributions and unequal variances, they also conclude that no single test can be recommended for all scenarios. Furthermore, transformations to overcome the heterogeneity of variances are also problematic (Grissom, 2000), in particular when samples are small (Neuhäuser, 2010).

When no test is ideal for all situation, one can try to combine different tests. Recently, Neuhäuser (2015) combined the t test and Wilcoxon’s rank-sum test in a maximum test. This maximum test controls the type I error rate and is a more powerful strategy than always selecting one of the single tests. The principle of using the maximum of several competing test statistics as a new statistic, combined with using the permutation distribution of the maximum for inference, is common in areas such as statistical genetics (Neuhäuser and Hothorn, 2006).

Here, we apply the idea of a maximum test to the non-parametric Behrens-Fisher problem. In the nonparametric Behrens-Fisher problem, one does not test the general alternative of any difference between the distribution functions of the two groups. Instead, one tests whether there is a tendency towards smaller, or larger, values in one group. An appropriate null hypothesis is $H_0^{BF}: p = 0.5$, with p being the relative effect defined as $p = P(X_i < Y_j) + 0.5 P(X_i = Y_j)$, where X_i and Y_j are observations in group 1 and 2, respectively. The random variable X tend to take smaller values than the random variable Y if $p > 0.5$; X tends to take larger values than Y , if $p < 0.5$; stochastic equality holds if $p = 0.5$ (Neuhäuser, 2012; Brunner and Munzel, 2013).

A possible test for the nonparametric Behrens-Fisher problem was proposed by Brunner and Munzel (2000). Other suitable test statistics might be the two-sample t test and the Welch t test, both based on ranks. The latter tests were proposed since stochastic equality

is equivalent to the equality of expected values of rank scores (Vargha and Delaney, 1998). However, it should be noted that these t tests have a heuristic justification only, their appropriateness and robustness for the nonparametric Behrens-Fisher problem is based on empirical studies only (Delaney and Vargha, 2002). In general, the rank transformation is not valid in the Behrens-Fisher problem (Brunner and Munzel, 2013). Indeed, even the rank Welch t test can become liberal (i.e. taking a true type I error rate greater than the nominal level) when the variance difference between the groups is large, and for discrete distributions when sample sizes are small. However, Cribbie et al. (2007) demonstrated in a simulation study that both the Brunner-Munzel test and the Welch t test based on ranks control the type I error rate for a wide range of situations. With regard to power, the Welch t test was superior to the Brunner-Munzel test across the situations explored.

In this article, we investigate several tests, including some maximum tests, in a simulation study, and apply the proposed test to an example data set.

2. Methods

We compare two independent random samples X_1, \dots, X_n and Y_1, \dots, Y_m , where $X_k \sim F_1$ i.i.d., $k = 1, \dots, n$, and $Y_i \sim F_2$ i.i.d., $i = 1, \dots, m$, $N = n + m$. The distribution functions F_1 and F_2 are arbitrary distributions, but one-point distributions are excluded. We perform two-sided tests for the non-parametric Behrens-Fisher problem, i.e.

$$H_0^{BF}: p = 0.5 \text{ versus } H_1^{BF}: p \neq 0.5.$$

In the case of symmetric distributions with finite expected values, testing stochastic equality is equivalent to the test of equality of expected values. Therefore the classical parametric Behrens-Fisher problem is a special case of the non-parametric Behrens-Fisher problem (Neuhäuser, 2012).

As test statistics we consider the classical t test as well as the Welch t test (both based on ranks), and the test proposed by Brunner and Munzel (2000). Brunner and Munzel's test

statistic is based on ranks too; for $\min(n, m) \geq 10$ its null distribution can be approximated by a t distribution (Brunner and Munzel, 2000).

As a new test we combine two of the three above-mentioned test statistics. In order to make the statistics comparable, they are standardized by dividing each statistic t_i by its standard deviation sd_i . Since the statistics used are approximately t distributed, the standard deviation sd_i is approximated by the corresponding degrees of freedom, i.e. $sd = \sqrt{\frac{df}{df-2}}$.

Because we consider the two-sided test, the absolute values of the standardized test statistics are used to construct the maximum test statistic as follows:

$$t_{MAX} = \max\left(\left|\frac{t_1}{sd_1}\right|, \left|\frac{t_2}{sd_2}\right|\right)$$

with t_1 and t_2 one of the above-mentioned test statistics t_{rank} , t_{Wrank} or t_{BM} .

The single tests as well as the maximum tests are performed as permutation tests, i.e. the inference is based on the permutation null distribution of the test statistic (see e.g. Berry et al., 2016). Thus, the tests can also be used in the presence of ties as well as for small samples. The p-value of the permutation test is the proportion of permutations where the corresponding absolute value of the respective test statistic is higher than or equal to the absolute value of the statistic computed for the original data. The permutation test can be based on all possible permutations, in total $\binom{N}{n}$ permutations, or as an approximate permutation test based on a simple random sample of permutations.

Permutation tests require the exchangeability of the observations (see e.g. Berry et al., 2014), thus they can be carried out for the general alternative $F_1 \neq F_2$. This is not guaranteed for our situation because the two distributions functions F_1 and F_2 can differ under H_0^{BF} . However, Neubert and Brunner (2007) showed that a permutation test with the Brunner-Munzel test statistic can guarantee the type I error asymptotically for testing H_0^{BF} . Therefore, and because of their simulation results, Neubert and Brunner (2007) proposed the permutation

test with the Brunner-Munzel statistic. We also use this approach of Neubert and Brunner (2007) including the way they compute the variance of the Brunner-Munzel statistic.

Note that, by choosing t_{rank} as the test statistic, the Wilcoxon rank-sum test is applied indirectly, because t_{rank} is a monotone function of the Wilcoxon rank-sum statistic (Conover and Iman, 1981).

In order to evaluate differences between the actual type I error rates and the nominal significance level α , Bradley's (1978) liberal criterion is used. According to this criterion for robustness, applied by other recent investigations such as Haidous and Sawilowsky (2013) and Nguyen et al. (2016), an actual rate between 0.5α and 1.5α is deemed acceptable.

3. Simulation Study

In a simulation study performed with R (using the libraries `stats` and `lawstat`), we evaluate the maximum tests as well as the single tests. All tests were carried out as permutation tests. As mentioned above, in the non-parametric Behrens-Fisher problem we cannot conclude that a permutation test guarantees the nominal significance level. Therefore, it is important to investigate the actual type I error as well as the power of the investigated tests.

We consider different distributions, including the distributions discussed by Neubert and Brunner (2007). The distributions are:

- (i) Two normal distributions $X \sim N(0,1)$ and $Y \sim N(shift, \sigma_Y^2)$
- (ii) Two uniform distributions $X \sim U[0,1]$ and $Y \sim U[shift, shift + \sigma_Y]$
- (iii) Two Poisson distributions $X \sim Pois(\lambda = 5)$ and $Y \sim \sigma_Y \cdot Pois(\lambda = 5) + shift$
- (iv) Two log-normal distributions $X \sim logNorm(\mu = 0, \sigma^2 = 1) - 1$ and
 $Y \sim \sigma_Y \cdot (logNorm(\mu = 0, \sigma^2 = 1) - 1 - shift)$
- (v) Two exponential distributions $X \sim Exp(\lambda = 2) - \frac{\ln(2)}{2}$ and

$$Y \sim \sigma_Y \cdot \left(\text{Exp}(\lambda = 2) - \frac{\ln(2)}{2} - \text{shift} \right)$$

By choosing the values 1, $\sqrt{2}$, and 2 for the parameter σ_Y , we realize the variance ratios (VR) 1:1, 1:2 and 1:4. The distributions in situations (iv) and (v) are shifted by 1 or $\frac{\ln(2)}{2}$, respectively, in order that their medians are 0, thus for $\text{shift} = 0$ the medians of both groups are equal.

The distributions discussed in Neubert and Brunner (2007) are a normal distribution against one χ^2 distribution and two bimodal distributions:

(vi) A normal distribution $X \sim N(\mu = 2.5745, \sigma^2 = 2)$ against a χ^2 distribution

$$Y \sim \chi_{df=3}^2 + \text{shift}$$

(vii) Two bimodal distributions $X \sim 0.7 \cdot N(\mu = 4, \sigma^2 = 1) + 0.3 \cdot N(\mu = 8, \sigma^2 = 1)$ and

$$Y \sim 0.3 \cdot N(\mu = 2.07 + \text{shift}, \sigma^2 = 2) + 0.7 \cdot N(\mu = 3 \cdot (2.07 + \text{shift}), \sigma^2 = 2)$$

The VR in (vi) is 1:3 and the VR in (vii) is 1:2. By setting $\text{shift} = 0$ in (vi) and (vii) the relative effect p is equal to 0.5.

Simulations were performed for balanced and unbalanced sample sizes with $(n, m) = (10, 10)$, $(10, 20)$, and $(20, 10)$, combined with the different variance ratios mentioned above. For each configuration, 10,000 simulation runs were performed, in each run 1,000 permutations were chosen to compute p-values.

Figures 1 and 2 display simulated actual type I error rates for the three possible maximum tests. The Brunner-Munzel test is denoted by BM, the Welch t test based on ranks by Wranks, and the t test based on ranks by Tranks. For both the normal (Fig. 1) and the uniform (Fig. 2) distribution Tranks, i.e. the t test based on ranks, is not robust, its size can be outside the limits set by Bradley's liberal criterion. As a consequence, a maximum test including Tranks, is not robust, either (see Fig. 2). In contrast, the maximum test using Wranks

and BM has a type I error rate much closer to α . Therefore, we propose the maximum test with Welch t statistic on ranks and the Brunner-Munzel statistic. As the displayed results indicate, this maximum test has a type I error rate relatively close to the nominal level 5%, often closer to 5% than the single tests, in particular when the smaller sample has the higher variance, a situation where all the single tests are liberal. Further results for this maximum test using Wrank and BM are presented below.

Fig. 1 and 2 about here

Tables 1 to 3 show the simulated type I error rates and the power of the proposed maximum test with Welch t statistic on ranks and the Brunner-Munzel statistic (abbreviated by MAX) and the single tests used to construct this maximum, for different distributions (log-normal, exponential, and Poisson). Again, the tests are robust according to Bradley's criterion, the maximum test's control of the type I error rate seems acceptable and is usually better than that of the single tests. The results for the distributions (vi) and (vii) are similar, see Table 4.

For all investigated distributions the maximum test stabilizes the power; the power of the maximum is always between the powers of the single tests, often the maximum test has a power similar to that of the more powerful of the two single tests.

Above, the nominal significance level 5% was used. However, we also investigated the nominal levels 1%, 2.5% and 10%. In these cases, the results are analogous, see Supplementary tables 1-3. The tests Wrank, BM and the proposed maximum test consisting of these two tests are robust according Bradley's criterion. The proposed maximum test violates Bradley's criterion only in the case of $\alpha = 1\%$ with a variance ratio 1:4 (smaller group has larger variance) for the exponential and the Poisson distribution: in these two cases the simulated type I error rate is 0.016 (Supplementary table 1), slightly outside the range 0.005 to 0.015 defined by Bradley's liberal criterion. The single tests violate Bradley's criterion

more clearly and a few times more often. However, there are also scenarios where one of the single tests has a type I error closer to α than the maximum test, in particular for $\alpha = 10\%$.

Table 1. Simulated type I error rates and power in the case of the log-normal distribution ($\alpha=5\%$)

(n,m)=(10,10)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-------|-------|-------|-------|-------|-------|
| shift= | 0 | 1.5 | 0 | 1.5 | 0 | 1.5 |
| Wrank | 0.046 | 0.759 | 0.051 | 0.759 | 0.060 | 0.755 |
| BM | 0.050 | 0.737 | 0.054 | 0.725 | 0.056 | 0.717 |
| MAX | 0.050 | 0.749 | 0.054 | 0.746 | 0.058 | 0.744 |

(n,m)=(10,20)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-------|-------|-------|-------|-------|-------|
| shift= | 0 | 1 | 0 | 1 | 0 | 1 |
| Wrank | 0.049 | 0.780 | 0.054 | 0.821 | 0.067 | 0.839 |
| BM | 0.048 | 0.747 | 0.051 | 0.769 | 0.056 | 0.774 |
| MAX | 0.050 | 0.780 | 0.056 | 0.817 | 0.067 | 0.835 |

(n,m)=(20,10)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-----|---|-------|-------|-------|-------|
| shift= | 0 | 1 | 0 | 1.4 | 0 | 1.4 |
| Wrank | - | - | 0.061 | 0.738 | 0.065 | 0.732 |
| BM | - | - | 0.062 | 0.714 | 0.063 | 0.706 |
| MAX | - | - | 0.059 | 0.713 | 0.059 | 0.709 |

Table 2. Simulated type I error rates and power in the case of the exponential distribution ($\alpha=5\%$)

(n,m)=(10,10)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-------|-------|-------|-------|-------|-------|
| shift= | 0 | 0.55 | 0 | 0.5 | 0 | 0.55 |
| Wrank | 0.049 | 0.772 | 0.050 | 0.742 | 0.060 | 0.788 |
| BM | 0.051 | 0.760 | 0.053 | 0.717 | 0.058 | 0.754 |
| MAX | 0.052 | 0.767 | 0.054 | 0.729 | 0.060 | 0.777 |

(n,m)=(10,20)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-------|-------|-------|-------|-------|-------|
| shift= | 0 | 0.4 | 0 | 0.4 | 0 | 0.35 |
| Wrank | 0.049 | 0.816 | 0.054 | 0.864 | 0.066 | 0.811 |
| BM | 0.048 | 0.792 | 0.050 | 0.826 | 0.054 | 0.75 |
| MAX | 0.049 | 0.815 | 0.054 | 0.862 | 0.065 | 0.808 |

(n,m)=(20,10)

| VR= | 1:1 | | 1:2 | | 1:4 | |
|--------|-----|-----|-------|-------|-------|-------|
| shift= | 0 | 0.4 | 0 | 0.6 | 0 | 0.5 |
| Wrank | - | - | 0.056 | 0.857 | 0.065 | 0.755 |
| BM | - | - | 0.057 | 0.840 | 0.063 | 0.729 |
| MAX | - | - | 0.053 | 0.838 | 0.060 | 0.729 |

Table 3. Simulated type I error rates and power in the case of the Poisson distribution ($\alpha=5\%$)

| (n,m)=(10,10) | | | | | | |
|---------------|-------|-------|-------|-------|-------|-------|
| VR= | 1:1 | | 1:2 | | 1:4 | |
| shift= | 0 | 3 | 0 | 3.5 | 0 | 5 |
| Wrank | 0.047 | 0.795 | 0.056 | 0.769 | 0.061 | 0.826 |
| BM | 0.048 | 0.799 | 0.052 | 0.765 | 0.056 | 0.82 |
| MAX | 0.049 | 0.800 | 0.054 | 0.768 | 0.057 | 0.823 |

| (n,m)=(10,20) | | | | | | |
|---------------|-------|-------|-------|-------|-------|-------|
| VR= | 1:1 | | 1:2 | | 1:4 | |
| shift= | 0 | 2.75 | 0 | 3 | 0 | 4 |
| Wrank | 0.050 | 0.752 | 0.052 | 0.779 | 0.061 | 0.827 |
| BM | 0.050 | 0.747 | 0.047 | 0.774 | 0.049 | 0.816 |
| MAX | 0.049 | 0.739 | 0.050 | 0.775 | 0.060 | 0.828 |

| (n,m)=(20,10) | | | | | | |
|---------------|-----|------|-------|-------|-------|-------|
| VR= | 1:1 | | 1:2 | | 1:4 | |
| shift= | 0 | 2.75 | 0 | 3.25 | 0 | 5 |
| Wrank | - | - | 0.059 | 0.810 | 0.067 | 0.796 |
| BM | - | - | 0.057 | 0.809 | 0.063 | 0.783 |
| MAX | - | - | 0.055 | 0.802 | 0.058 | 0.776 |

Table 4. Simulated type I error rates and power in the case of the distributions discussed by Neubert and Brunner (2007) ($\alpha=5\%$)

| VR=1:3 distribution (vi) | | | | | | |
|---------------------------------|---------|-------|---------|-------|---------|-------|
| (n,m)= | (10,10) | | (10,20) | | (20,10) | |
| shift= | 0 | 2 | 0 | 1.75 | 0 | 1.75 |
| Wrank | 0.051 | 0.752 | 0.051 | 0.769 | 0.056 | 0.774 |
| BM | 0.052 | 0.777 | 0.046 | 0.777 | 0.056 | 0.784 |
| MAX | 0.053 | 0.777 | 0.051 | 0.773 | 0.054 | 0.779 |

| VR=1:2 distribution (vii) | | | | | | |
|----------------------------------|---------|-------|---------|-------|---------|-------|
| (n,m)= | (10,10) | | (10,20) | | (20,10) | |
| shift= | 0 | 2.25 | 0 | 1.75 | 0 | 2 |
| Wrank | 0.055 | 0.736 | 0.058 | 0.881 | 0.060 | 0.726 |
| BM | 0.056 | 0.717 | 0.054 | 0.844 | 0.057 | 0.703 |
| MAX | 0.058 | 0.728 | 0.057 | 0.878 | 0.059 | 0.698 |

The actual type I error and the power of the single tests were also simulated based on the approximate t distributions. The results are very similar to those based on the permutation approach (results not shown).

4. Example

As an example we consider data presented by Hand et al. (1994), see Table 5. Survival times were obtained for 6 patients with ovary cancer and 11 patients with breast cancer (there are no censored observations). Hence, sample sizes are small and unbalanced (for further details see also Cameron and Pauling, 1978). There are no ties, the empirical variances are 1206875 for ovary cancer and 1535038 for breast cancer, which indicates heteroscedasticity.

Table 5: Survival times of cancer patients

| | | | | | | | | | |
|--------|------|-----|------|------|------|-----|------|-----|------|
| Ovary | 1234 | 89 | 201 | 356 | 2970 | 456 | | | |
| Breast | 1235 | 24 | 1581 | 1166 | 40 | 727 | 3808 | 791 | 1804 |
| | 3460 | 719 | | | | | | | |

Data Source: Hand et al. (1994, p. 255)

There seems to be a tendency for the patients with breast cancer to have larger values. However, the tests are not significant: the p-values are 0.312 for the Welch t test on ranks, 0.320 for the Brunner-Munzel test, and 0.309 for the maximum test based on these two tests (exact permutation tests). This example shows that the maximum test can have a smaller p-value than both single tests. The absolute values of the standardized statistics are $1.041/1.100 = 0.946$ for Welch t test on ranks, and $0.995/1.089 = 0.914$ for the Brunner-Munzel test. Thus, the test statistic of the maximum test is 0.946. The R code written to analyze this example is available from the Dryad Digital Repository.

5. Discussion

Non-normal data are common in practice. Different tests have been proposed for this case, especially for the situation when non-normality is combined with heteroscedasticity. In the literature there is a large variety of studies comparing the different tests. The usual conclusion is that no single test can be recommended for all scenarios (see Introduction). A straightforward solution in such a case is to combine different tests. This combination is

possible in a maximum test. For such tests, inference can be based on the permutation null distribution of the maximum, this is useful especially when the distribution of the maximum is not known.

Recently, Neuhäuser (2015) proposed a maximum test for the location-shift model, i.e. when there is no difference in the variances of the two groups. In that case Student's t test and the Wilcoxon-Mann-Whitney test can be combined. Here, we generalize this idea for the nonparametric Behrens-Fisher problem. We propose a maximum test based on Welch's t test computed on ranks and the Brunner-Munzel statistic. Our simulation study indicates that the proposed maximum test controls the type I error and stabilizes the power. Thus, we recommend the maximum test. When applying the maximum test there is no need to select a single test. We also investigated the maximum test with all three considered single tests; however, this maximum test seems to be not better than the recommended test (results not shown).

For large sample sizes, a permutation test can be performed using a simple random sample of permutations. SAS and R programs to carry out permutation tests are given by, for example, Zieffler et al. (2011) and Neuhäuser (2012). Our R code is available from the Dryad Digital Repository.

Finally, it should be noted again that the Welch t test based on ranks, and therefore the recommended maximum test as well, have a heuristic justification only. However the Welch t test based on ranks was investigated and suggested in several studies, the appropriateness and robustness is based on large empirical studies.

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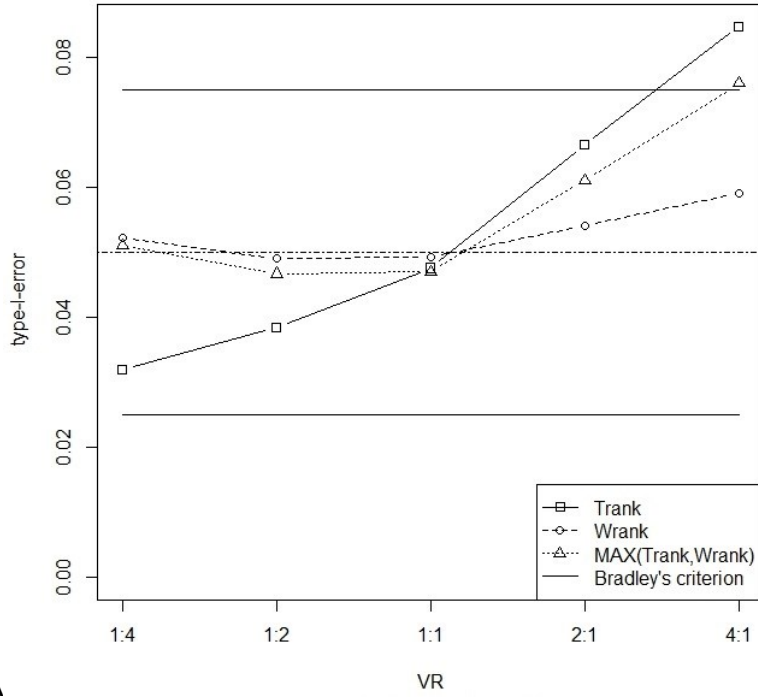
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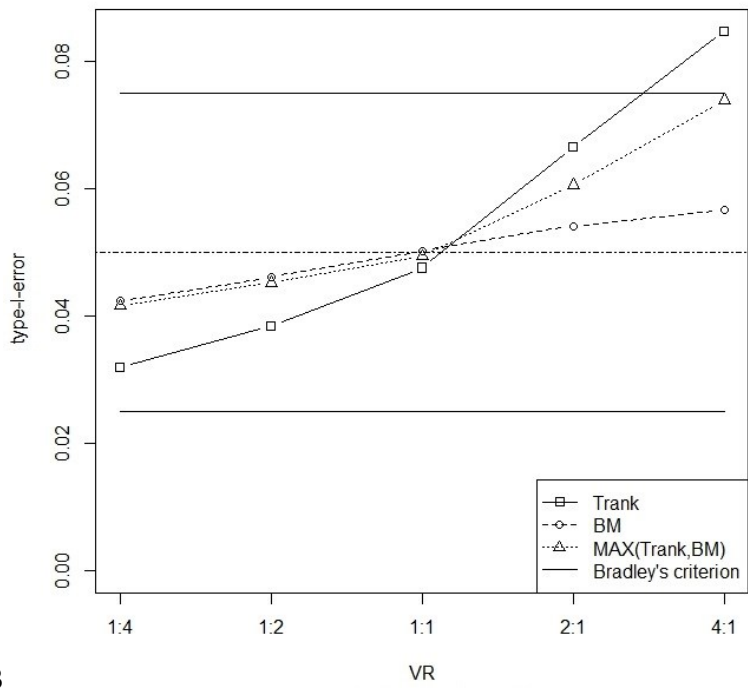
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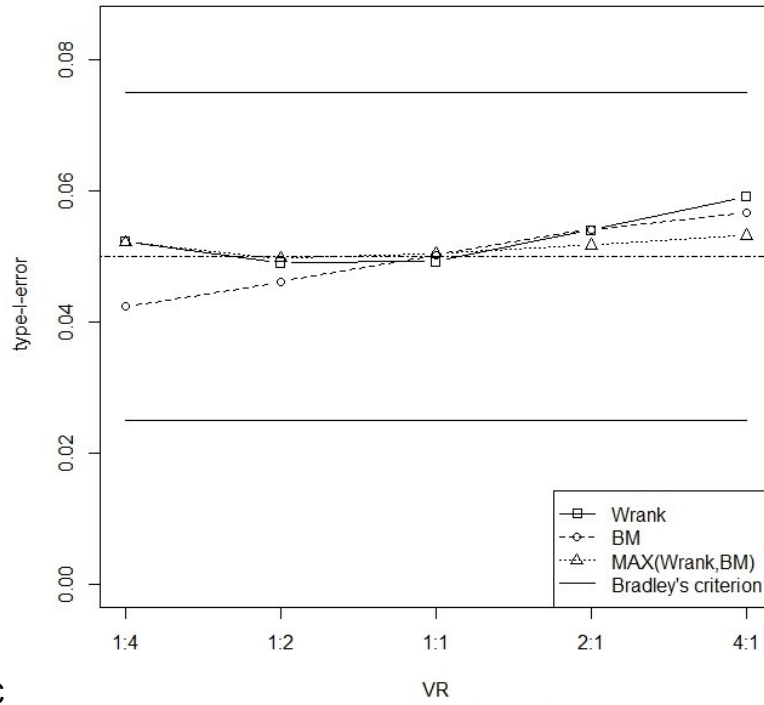
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A

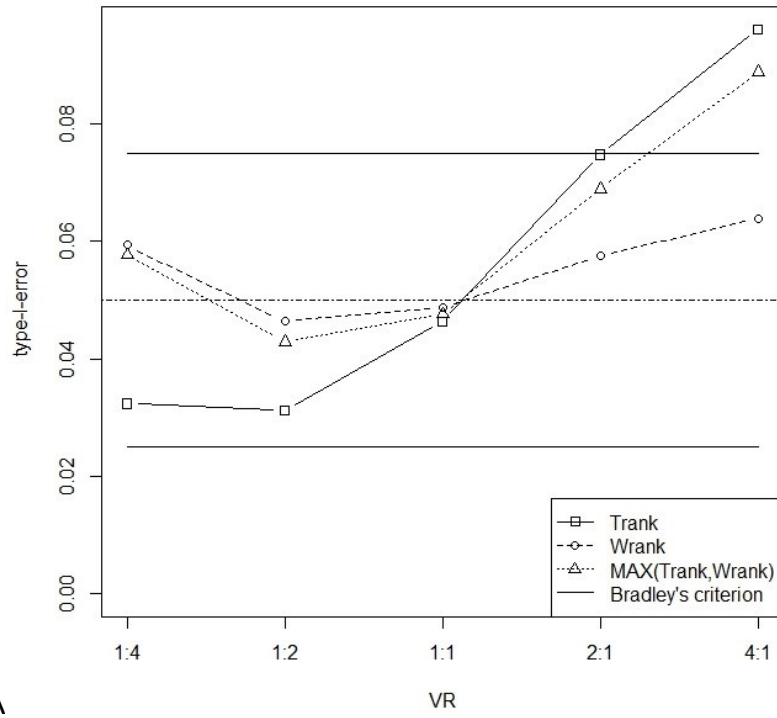


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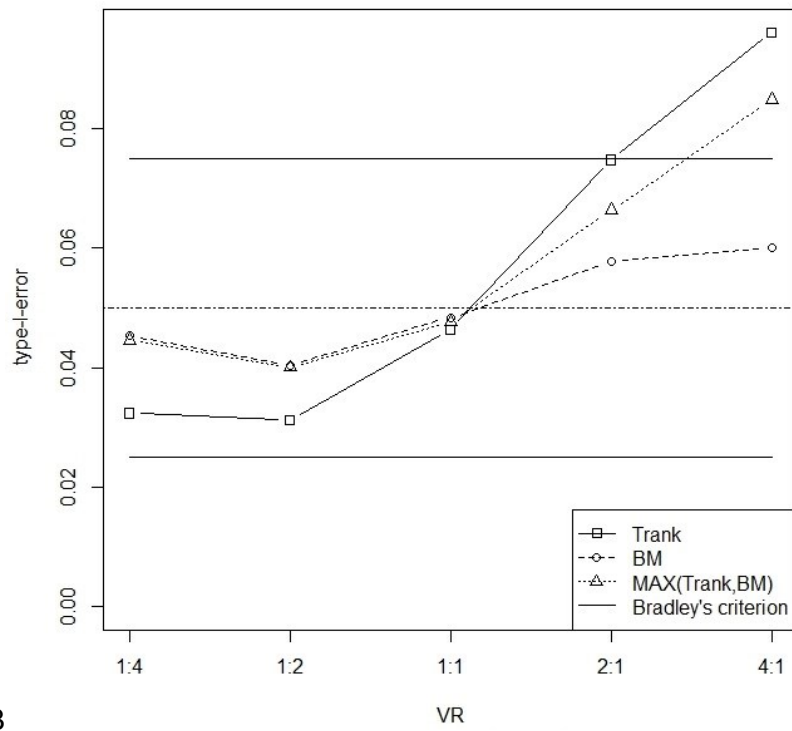


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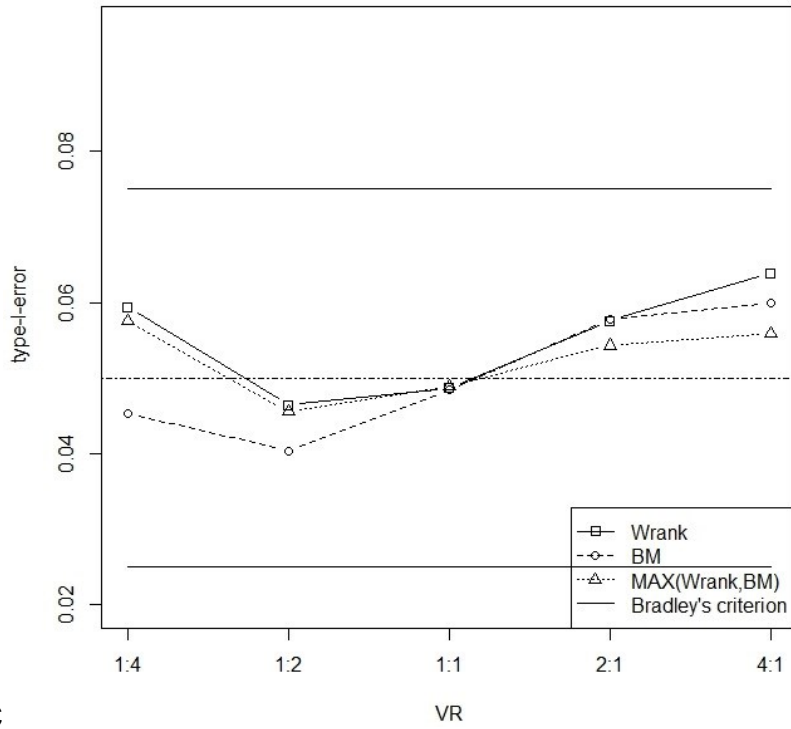
Figure 1: Simulated type I error rates in the case of the normal distribution ($\alpha=5\%$, sample sizes: $n = 10$, $m = 20$)



A



B



C

Figure 2: Simulated type I error rates in the case of the uniform distribution ($\alpha=5\%$, sample sizes: $n = 10, m = 20$)

Supplementary table 1. Simulated type I error rates for $\alpha = 1\%$

| level=1% | | sample size: 10,10 | | |
|----------|-------|--------------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.010 | 0.013 | 0.012 |
| | BM | 0.012 | 0.014 | 0.013 |
| | MAX | 0.012 | 0.014 | 0.013 |
| uniform | Wrank | 0.011 | 0.012 | 0.014 |
| | BM | 0.012 | 0.012 | 0.014 |
| | MAX | 0.012 | 0.012 | 0.013 |
| poisson | Wrank | 0.009 | 0.014 | 0.014 |
| | BM | 0.010 | 0.014 | 0.013 |
| | MAX | 0.009 | 0.013 | 0.013 |
| | | sample size: 10,20 | | |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.011 | 0.010 | 0.009 |
| | BM | 0.011 | 0.009 | 0.007 |
| | MAX | 0.011 | 0.009 | 0.008 |
| uniform | Wrank | 0.012 | 0.009 | 0.011 |
| | BM | 0.012 | 0.007 | 0.006 |
| | MAX | 0.011 | 0.008 | 0.008 |
| poisson | Wrank | 0.011 | 0.012 | 0.011 |
| | BM | 0.010 | 0.010 | 0.008 |
| | MAX | 0.011 | 0.010 | 0.010 |
| | | sample size: 20,10 | | |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | - | 0.015 | 0.016 |
| | BM | - | 0.015 | 0.016 |
| | MAX | - | 0.014 | 0.014 |
| uniform | Wrank | - | 0.017 | 0.019 |
| | BM | - | 0.017 | 0.018 |
| | MAX | - | 0.015 | 0.015 |
| poisson | Wrank | - | 0.016 | 0.019 |
| | BM | - | 0.015 | 0.018 |
| | MAX | - | 0.015 | 0.016 |

| level=1% | | sample size: | | 10,10 |
|-------------|-------|--------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.012 | 0.011 | 0.016 |
| | BM | 0.011 | 0.012 | 0.015 |
| | MAX | 0.011 | 0.012 | 0.015 |
| exponential | Wrank | 0.012 | 0.012 | 0.017 |
| | BM | 0.011 | 0.012 | 0.015 |
| | MAX | 0.011 | 0.012 | 0.015 |
| | | sample size: | | 10,20 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.010 | 0.013 | 0.014 |
| | BM | 0.010 | 0.011 | 0.011 |
| | MAX | 0.010 | 0.012 | 0.013 |
| exponential | Wrank | 0.012 | 0.011 | 0.014 |
| | BM | 0.012 | 0.010 | 0.011 |
| | MAX | 0.013 | 0.011 | 0.012 |
| | | sample size: | | 20,10 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | - | 0.016 | 0.019 |
| | BM | - | 0.016 | 0.018 |
| | MAX | - | 0.015 | 0.015 |
| exponential | Wrank | - | 0.014 | 0.020 |
| | BM | - | 0.015 | 0.019 |
| | MAX | - | 0.014 | 0.016 |

Supplementary table 2. Simulated type I error rates for $\alpha = 2.5\%$

| level=2.5% | | sample size: | | 10,10 |
|------------|-------|--------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.024 | 0.028 | 0.030 |
| | BM | 0.026 | 0.030 | 0.029 |
| | MAX | 0.026 | 0.030 | 0.030 |
| uniform | Wrank | 0.026 | 0.028 | 0.034 |
| | BM | 0.027 | 0.028 | 0.030 |
| | MAX | 0.027 | 0.029 | 0.029 |
| poisson | Wrank | 0.023 | 0.028 | 0.030 |
| | BM | 0.023 | 0.028 | 0.028 |
| | MAX | 0.023 | 0.028 | 0.029 |
| | | sample size: | | 10,20 |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.027 | 0.025 | 0.024 |
| | BM | 0.027 | 0.023 | 0.019 |
| | MAX | 0.027 | 0.025 | 0.023 |
| uniform | Wrank | 0.027 | 0.024 | 0.032 |
| | BM | 0.027 | 0.020 | 0.021 |
| | MAX | 0.027 | 0.023 | 0.030 |
| poisson | Wrank | 0.026 | 0.029 | 0.028 |
| | BM | 0.026 | 0.024 | 0.022 |
| | MAX | 0.026 | 0.027 | 0.026 |
| | | sample size: | | 20,10 |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | - | 0.029 | 0.032 |
| | BM | - | 0.029 | 0.031 |
| | MAX | - | 0.028 | 0.029 |
| uniform | Wrank | - | 0.033 | 0.038 |
| | BM | - | 0.033 | 0.037 |
| | MAX | - | 0.031 | 0.032 |
| poisson | Wrank | - | 0.033 | 0.037 |
| | BM | - | 0.032 | 0.035 |
| | MAX | - | 0.030 | 0.031 |

| level=2.5% | | sample size: | | 10,10 |
|-------------|-------|--------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.025 | 0.025 | 0.033 |
| | BM | 0.026 | 0.027 | 0.032 |
| | MAX | 0.027 | 0.027 | 0.032 |
| exponential | Wrank | 0.025 | 0.026 | 0.035 |
| | BM | 0.026 | 0.029 | 0.033 |
| | MAX | 0.026 | 0.029 | 0.033 |
| | | sample size: | | 10,20 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.024 | 0.030 | 0.035 |
| | BM | 0.025 | 0.028 | 0.026 |
| | MAX | 0.024 | 0.029 | 0.032 |
| exponential | Wrank | 0.027 | 0.029 | 0.034 |
| | BM | 0.026 | 0.026 | 0.026 |
| | MAX | 0.026 | 0.028 | 0.031 |
| | | sample size: | | 20,10 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | - | 0.032 | 0.039 |
| | BM | - | 0.033 | 0.036 |
| | MAX | - | 0.031 | 0.034 |
| exponential | Wrank | - | 0.031 | 0.041 |
| | BM | - | 0.032 | 0.040 |
| | MAX | - | 0.030 | 0.036 |

Supplementary table 3. Simulated type I error rates for $\alpha = 10\%$

| level=10% | | sample size: 10,10 | | |
|-----------|-------|--------------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.094 | 0.100 | 0.113 |
| | BM | 0.098 | 0.102 | 0.110 |
| | MAX | 0.099 | 0.104 | 0.114 |
| uniform | Wrank | 0.098 | 0.103 | 0.112 |
| | BM | 0.102 | 0.104 | 0.105 |
| | MAX | 0.103 | 0.107 | 0.111 |
| poisson | Wrank | 0.094 | 0.105 | 0.111 |
| | BM | 0.097 | 0.102 | 0.102 |
| | MAX | 0.096 | 0.105 | 0.107 |
| | | sample size: 10,20 | | |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | 0.100 | 0.102 | 0.108 |
| | BM | 0.101 | 0.098 | 0.091 |
| | MAX | 0.100 | 0.104 | 0.109 |
| uniform | Wrank | 0.101 | 0.098 | 0.121 |
| | BM | 0.100 | 0.089 | 0.098 |
| | MAX | 0.101 | 0.100 | 0.123 |
| poisson | Wrank | 0.105 | 0.107 | 0.113 |
| | BM | 0.104 | 0.100 | 0.097 |
| | MAX | 0.105 | 0.107 | 0.113 |
| | | sample size: 20,10 | | |
| VR: | | 1:1 | 1:2 | 1:4 |
| normal | Wrank | - | 0.107 | 0.116 |
| | BM | - | 0.107 | 0.109 |
| | MAX | - | 0.105 | 0.106 |
| uniform | Wrank | - | 0.108 | 0.126 |
| | BM | - | 0.107 | 0.114 |
| | MAX | - | 0.103 | 0.112 |
| poisson | Wrank | - | 0.112 | 0.117 |
| | BM | - | 0.107 | 0.113 |
| | MAX | - | 0.106 | 0.109 |

| level=10% | | sample size: | | 10,10 |
|-------------|-------|--------------|-------|-------|
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.098 | 0.101 | 0.117 |
| | BM | 0.104 | 0.102 | 0.112 |
| | MAX | 0.105 | 0.104 | 0.118 |
| exponential | Wrank | 0.095 | 0.103 | 0.119 |
| | BM | 0.100 | 0.103 | 0.114 |
| | MAX | 0.100 | 0.105 | 0.118 |
| | | sample size: | | 10,20 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | 0.099 | 0.110 | 0.127 |
| | BM | 0.099 | 0.104 | 0.112 |
| | MAX | 0.100 | 0.113 | 0.129 |
| exponential | Wrank | 0.101 | 0.112 | 0.129 |
| | BM | 0.101 | 0.107 | 0.110 |
| | MAX | 0.101 | 0.114 | 0.130 |
| | | sample size: | | 20,10 |
| VR: | | 1:1 | 1:2 | 1:4 |
| log-normal | Wrank | - | 0.110 | 0.125 |
| | BM | - | 0.109 | 0.119 |
| | MAX | - | 0.104 | 0.116 |
| exponential | Wrank | - | 0.111 | 0.129 |
| | BM | - | 0.110 | 0.122 |
| | MAX | - | 0.105 | 0.119 |