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| **Complete List of Authors** | Efang Kong,<br>Yu Liu and<br>Yingcun Xia |
| **Corresponding Authors** | Efang Kong |
| **E-mails** | singeu@live.co.uk |

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# Power Boosting: Fusion of Multiple Test Statistics via Resampling

Efang Kong[1] Yu Liu[1] and Yingcun Xia[2,1]

[1]*School of Mathematical Sciences, University of Electronic Science and Technology of China*
[2]*Department of Statistics and Data Science, National University of Singapore*

*Abstract:* For the same null hypothesis, there usually exist multiple valid test statistics. In nearly all cases, any individual statistic is only powerful against specific types of alternatives, and could be rather weak in picking up signals of other types. It is thus crucial, especially in high-dimensional settings, to combine the information contained in different test statistics in order to maintain robust power against a wide range of alternatives, thus avoiding the worst-case scenario. Methods have been proposed for similar purposes, but they are either computationally expensive or lack theoretical justification. In this paper, we present a general and easy-to-implement procedure for fusing multiple valid statistics using resampling methods, such as bootstrap or permutation. The consistency of this procedure is proved for three popular high-dimensional hypothesis testing problems. The results of numerical studies show that this fusion procedure maintains robust performance against a wide range of alternatives, whereas individual test statistics often suffer from extremely low power.

*Key words and phrases:* two-sample mean comparison; consistency of test; high-dimensional data; independence test; permutation.

## 1. Introduction

Testing high-dimensional null hypotheses has been the subject of intensive studies. One popular approach, which includes the works of Kosorok and Ma (2007), Bancroft et al. (2013), and Liang (2016), breaks the null hypothesis into multiple univariate tests, and focuses on the false discovery rate. For studies on power, the family-wise error, Kim and Akritas (2010) note that for any given null hypothesis, there usually exist multiple valid statistics, each of which may detect certain types of signals, but suffer from very low power against others. Thus the test statistic and types of alternatives are connected in terms of power enhancement or boosting. For example, with the alternative restricted to be sparse, Fan et al. (2015) shows how a given test statistic can be made consistent and more powerful for cross-sectional data. This idea of possible power enhancement against specific alternatives is later examined in a more general framework by Kock and Preinerstorfer (2019). We study a similar problem of power boosting from a different, yet more practical angle. We propose an efficient procedure for fusing statistics that could ensure robust power performance against arbitrary alternatives, thus avoiding the worst-case scenario. In this sense, fusing test statistics is particularly useful in practice when choosing between opposing recommendations made based on different test statistics.

To formulate the setup, suppose $\{T_{n,k},\, k = 1, \cdots, K\}$ is a collection of statistics, where $K$ is a fixed integer, such that for any given $k$, $H_0$ is rejected for

Correspondence should be addressed to: kongefang@uestc.edu.cn

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large $T_{n,k}$. Note that a naive form of combination, such as a weighted average $\sum_{k=1}^{K} a_k T_{n,k}$, with $a_k \geq 0$, is not a good choice, because it is difficult to specify appropriate values for the coefficients $a_k$ so that the statistical significance of one $T_{n,k}$ is not obscured by trivial variations in other $T_{n,k}$ of a larger scale. This is one of the motivating factors behind the monotone transformation of individual statistics to make them relatively comparable before being combined. One example is Fisher's combined $p$-value

$$U_n := -2 \sum_{k=1}^{K} \log(1 - F_{n,k}(T_{n,k})), \tag{1.1}$$

where $F_{n,k}(.)$ is the null distribution function of $T_{n,k}$. Its relative popularity is largely because it follows a $\chi^2(.)$ distribution if $T_{n,k}$, for $k = 1, \cdots, K$, are independent. Another related example is an equivalence of the smallest $p$-value:

$$U_n := \max_{k=1,\cdots,K} F_{n,k}(T_{n,k}), \tag{1.2}$$

and $H_0$ is rejected whenever the $p$-value associated with some $T_{n,k}$ is too small. Examples of fusion statistics like (1.1) and (1.2) both suggest that transforming $T_{n,k}$ using its distribution function into a uniform $(0, 1)$ is a reasonable choice. However, be it (1.1) or (1.2), in practice, the unknown $F_{n,k}(.)$ has to be replaced with their respective estimates first in order to obtain an empirical version $\hat{U}_n$. The biggest challenge in their use is to obtain an efficient approximation of the null joint distribution of $\{T_{n,k}, k = 1, \cdots, K\}$. Using (1.2) in a high-dimensional setting is discussed in Xu et al. (2016) for the two-sample mean comparison problem, where the approximation of the null distribution is obtained using the standard two-step procedure: first, derive the (asymptotic) form of $F_{n,k}(.)$ and $F_n(.)$, the latter being the (null) joint distribution of $\{T_{n,k}, k = 1, \cdots, K\}$; second, find the tail probabilities associated with these asymptotic (null) distributions using numerical approximations (with plugged-in estimates of the parameters). This classical two-step approach is not only computationally intensive, but also suffers from low numerical efficiency.

In this study, we investigate how to use resampling methods, either bootstrap or permutation, depending on the specific testing problem, to directly approximate the null distributions of $U_n$, or rather $\hat{U}_n$, for the purpose of fusing test statistics in high-dimensional hypothesis testing, where the dimension of the data is not negligible relative to the sample size. A streamlined setup is as follows, with (1.2) as the fusion statistic. Let $\mathbf{X}_1^n = \{X_1, ..., X_n\}$ denote the original sample. With a sufficiently large number $B$, $\mathbf{X}_1^{n,(b)}$, for $b = 1, \cdots, B$, denotes $B$ new samples generated using either bootstrap or permutation, for which $H_0$ holds true. For $b = 1, \cdots, B$ and $k = 1, \cdots, K$, let $T_{n,k}^{(b)}$ denote the values of the test statistic $T_{n,k}$ calculated from the sample $\mathbf{X}_1^{n,(b)}$. For any $k = 1, \cdots, K$, we estimate $F_{n,k}(.)$ by $\hat{F}_{n,k}(.)$, the empirical distribution function based on $\{T_{n,k}^{(1)}, \cdots, T_{n,k}^{(B)}\}$. An empirical version of (1.2) is then defined as

$$\hat{U}_n := \max_{k=1,\cdots,K} \hat{F}_{n,k}(T_{n,k}). \tag{1.3}$$

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Next, we compare this with the empirical distribution function of its resampling counterpart:

$$\hat{U}_n^{(b)} := \max_{k=1,\cdots,K} \hat{F}_{n,k}(T_{n,k}^{(b)}), \quad b = 1, \cdots, B. \tag{1.4}$$

Lastly, at significance level $\alpha$, we reject $H_0$ if

$$B^{-1} \sum_{b=1}^{B} I(\hat{U}_n^{(b)} \geq \hat{U}_n) \leq \alpha, \tag{1.5}$$

where $I(.)$ denotes the indicator function. We say a statistical test is consistent if its type-I error is identical to the nominal significance level $\alpha$, at least asymptotically. In this paper, we prove the consistency of the above fusion procedure, namely, (1.3)–(1.5), in the context of three popular high-dimensional hypothesis testing problems, discussed in, among others Chung and Romano (2016), Cai et al. (2014), and Heller et al. (2013), for a selection of test statistics. Our main results are summarized as follows:

**(i)** we show the consistency of the empirical bootstrap-based fusion procedure for the one-sample mean test, where $K$ is the number of statistics to be fused, and can increase with $n$;

**(ii)** we show the consistency of the permutation-based fusion procedure for the two-sample mean comparison, where $K$ can also increase with $n$;

**(iii)** we show the consistency of the permutation-based fusion procedure for the test of independence between two random vectors; as a byproduct, we provide a theoretical justification for the practice in Heller et al. (2013), where the permutation distribution of the HHG statistic is used to approximate its null distribution.

The rest of the paper is organized as follows. Section 2 and Section 3 present the one-sample mean test and the two-sample mean comparison, respectively. Section 4 discusses testing the independence between two (high-dimensional) random vectors. A brief discussion on possible extensions is given in Section 5. Numerical results are given in Section 6. Regulation conditions and proofs are gathered in the Appendix.

## 2. Test of one-sample mean

Suppose $X_i \in R^p$, for $i = 1, \cdots, n$, are independent copies of $X = (X^1, \cdots, X^p)^\top$, with mean $\mu$ and covariance matrix $\Sigma^X$. Without loss of generality, suppose the diagonal elements of $\Sigma^X$ are all ones. Testing $H_0 : \mu = 0$, referred to as the one-sample location model in Kock and Preinerstorfer (2019), is based on the sample mean $\bar{X}_n$, usually standardized by the sample covariance matrix. When $p$ is large, so that the inversion of a $p \times p$ matrix is much less feasible, if at all possible, a more popular replacement is given by

$$\delta_n = (\delta_{n,1}, ..., \delta_{n,p})^\top = n^{1/2} \hat{D}_n^{-1/2} \bar{X}_n,$$

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where $\hat{D}_n = \text{diag}(\hat{\sigma}_{nj}^2,\, j = 1, \cdots, p)$ is a diagonal matrix of the sample variances. The use of $\hat{D}_n$ instead of the sample covariance matrix is to avoid having to compute the inverse of a high-dimensional matrix; see, for example, Bai and Saranadasa (1996), Srivastava and Du (2008), and Kong et al. (2022). For any integer $k \geq 1$, let $A_k(.)$ be a function so that for any vector $\nu \in R^p$, $A_k(\nu)$ returns the average of its largest (in absolute value) $k$ elements. Apparently, for any $k \geq 1$, $A_k(\delta_n)$ is a pivotal statistic, so that we reject $H_0$ if $A_k(\delta_n)$ is too large. However, as noted in Cai et al. (2014), Kim and Akritas (2010), and Gregory et al. (2015), no statistic is uniformly more powerful than others (against all possible alternatives). For example, when the signals are sparse, but strong, $A_1(\delta_n)$, namely, the supremum statistic considered in Chernozhukov et al. (2019) and Cai et al. (2014), has greater power than $A_k(\delta_n)$ with a large $k$, because the latter is not greatly influenced by a small number of large differences. Similarly, in the case of dense, but weak alternatives, $A_k(\delta_n)$ with a small $k$ is not likely to be extreme enough to serve as evidence to reject $H_0$. Furthermore, as demonstrated in Kong et al. (2022), in the latter case, it is also beneficial to consider $A_k(\delta_n)$ with $k = s_n$, where $s_n$ is some positive integer that can increase with $n$.

Without loss of generality, suppose $1 \leq l_1 \leq l_2 \leq \cdots \leq l_K \leq s_n$ is a sequence of positive integers. For $k = 1, \cdots, K$, let

$$T_{n,k} = T_{n,k}(\delta_n) = A_{l_k}(\delta_n), \tag{2.6}$$

be the corresponding sequence of statistics. We now show that they can be combined using the empirical bootstrap-based fusion procedure (1.3)–(1.5). For $b = 1, \cdots, B$, let $\mathbf{X}_1^{n,(b)} = \{X_1^{n,(b)}, \cdots, X_n^{n,(b)}\}$ be an empirical bootstrapped sample, that is $X_i^{n,(b)}$, for $i = 1, \cdots, n$, are independent and identically distributed (i.i.d) draws (with replacement) from $\mathbf{X}_1^n = \{X_i,\, i = 1, \cdots, n\}$. Let $\bar{X}_n^{(b)} = n^{-1}\sum_i X_i^{n,(b)}$ denote the bootstrapped sample mean, and $\hat{D}_n^{(b)}$ the bootstrap version of $\hat{D}_n$. Write $\delta_n^{(b)} = n^{1/2}(\hat{D}_n^{(b)})^{-1/2}(\bar{X}_n^{(b)} - \bar{X}_n)$,

$$T_{n,k}^{(b)} = A_{l_k}(\delta_n^{(b)}), \quad k = 1, \cdots, K,\ b = 1, \cdots, B,$$

and carry out steps (1.3)–(1.5). For any nondecreasing function $G_{n,k}(.)$, for $k = 1, \cdots, K$,

$$I\Big(\bigcap_{k=1}^{K}\{G_{n,k}(T_{n,k}(\delta_n)) \leq u\}\Big) = I\Big(\bigcap_{k=1}^{K}\{T_{n,k}(\delta_n) \leq G_{n,k}^{-1}(u)\}\Big). \tag{2.7}$$

Thus, the consistency of this bootstrap-based fusion procedure is a direct consequence of the theorem below. Let $F_n(.)$ denote the joint distribution of $\{T_{n,k},\, k = 1, \cdots, K\}$ under $H_0$, and $F_n^*(.|\mathbf{X}_1^n)$ denote their joint bootstrap distribution, namely, the joint distribution of $\{T_{n,k},\, k = 1, \cdots, K\}$, calculated using the bootstrap samples derived from $\mathbf{X}_1^n$, as described above.

**Theorem 1.** Suppose Conditions (C1)–(C3) in the Appendix hold. Then,

$$\sup_{t_1,\cdots,t_k \in R}\Big|F_n(t_1, \cdots, t_K) - \text{P}\Big(\bigcap_{k=1}^{K}\{T_{n,k}(\underline{Z}) \leq t_k\}\Big)\Big| = o(1),$$

$$\sup_{t_1,\cdots,t_k \in R}\Big|F_n^*(t_1, \cdots, t_K|\mathbf{X}_1^n) - \text{P}\Big(\bigcap_{k=1}^{K}\{T_{n,k}(\underline{Z}) \leq t_k\}\Big)\Big| = o_p(1),$$

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where $\underline{Z} \sim N(0, \Sigma^X)$ denotes the multivariate normal distribution with mean zero and covariance matrix $\Sigma^X$, and $T_{n,k}(\underline{Z})$ is as defined in (2.6), with $\delta_n$ replaced with $\underline{Z}$.

**Remark 1.** Chernozhukov et al. (2019) discuss testing $H_0$ based on the supremum statistic, where its null distribution is also approximated using an empirical bootstrap, with the only difference being that the same sample $\hat{D}_n$, instead of its bootstrapped version, is used to standardize the bootstrapped sample mean, that is, $\delta_n^{(b)}$ is defined as $n^{1/2}(\hat{D}_n)^{-1/2}(\bar{X}_n^{(b)} - \bar{X}_n)$. The second identity in Theorem 1 about the bootstrap distribution still holds in this case; nevertheless, a simulation study indicates that doing so tends to incur larger type-I errors; see Kong et al. (2022).

## 3. Two-sample mean comparison

Suppose $p$-dimensional random vectors $X_1, \cdots, X_m$ are independent copies of $X \sim P_1(.)$, with mean $\mu^X$ and variance $\Sigma^X$, and $Y_1, \cdots, Y_n$ are independent copies of $Y \overset{i.i.d.}{\sim} P_2(.)$, with mean $\mu^Y$ and variance $\Sigma^Y$. The null hypothesis of interest is $H_0 : \mu^X = \mu^Y$, which is referred to as the two-sample location model in Kock and Preinerstorfer (2019). The procedure and the main results in this section are stated for equal sample sizes, that is, $m = n$. A brief discussion is given at the end of this section on how the method can be adapted to the samples of unequal sizes.

As in the one-sample case, nearly all existing statistics for testing $H_0$ are based on the sample-mean difference $\delta_n = \bar{X}_m - \bar{Y}_n$; see, for example, Xue and Yao (2020), Cai et al. (2014), and Zhang et al. (2020). For any $k = 1, \cdots, K$, let $T_{n,k}(\delta_n)$ be as defined in (2.6), and reject $H_0$ if $T_{n,k}(\delta_n)$ is too large. For any of these tests to be consistent, valid approximations to its null distribution are essential. Xue and Yao (2020) use an empirical bootstrap to determine the critical values for the supremum statistic. A different option is to use the permutation method. Chung and Romano (2016) prove that for a multivariate two-sample mean comparison, certain statistics are proper, in the sense that its permutation distribution function converges (uniformly) to its null distribution. The permutation method is also popular in practice; see, for example, Nettleton et al. (2008), Chang and Tian (2016), and Efron and Tibshirani (2007). Its theoretical properties are examined in Kong et al. (2022) for the problem of a high-dimensional two-sample mean comparison, and it is shown to outperform the bootstrap method by a significant margin.

In the present context, the permutation procedure for fusing the sequence of statistics $\{T_{n,k}(\delta_n),\ k = 1, \cdots, K\}$ goes as follows. Following the notation used in Chung and Romano (2016), write $N = 2n$ and the pooled-sample $Z^N = \{Z_1, \cdots, Z_N\}$, where $Z_i = X_i$, for $i = 1, \cdots, n$, and $Z_{n+j} = Y_j$, for $j = 1, \cdots, n$. Thus, $\bar{X}_n$ can be interpreted as the average of the first half of the sample, $\{Z_1, \cdots, Z_n\}$, and $\bar{Y}_n$ is the average of the second half of the sample, $\{Z_{n+1}, \cdots, Z_N\}$.

Let $G_N$ denote the set of all permutations of $\{1, \cdots, N\}$. For any $\pi = (\pi(1), ..., \pi(N)) \in G_N$, let $Z_\pi^N$ denote the rearranged $Z^N$ through permutation $\pi$, and $Z_{\pi(i)}^N$, for $i = 1, \cdots, N$, be the $i$th entry of $Z_\pi^N$. Recompute $\bar{X}_n$ and $\bar{Y}_n$ for $Z_\pi^N$, and denote

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the difference between them as $\delta_n(Z_\pi^N)$. Note that we use the notation $\delta_n(Z_\pi^N)$ to highlight its dependence on the permutated sample $Z_\pi^N$, whereas the simple $\delta_n$ is reserved for the sample mean difference calculated for the original (unpermutated) sample. For any $k = 1, \cdots, K$, let $T_{n,k}(Z_\pi^N)$ denote the value of $T_{n,k}(.)$, as in (2.6), when evaluated for $\delta_n(Z_\pi^N)$; its marginal (permutation) distribution of $T_{n,k}(Z_\pi^N)$ conditional on $Z^N$ is thus

$$\hat{F}_{n,k}(t|Z^N) = \frac{1}{N!}\sum_{\pi\in G_N} I\Big(T_{n,k}(Z_\pi^N) \le t\Big), \quad t \in R. \tag{3.8}$$

In this case, $\hat{U}_n$ of (1.3) is given by $\hat{U}_n = \max\limits_{k=1,\cdots,K} \hat{F}_{n,k}(T_{n,k}(\delta_n)|Z^N)$. We reject $H_0$ if

$$\frac{1}{N!}\sum_{\pi\in G_N} I\Big(\max_{k=1,\cdots,K} \hat{F}_{n,k}(T_{n,k}(Z_\pi^N)) < \hat{U}_n\Big) > 1-\alpha. \tag{3.9}$$

As a result of (2.7), the consistency of the above procedure (3.8)–(3.9) is a direct consequence of the next theorem. Let $F_n(.)$ denote the joint distribution of $\{T_{n,k}(\delta_n),\, k = 1, \cdots, K\}$ under $H_0$, and $F_n^*(.|Z^N)$ denote their joint permutation distribution, that is,

$$F_n^*(t_1, \cdots, t_K|Z^N) := \frac{1}{N!}\sum_{\pi\in G_N} I\Big(\bigcap_{k=1}^{K}\{T_{n,k}(Z_\pi^N) \le t_k\}\Big), \quad t_1, \cdots, t_K \in R,$$

the joint distribution of $\{T_{n,k}(Z_\pi^N),\, k = 1, \cdots, K\}$ calculated for the randomized sample derived from $Z^N$(via permutation $\pi$ uniformly distributed on $G_N$).

**Theorem 2.** Suppose Conditions (C1)–(C3) in the Appendix hold and that the same set of conditions also hold when $(Y, \Sigma^Y)$ replaces $(X, \Sigma^X)$. Then,

$$\sup_{t_1,\cdots,t_K\in R}\Big|F_n^*(t_1, \cdots, t_K|Z^N) - F_n(t_1, \cdots, t_K)\Big| \to 0, \text{ in probability.} \tag{3.10}$$

**Remark 2.** Similarly to Section 2, we can also consider cases where the test statistics $\{T_{n,k}(\delta_n),\, k = 1, \cdots, K\}$ are evaluated for marginal-standardized $\delta_n$, that is, $\delta_n = n^{1/2}(\hat{D}_n)^{-1/2}(\bar{X}_n - \bar{Y}_n)$, where $\hat{D}_n = \mathrm{diag}(\hat{\Sigma}_n)$, the diagonal matrix consisting of the diagonal elements of

$$\hat{\Sigma}_n = \frac{1}{2n}\sum_{i=1}^{n}(X_i - \bar{X}_n)(X_i - \bar{X}_n)^\top + \frac{1}{2n}\sum_{i=1}^{n}(Y_i - \bar{Y}_n)(Y_i - \bar{Y}_n)^\top.$$

In this case, $\hat{D}_n$ is recomputed for each permutated sample, and Theorem 2 continues to hold if $\hat{D}_n$ is accurate enough, as per Assumption (A6) of Kong et al. (2022).

**Remark 3.** When the two samples are of unequal sizes ($m \neq n$), Kong et al. (2022) prove that the limit of the permutation distribution of the statistics, be it $T_{n,k}(\delta_n)$ or its marginally standardized version, does not coincide with their respective (null) distributions, unless $\Sigma^X = \Sigma^Y$. One solution is to apply the binning procedure in Kong et al. (2022) to obtain pseudo samples of equal sizes, and then proceed as before. If $m/(m+n) = c + O(N^{-1/2})$, for some $c \in (0, 1)$, then similarly to Theorem 2, we can prove the consistency of the fusion procedure (3.8)–(3.9) based on these pseudo samples.

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## 4. Test of vector independence

Let $X$ and $Y$ stand for random vectors of dimension $p$ and $q$, respectively, with $\mathcal{D}_X$ and $\mathcal{D}_Y$ as their respective domains. Suppose we have $n$ independent copies $\{(X_i, Y_i)\}_{i=1}^n$ of $(X, Y)$, and we are interested in testing the null hypothesis $H_0$: $X$ and $Y$ are independent. Write $\mathbf{X}_1^n = \{X_1, \cdots, X_n\}$ and $\mathbf{Y}_1^n = \{Y_1, \cdots, Y_n\}$. In the univariate case, DiCiccio and Romano (2017) consider the test of $H_0$ based on the sample correlation $\rho_n(.)$, and prove that its null distribution can be approximated by random permutations of $\mathbf{Y}_1^n$ or $\mathbf{X}_1^n$.

Compared with $\rho_n(.)$, the HHG statistic of Heller et al. (2013) is able to identify nonlinear association. The notion behind it is simple: suppose $d_X(.)$ and $d_Y(.)$ are two distance metrics, such as the Euclidean distance; if $H_0$ is false, then there must exist two distinct points $(\mathbf{x}_1, \mathbf{y}_1)$, $(\mathbf{x}_2, \mathbf{y}_2) \in \mathcal{D} = \mathcal{D}_X \times \mathcal{D}_Y$, so that the two binary random variables $I\{d_X(X, \mathbf{x}_1) \le d_X(\mathbf{x}_1, \mathbf{x}_2)\}$ and $I\{d_Y(Y, \mathbf{y}_1) \le d_Y(\mathbf{y}_1, \mathbf{y}_2)\}$ are correlated. The HHG statistic is then based on the Pearson's correlation for the corresponding $2 \times 2$ contingency table:

$$T_n(\mathbf{x}_1, \mathbf{y}_1, \mathbf{x}_2, \mathbf{y}_2; d_X(.), d_Y(.)) = n^{1/2}(A_{1,1} - A_{1.}A_{.1})/(A_{1.}A_{.1})^{1/2}, \tag{4.11}$$

where

$$\begin{aligned} A_{1,1} &:= A_{1,1}(\mathbf{x}_1, \mathbf{y}_1, \mathbf{x}_2, \mathbf{y}_2; d_X(.), d_Y(.)) \\ &= \frac{1}{n}\sum_{i=1}^n I\big(d_X(X_i, \mathbf{x}_1) \le d_X(\mathbf{x}_1, \mathbf{x}_2)\big) I\big(d_Y(Y_i, \mathbf{y}_1) \le d_Y(\mathbf{y}_1, \mathbf{y}_2)\big), \\ A_{1.} &:= A_{1.}(\mathbf{x}_1, \mathbf{x}_2; d_X(.)) = \frac{1}{n}\sum_{i=1}^n I\big(d_X(X_i, \mathbf{x}_1) \le d_X(\mathbf{x}_1, \mathbf{x}_2)\big), \\ A_{.1} &= A_{.1}(\mathbf{y}_1, \mathbf{y}_2; d_Y(.)) = \frac{1}{n}\sum_{i=1}^n I\big(d_Y(Y_i, \mathbf{y}_1) \le d_Y(\mathbf{y}_1, \mathbf{y}_2)\big). \end{aligned} \tag{4.12}$$

In Heller et al. (2013), the null distribution of the statistic (4.11) is approximated by random permutations of $\mathbf{Y}_1^n$. This practice is intuitively correct, but no theoretical justification has been provided yet. Because $A_{1.}$ and $A_{.1}$, the two marginal terms in (4.11), are both invariant to permutations (of $\mathbf{Y}_1^n$), it is the numerator, $A_{1,1} - A_{1.}A_{.1}$, that determines the permutation distribution of (4.11). Thus, henceforth, we do not discriminate between (4.11) and its numerator. Variations of (4.11), while retaining its contingency-table-derived form, can be constructed by altering choices for the following two factors:

(i) values specified for $(\mathbf{x}_1, \mathbf{y}_1)$ and $(\mathbf{x}_2, \mathbf{y}_2)$. Apparently, the statistic (4.11) associated with any specific values of $(\mathbf{x}_1, \mathbf{y}_1)$ and $(\mathbf{x}_2, \mathbf{y}_2)$ is more sensitive to dependency that occurs close to the specified locations. Violations of $H_0$ in locations further away might not be strong enough to yield significant changes. By combining statistics associated with varied choices of $(\mathbf{x}_1, \mathbf{y}_1)$ and $(\mathbf{x}_2, \mathbf{y}_2)$ scattered in $\mathcal{D}$, we can gather evidence (of dependence) from different locations.

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(ii) types of distance metrics for $d_X(.)$ and $d_Y(.)$. This factor, as noted in Heller et al. (2013), could be designed to capture the localized dependency between $X$ and $Y$. For example, we could consider distance metrics $d_X(.)$ that depend only on a certain sub-vector $X_{\mathcal{S}}$ of $X$, so that the resulting statistic is more powerful against alternatives when the association between $(X, Y)$ is largely due to that between the sub-vector $X_{\mathcal{S}}$ and $Y$.

These variations of (4.11), notwithstanding belong to a general class of statistics of the following form:

$$n^{-1}\sum_{i=1}^{n}(a(X_i)-\bar{a}_n)(d(Y_i)-\bar{d}_n), \tag{4.13}$$

where $a(.)$ and $d(.)$ are both square integrable functions, with $d(.)$ being categorical (i.e., taking only a finite number of possible values), and $\bar{a}_n = n^{-1}\sum a(X_i)$ and $\bar{d}_n = n^{-1}\sum d(Y_i)$ are their respective sample averages. To see this is the case, set

$$a(X) = I\big(d_X(X,\mathbf{x}_1) \le d_X(\mathbf{x}_1,\mathbf{x}_2)\big), \quad d(Y) = I\big(d_Y(Y,\mathbf{y}_1) \le d_Y(\mathbf{y}_1,\mathbf{y}_2)\big).$$

Then, (4.13) reduces to the numerator in (4.11).

Without loss of gerality, suppose for $k = 1, \cdots, K$, $a_k(.)$ and $d_k(.)$ are functions satisfying the requirements above specified for (4.13). Write

$$T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^n) = n^{-1/2}\sum_{i=1}^{n}(a_k(X_i)-\bar{a}_n^{(k)})(d_k(Y_i)-\bar{d}_n^{(k)}), \quad k = 1, \cdots, K, \tag{4.14}$$

where, $\bar{a}_n^{(k)}$ and $\bar{d}_n^{(k)}$, for $k = 1, \cdots, K$, are the sample averages of $a_k(X_i)$ and $d_k(Y_i)$, respectively. In the language of Hajek et al. (1999), $a_k(X_i)$ is referred to as the coefficient, and $d_k(Y_i)$ are the scores. We focus on the combination of statistics of this general form using the fusion procedure, where the resampling is done via random permutations of $\mathbf{Y}_1^n$.

For any $\pi \in G_n$, let $\{\pi(1), \cdots, \pi(n)\}$ denote the rearranged $\{1, \cdots, n\}$ through permutation $\pi$, and $\mathbf{Y}_1^{n,\pi} = \{Y_{\pi(1)}, \cdots, Y_{\pi(n)}\}$. For $k = 1, \cdots, K$, evaluate $T_{n,k}(.)$ for the permuted sample as

$$T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{n,\pi}) = n^{-1/2}\sum_{i=1}^{n}(a_k(X_i)-\bar{a}_n^{(k)})(d_k(Y_{\pi(i)})-\bar{d}_n^{(k)}), \tag{4.15}$$

with their marginal and joint permutation distributions given by

$$\hat{F}_{n,k}(t|\mathbf{X}_1^n, \mathbf{Y}_1^n) = \frac{1}{n!}\sum_{\pi\in G_n} I\Big(T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{\pi(n)}) \le t\Big), \quad t \in R, \tag{4.16}$$

$$\hat{F}_n(t_1, \cdots, t_K|\mathbf{X}_1^n, \mathbf{Y}_1^n) := \frac{1}{n!}\sum_{\pi\in G_n} I\Big(\bigcap_{k=1}^{K}\{T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{\pi(n)}) \le t_k\}\Big), \tag{4.17}$$

respectively. Let $\hat{U}_n$ be as defined in (1.3), with $\hat{F}_{n,k}(.|\mathbf{X}_1^n, \mathbf{Y}_1^n)$ replacing $\hat{F}_{n,k}(.)$, for $k = 1, \cdots, K$. Similarly to (3.9), we reject $H_0$ if $\hat{R}_n^U(\hat{U}_n|\mathbf{X}_1^n, \mathbf{Y}_1^n) \ge 1-\alpha$, where

$$R_n^{\hat{U}}(u|\mathbf{X}_1^n, \mathbf{Y}_1^n) := \frac{1}{n!}\sum_{\pi\in G_n} I\Big(\bigcap_{k=1}^{K}\{F_{n,k}(T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{\pi(n)})|\mathbf{X}_1^n, \mathbf{Y}_1^n) \le u\}\Big). \tag{4.18}$$

Let $F_n(.)$ denote the joint distribution of $\{T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^n),\ k = 1, \cdots, K\}$ under $H_0$.

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**Theorem 3.** Under $H_0$, with probability one,

$$\sup_{t_1,\cdots,t_K\in R}\left|\hat{F}_n(t_1,\cdots,t_K|\mathbf{X}_1^n,\mathbf{Y}_1^n)-F_n(t_1,\cdots,t_K)\right|=o(1). \tag{4.19}$$

Based on Theorem 3, the consistency of the fusion procedure (4.16)–(4.18) is a straightforward result.

**Corollary 1.** Under $H_0$, with probability one,

$$\sup_{u\in(0,1)}|\hat{R}_n^U(u|\mathbf{X}_1^n,\mathbf{Y}_1^n)-\mathrm{P}(\hat{U}_n\le u)|=o(1).$$

**Remark 4.** Based on Theorem 3 and the continuous mapping theorem, it is straightforward to see that the fusion procedure (4.16)–(4.18) is also consistent if the fusion statistic $U_n$ of (1.2) is replaced with any continuous function of $\{T_{n,k}(.),\ k=1,\cdots,K\}$. For example, suppose $\{(\mathbf{x}_k,\mathbf{y}_k):k=1,\cdots,K\}$ is a collection of (fixed) grid points in $\mathcal{D}$. We could then consider the summation, or the maximum, of the squared (4.11) taken over these grid points; that is,

$$\tilde{U}_n=\sum_{k,l=1}^{K}T_n^2(\mathbf{x}_k,\mathbf{y}_k,\,\mathbf{x}_l,\mathbf{y}_l;d_X(.),d_Y(.)), \tag{4.20}$$

$$\tilde{U}_n=\max_{k,l}T_n^2(\mathbf{x}_k,\mathbf{y}_k,\,\mathbf{x}_l,\mathbf{y}_l;d_X(.),d_Y(.)). \tag{4.21}$$

Note that (4.20) is the Cramér–von-Mises-type of statistic studied in Heller et al. (2013, 2016). Thus, as a byproduct, Theorem 3 also provides theoretical justifications for the practice in Heller et al. (2013, 2016) of approximating the null distributions of these aggregations numerically by using their permutation distributions.

For the same reason, the consistency of the fusion procedure (4.16)–(4.18) also holds for the Kolmogorov–Smirnov-type statistic (4.21), or when $T_n(.)$ in (4.20) or (4.21) is replaced by the $G$ likelihood-ratio,

$$A_{1,1}\log\left(\frac{A_{1,1}}{A_{1.}A_{.1}}\right)+A_{1,2}\log\left(\frac{A_{1,2}}{A_{1.}A_{.2}}\right)+A_{2,1}\log\left(\frac{A_{2,1}}{A_{2.}A_{.1}}\right)+A_{2,2}\log\left(\frac{A_{2,2}}{A_{2.}A_{.2}}\right), \tag{4.22}$$

where $A_{i,j}$, $A_{i,.}$, $A_{.,j}$, for $i,j=1,2$, are as given in (4.12). These four fused statistics can go through one more round of the fusion procedure, and the resulting test procedure would still be consistent.

**Remark 5.** For the proof of Theorem 3, the permutation distribution is derived based on the notion that when $\pi$ is uniformly distributed on $G_n$, $\pi(i)$ can be interpreted as the rank of $U_i$, for $i=1,\cdots,n$, where $U_1,\cdots,U_n$ are i.i.d. $U(0,1)$. In this sense, $T_{n,k}(\mathbf{X}_1^n,\mathbf{Y}_1^{n,\pi})$ of (4.15) falls into the category of simple linear rank statistics (Hajek et al., 1999). The theoretical tools currently available are enough to derive the limiting distribution of individual rank statistics, but not for their joint limiting distributions, as required in our case. It is for this extension to the multivariate case that we require the function $d_k(.)$ to be categorical. Removing of such restrictions is left to future research.

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## 5. Extensions

Engaging fusion statistics other than (1.2) is perfectly possible. Indeed, the results in Theorems 1–3 continue to hold if $F_{n,k}(.)$ in the definition of (1.3) is replaced with any monotone function.

As observed in Sections 2 to 4, the consistency of the fusion procedure (1.3)–(1.5), depends on both the sequence of the test statistics $\{T_{n,k},\, k = 1, \cdots, K\}$ to be fused and the fusion statistic, $U_n$, itself. For the fusion statistic (1.2), the fusion procedure is consistent as long as the joint bootstrap (or permutation) distribution function of $\{T_{n,k},\, k = 1, \cdots, K\}$ is a valid approximation of their joint null distribution. Were we to consider a sequence of test statistics other than those studied here, then the consistency of the fusion procedure needs to be re-evaluated, because the bootstrap (or permutation) distribution is not necessarily always a valid approximation of the null, even in the non-high-dimensional (fixed-dimensional) setting; see, for example, Chung and Romano (2013, 2016).

Having said that, certain variations (or extensions) of the proposed procedure can be verified in a relatively straightforward manner. For example, $F_{n,k}(.)$ in (1.2) or $\hat{F}_{n,k}(.)$ in (1.3) can be replaced with an arbitrary monotone function, and the results in Theorem 1, Theorem 2, and Theorem 3 will continue to hold. Another possibility is to allow $K$, the number of statistics to be fused, to also increase with $n$. For example, in the two-sample mean comparison problem of Section 3, we do not known a priori the number of coordinates where $\mu^X$ and $\mu^Y$ differ from each other. Thus, $T_{n,k}(\delta_n)$ is calculated for as many $k$ as possible, hoping that one of these $k$-values is close to the true count. Without loss of generality, for $k = 1, \cdots, s_n(\leq p)$, define

$$T_{n,k} = A_k(\delta_n);$$

we can then repeat the fusion procedure (3.8) – (3.9) with $K$ replaced by $s_n$. The proof of the consistency of the procedure is similar to when $K$ is fixed, if the rate at which $s_n \to \infty$ is slow enough. Specifically, if $s_n$ is allowed to be as large as $p$, then $p$ is at most of order $o(n^{1/7})$, rather than the exponential rate implied by Condition (C3) in the Appendix.

we cannot make general recommendations for choosing between different fusion statistics, because the existence of an optimal fusion statistic is, to the best of our knowledge, still an open question. For the sequence of test statistics of (2.6), a general form of the type of fusion statistic for which the consistency of the corresponding fusion procedure still holds is

$$U_n = F(f_k(T_{n,k}),\, k = 1, \cdots, K), \tag{5.23}$$

where $F(.) : R^K \to R$ and $f_k(.) : R \to R$, for $k = 1, \cdots, K$. For the overall function to be convex, it is sufficient that either

- $f_k(.)$ are all convex; $F(.)$ is convex and nondecreasing in each argument, or
- $f_k(.)$ are all concave; $F(.)$ : is convex and nonincreasing in each argument.

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As a result, we have for any $u \in R$, there exists some $s_n$-sparsely convex set $A \subset \mathbb{R}^p$ (Definition 3.1 of Chernozhukov et al. (2017)), such that

$$I(U_n \le u) = I(\delta_n \in A).$$

Write $\underline{T}_n = (T_{n,k}(\delta_n),\, k = 1, \cdots, K)$, $\underline{T}_n^{(b)} = (T_{n,k}(\delta_n^{(b)}),\, k = 1, \cdots, K)$. Under certain regularity conditions, we can apply Proposition 3.2 of Chernozhukov et al. (2017) and prove, similarly to Theorem 1, that

$$\sup_{A \in \mathcal{A}^{sp}(s_n)} \left| \mathrm{P}_n^*(\underline{T}_n^{(b)} \in A | \mathbf{X}_1^n) - \mathrm{P}(\underline{T}_n \in A) \right| = o_p(1),$$

where $\mathcal{A}^{sp}(s_n)$ denotes the class of all $s_n$ sparsely convex sets in $\mathbb{R}^p$, and $\mathrm{P}_n^*(.|.)$ denotes the bootstrap distribution conditional on $\mathbf{X}_1^n$. An analogue of Theorem 2, and consequently the consistency of the corresponding fusion procedure, can then be proved similarly.

Asymptotically the empirical version of the aforementioned Fisher's combined $p$-value of (1.1) can be written in the form of (5.23). To see this, first note that, based on Theorem 1, we have for any given $k$, $T_{n,k}(.)$ converges in distribution to $T_{n,k}(\underline{Z})$, which, as shown in the proof of Theorem 1, is equivalent to the maximum of a Gaussian vector of dimension $2^k\binom{p}{k}$. Second, Theorem 1 of Cai et al. (2014) states that under certain regularity conditions, the maximum of a $p$-dim Gaussian vector with unit variances has its limiting distribution as the type-I extreme value distribution, that is,

$$\exp\Big( - \pi^{-1/2} \exp\{-(t^2 - 2\log p + \log\log p)/2\}\Big).$$

Finally, it is easy to check that

$$-\log\Big(1 - \exp\Big( - \pi^{-1/2} \exp\{-(t^2 - 2\log p + \log\log p)/2\}\Big)\Big)$$

is indeed convex in $t$.

## 6. Simulation studies

In this section, we examine the performance of the fusion procedure (1.3)–(1.5), denoted by $fused$, when it is applied to the three testing problems discussed in Sections 2–4.

We use the following notation: $I_p$, the $p \times p$ identity matrix; $N_p(\mu, \Sigma)$, the $p$-dim normal with mean $\mu$ and covariance matrix $\Sigma$; and $T_p(k, \mu, \Sigma)$, the $p$-dim $t$-distribution with $k$ degrees of freedom, mean $\mu$, and covariance $\Sigma$. The significance level $\alpha$ is fixed as 5%. Empirical sizes are calculated based on 5000 repetitions, and the empirical powers are based on 1000 repetitions. Within each repetition, the bootstrap (or permutation) distributions are calculated based on $B(= 10000)$ resampling via bootstrap (or permutation).

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### 6.1 One-sample mean test

In testing $H_0 : \mu = 0$, the performance of the fusion procedure is compared with that of the individual test statistics, namely, $T_{n,1}$ and $T_{n,p}$ of (2.6). Also included in the comparison are the statistics of Bai and Saranadasa (1996), denoted by $T_{BS}$, and Srivastava and Du (2008), denoted by $T_{SD}$. These two summation-type statistics were originally proposed for a two-sample mean comparison, and are now adopted for the current purpose. Their p-values should be decided based on their asymptotic distributions, but because these tend to be over-inflated, we use the bootstrap.

The sample size is fixed at 100. We consider two designs for $X$: $N_p := N_p(\mu, \Sigma)$ and $T_p := T_p(5, \mu, \Sigma)$ with $\Sigma = D^{\frac{1}{2}} R D^{\frac{1}{2}}$, where $D$ and $R$ are generated as follows:

$\Sigma_1$ : $D = I_p$, $R = (\rho_{i,j})$, where $\rho_{i,i} = 1$, and $\rho_{i,j} = 0.25$, if $i \neq j$.

$\Sigma_2$ : $D = \text{diag}(\sigma^2)$, where $\sigma_j$, $j = 1, \cdots, p$, $\overset{i.i.d.}{\sim} U(2, 3)$; $R = (\rho_{i,j})$ with $\rho_{i,j} = 0.25^{|i-j|}$.

$\Sigma_3$ : $D$ is the same as in $\Sigma_2$; $R$ is the same as in $\Sigma_1$.

The results for the empirical sizes, for different combinations of distributions, $\Sigma$ and dimension $p$, are given in Table 1. The size of $fused$ is fairly close to the nominal size in nearly all settings, and is relatively more stable than its competitors.

Table 1: Empirical sizes(%) of different tests

| $(Dist., \Sigma)$ | $p$ | $T_{n,1}$ | $T_{n,p}$ | $fused$ | $T_{BS}$ | $T_{SD}$ |
|---|---|---|---|---|---|---|
| $(N_p, \Sigma_1)$ | 100 | 4.88 | 4.88 | 5.08 | 5.12 | 5.60 |
| | 200 | 5.20 | 4.70 | 5.14 | 4.92 | 5.46 |
| | 500 | 5.40 | 5.50 | 5.24 | 5.50 | 6.06 |
| | 1000 | 4.98 | 4.90 | 4.86 | 5.06 | 5.60 |
| $(T_p, \Sigma_1)$ | 100 | 3.48 | 4.16 | 3.66 | 4.22 | 4.78 |
| | 200 | 3.36 | 4.26 | 3.66 | 4.34 | 4.76 |
| | 500 | 3.36 | 4.32 | 3.90 | 4.38 | 5.00 |
| | 1000 | 3.08 | 4.30 | 3.58 | 4.50 | 4.92 |
| $(N_p, \Sigma_2)$ | 100 | 4.88 | 4.88 | 4.96 | 5.30 | 5.30 |
| | 200 | 5.34 | 5.34 | 5.44 | 5.76 | 5.76 |
| | 500 | 5.44 | 5.44 | 5.56 | 6.06 | 6.06 |
| | 1000 | 4.84 | 4.84 | 4.88 | 5.14 | 5.14 |
| $(N_p, \Sigma_3)$ | 100 | 5.22 | 4.94 | 5.32 | 5.16 | 5.58 |
| | 200 | 5.28 | 4.88 | 5.12 | 5.02 | 5.64 |
| | 500 | 5.62 | 5.44 | 5.54 | 5.50 | 6.02 |
| | 1000 | 5.28 | 4.68 | 4.88 | 4.86 | 5.42 |

Examples of alternatives are generated by specifying nonzero values for some entries of $\mu$ in the above examples. Specifically, for $d = 0.1, 0.5, 0.9$, $\lfloor dp \rfloor$ components of $\mu$ are randomly selected and are independently assigned values drawn from $U(-s, s)$, for some $s > 0$, and the other entries of $\mu$ remain zero. Here, $d$

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controls the sparsity of the signal, and $s$ determines the signal strength. Table 2 reports the empirical power for $p = 1000$, different combinations of distributions $(Dist)$, $\Sigma$ and $(d, s)$, for the four competing methods. What is immediately obvious is that the $fused$ statistics enjoy universally higher power than when using $T_{n,1}$ or $T_{n,p}$ alone. It also significantly outperforms both $T_{BS}$ and $T_{SD}$.

Table 2: Empirical powers(%) of different tests

| $(Dist., \Sigma)$ | $(d, s)$ | $T_{n,1}$ | $T_{n,p}$ | $fused$ | $T_{BS}$ | $T_{SD}$ |
|---|---|---|---|---|---|---|
| $(N_p, \Sigma_1)$ | (0.1, 0.31) | 89.7 | 9.9 | 92.1 | 10.2 | 11.7 |
| | (0.5, 0.22) | 82.7 | 42.7 | 92.9 | 45.1 | 53.0 |
| | (0.9, 0.19) | 77.2 | 85.2 | 94.3 | 87.3 | 91.0 |
| $(T_p, \Sigma_1)$ | (0.1, 0.41) | 89.2 | 10.1 | 92.7 | 9.9 | 11.8 |
| | (0.5, 0.28) | 78.0 | 43.4 | 87.8 | 39.8 | 49.4 |
| | (0.9, 0.25) | 76.2 | 84.7 | 91.4 | 81.7 | 88.3 |
| $(N_p, \Sigma_2)$ | (0.1, 7.20) | 92.8 | 4.4 | 93.6 | 5.0 | 5.0 |
| | (0.5, 6.50) | 94.8 | 5.4 | 94.9 | 5.9 | 6.2 |
| | (0.9, 6.20) | 93.5 | 7.0 | 93.5 | 7.1 | 7.3 |
| $(N_p, \Sigma_3)$ | (0.1, 0.75) | 90.0 | 9.5 | 92.1 | 9.7 | 11.0 |
| | (0.5, 0.55) | 87.8 | 50.1 | 96.8 | 45.6 | 59.4 |
| | (0.9, 0.45) | 77.3 | 75.2 | 91.6 | 70.5 | 83.0 |

### 6.2 Two-sample mean comparison

In this section, in addition to $T_{n,1}$ and $T_{n,p}$, we compare the proposed fusion procedure with the statistics considered in Xu et al. (2016) and Chen et al. (2019), referred to as $T_{XLPW}$ and $T_{CLZ}$, respectively. The statistics studied in Aoshima and Yata (2018), Chen and Qin (2010), and Zhang et al. (2020) are similar to $T_{CLZ}$ in definition, require similar assumptions, and show similar performance, and thus are excluded from the comparison. Simulation examples are taken from Xu et al. (2016), where the two $p$-dim random vectors $X$ and $Y$ are generated according to

$$X = (\xi^1, \xi^2), \quad Y = (\eta^1, \eta^2) + \mu^Y, \ \mu^Y = (\mu_1^Y, 0);$$

here, $\xi^1, \eta^1$ are both of length $p/2$, both with entries being independent $U(-1, 1)$, and $\xi^2$ and $\eta^2$ are independent $T_{p/2}(3, 0, \Sigma)$, with $\Sigma = (0.6^{|i-j|})$. When evaluating empirical sizes, $\mu_1^Y = 0$; for the empirical power comparison, with any given $\beta \in (0, 1)$ and $s \in (0, 1)$, $p_0 = \min(\lfloor p^\beta \rfloor, p/2)$ components of $\mu_1^Y$ are randomly selected and set to equal $s$, so that $s$ is an indicator of the signal strength, and the sparsity of the signals is controlled by $\beta$.

With $n = 100$, Table 3 shows the results for the empirical sizes of the various methods for different $p$. The two columns labelled $T_{XLPW}^a$ and $T_{CLZ}^a$ are the empirical sizes of $T_{XLPW}$ and $T_{CLZ}$, respectively, when the critical value is obtained based on the theoretical asymptotic null distributions, with plugged-in parameter estimates, as given in Xu et al. (2016) and Chen et al. (2019), respectively. Obviously, empirical sizes obtained in this manner are unduly high, but if the critical

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values are approximated using permutations, then the results for $T_{XLPW}$ and $T_{CLZ}$ and the other three statistics are all fairly close to the nominal 5%. Note that the computation times required by the first three methods are much shorter than those of $T_{XLPW}$ and $T_{CLZ}$, especially when $p$ gets larger.

Table 3: Size(%) (computation time in seconds) of different tests

| $p$ | $T_{n,1}$ | $T_{n,p}$ | $fused$ | $T_{XLPW}$ | $T_{CLZ}$ | $T^a_{XLPW}$ | $T^a_{CLZ}$ |
|---|---|---|---|---|---|---|---|
| 100 | 5.26 | 5.26 | 5.78 | 5.22 | 5.32 | 7.40 | 7.02 |
| | (0.04) | (0.03) | (0.29) | (1.57) | (1.91) | (0.66) | (0.001) |
| 200 | 5.28 | 4.96 | 5.18 | 5.22 | 4.72 | 7.07 | 6.94 |
| | (0.05) | (0.05) | (0.43) | (5.33) | (6.36) | (2.56) | (0.01) |
| 500 | 4.70 | 5.06 | 4.92 | 4.50 | 4.66 | 9.93 | 7.65 |
| | (0.10) | (0.09) | (0.93) | (31.70) | (39.68) | (15.55) | (0.04) |
| 1000 | 5.16 | 4.78 | 5.18 | 5.24 | 4.62 | 14.81 | 7.42 |
| | (0.19) | (0.16) | (1.79) | (127.73) | (164.40) | (91.34) | (0.24) |

With $p = 500$ and $\beta \in \{0.9, 0.8, 0.6, 0.5, 0.4, 0.2\}$, the empirical power of each method versus the signal strength $s$ is as depicted in Figure 1. For $T_{XLPW}$ and $T_{CLZ}$, because of their aforementioned unduly high type-I errors induced by the asymptotic distributions, we only report their power when the critical value is obtained using the permutation distribution. The general pattern is that as the degree of sparsity increases, the best method switches from $T_{n,p}$ to $T_{n,1}$. This is in line with the observation we made at the beginning of Section 2. In comparison, $fused$ is always among the top two best methods, regardless of the sparsity of the signals.

### 6.3 Independence test of random vectors

The code developed by Heller et al. (2013) calculates four HHG-type statistics: *hhg.sc* of (4.20), *hhg.mc* of (4.21), *hhg.sl*, and *hhg.ml*. The first two are defined as in (4.20) and (4.21), respectively, and the last two are also defined according to (4.20) and (4.21), but with $T_n^2$ replaced with the G likelihood-ratio of (4.22). Also included in the comparison is $fused$ of these four statistics, the corresponding testing procedure based on which, as noted in Section 4, continues to be consistent. Among the existing tests of independence, we select the two popular methods, namely, the Hilbert–Schmidt independence criterion (HSIC) of Pfister et al. (2018) and the distance correlation (DC) of Huo and Székely (2016), for comparison.

Observations of $X$ and $Y$ are generated according to the following models, some taken from Zeng et al. (2018). **M1**–**M4** are univariate, and **M5** and **M6** are multidimensional.

**M0(independent)** $X \sim N_p(0, I)$ and $Y \sim N_p(0, I)$ are independent.

**M1(linear with additive noise)** $Y = X + 2.6\epsilon$, where $X, \epsilon \overset{i.i.d}{\sim} N(0, 1)$.

**M2(circle with additive noise)** $X = \sin(2\pi\theta) + 0.35\epsilon$, $Y = \cos(2\pi\theta) + 0.35\varepsilon$, where $\epsilon, \varepsilon \overset{i.i.d}{\sim} N(0, 1)$, $\theta \sim U(0, 1)$.

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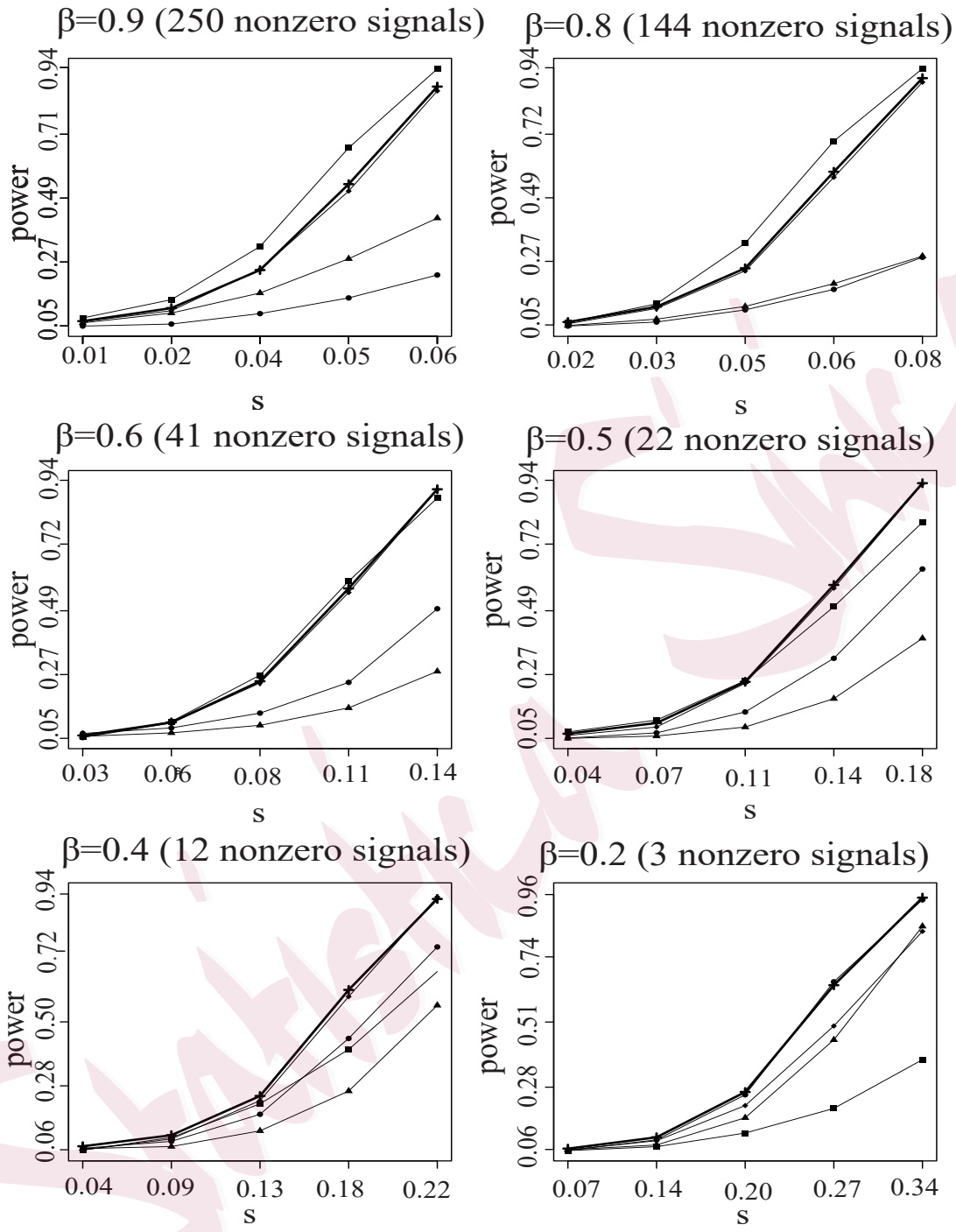


Figure 1: Power against signal strength $s$ with different sparsity $d$ and dimension $p$=500: —●— for $T_{n,1}$, —■— for $T_{n,p}$, —+— for $fused$, —▲— for $T_{XLPW}$, —♦— for $T_{CLZ}$.

**M3(quadratic with additive noise)** $Y = (X - 0.5)^2 + 0.76\epsilon$, $X, \epsilon \overset{i.i.d}{\sim} U(0, 1)$.

**M4(cloud with contaminated noise)** $(X, Y) = Z \times \{0.2\mu + 0.2(\epsilon_1, \varepsilon_1 + 0.5)\} + (1 - Z)(\epsilon_2, \varepsilon_2)$, where $Z = 1$ or 0 with probability 0.82 and 0.18, respec-

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tively, $\mu$ is evenly selected from $\{\mu_1 = (0,0), \mu_2 = (2,0), \mu_3 = (4,0), \mu_4 = (1,1), \mu_5 = (3,1), \mu_6 = (0,2), \mu_7 = (2,2), \mu_8 = (4,2), \mu_9 = (1,3), \mu_{10} = (3,3)\}$, $\epsilon_1, \epsilon_2, \varepsilon_1, \varepsilon_2 \overset{i.i.d}{\sim} U(0,1)$, and are independent of $\mu$ and $Z$.

**M5 (multivariate conditional variance)** $X = (X_1, ..., X_p)$ and $\phi = (\phi_1, ..., \phi_p)$ are independent $N_p(0, I_p)$; with $p_1 = \lfloor 0.7p \rfloor$, $Y_j = \phi_j(X_j + 0.6)$, $j = 1, \cdots, p_1$, $Y_j = \phi_j$, $j = p_1, \cdots, p$.

**M6(multivariate cloud with additive noise)** $\phi = (\phi_1, ..., \phi_p)$ and $\psi = (\psi_1, ..., \psi_p)$ are independent $N_p(0, I_p)$. With $p_1 = \lfloor 0.8p \rfloor$ and $\mu$ as specified in (**M4**), $(X_j, Y_j) = \mu + 0.2(\phi_j, \psi_j)$, $j = 1, \cdots, p_1$, $(X_j, Y_j) = (\phi_j, \psi_j)$, $j = p_1 + 1, \cdots, p$.

Table 4: Empirical sizes (%)

| $(n, p)$ | ① | ② | ③ | ④ | ①∼④ | *HSIC* | *DC* |
|---|---|---|---|---|---|---|---|
| (100, 1) | 5.08 | 4.48 | 4.92 | 4.68 | 4.78 | 5.06 | 5.54 |
| (200, 1) | 3.64 | 3.80 | 4.26 | 4.02 | 4.30 | 3.36 | 4.72 |
| (100, 4) | 5.32 | 4.92 | 3.72 | 4.58 | 4.10 | 5.80 | 5.42 |
| (100, 12) | 5.02 | 4.76 | 4.92 | 5.26 | 5.52 | 5.12 | 5.22 |
| (100, 20) | 3.58 | 3.32 | 5.12 | 5.72 | 4.24 | 5.14 | 4.92 |

①, ⋯, ④ represent the statistics *hhg.sc*, *hhg.sl*, *hhg.mc*, and *hhg.ml*, respectively. ①∼④ represents the *fusion* of statistic ① to statistic ④.

Table 5: Empirical powers (%)

| $(n, p)$ | M | ① | ② | ③ | ④ | ①∼④ | *HSIC* | *DC* |
|---|---|---|---|---|---|---|---|---|
| (100, 1) | 1 | 70.7 | 69.5 | 38.2 | 36.0 | 62.2 | 94.6 | 65.9 |
| | 2 | 49.9 | 54.5 | 53.3 | 51.6 | 53.6 | 6.4 | 53.6 |
| | 3 | 51.7 | 49.6 | 43.1 | 51.6 | 52.4 | 24.7 | 33.3 |
| | 4 | 4.2 | 3.8 | 29.4 | 28.2 | 24.0 | 0.0 | 0.0 |
| (200, 1) | 1 | 96.6 | 96.3 | 73.1 | 75.0 | 94.3 | 100.0 | 94.4 |
| | 2 | 93.6 | 94.6 | 87.6 | 89.7 | 91.7 | 16.4 | 93.8 |
| | 3 | 90.8 | 90.5 | 88.4 | 95.7 | 94.7 | 62.6 | 72.9 |
| | 4 | 60.6 | 59.4 | 93.7 | 95.9 | 93.8 | 0.6 | 0.6 |
| (100, 4) | 5 | 89.7 | 87.8 | 53.1 | 46.2 | 85.7 | 48.4 | 25.4 |
| | 6 | 52.2 | 41.3 | 88.1 | 87.9 | 85.2 | 0.0 | 0.0 |
| (100, 12) | 5 | 92.1 | 90.7 | 41.0 | 42.8 | 87.8 | 29.4 | 20.1 |
| | 6 | 18.3 | 11.0 | 60.6 | 87.6 | 74.7 | 0.0 | 0.0 |
| (100, 20) | 5 | 91.9 | 90.8 | 40.5 | 41.8 | 86.5 | 24.5 | 20.5 |
| | 6 | 20.4 | 10.0 | 63.7 | 96.3 | 91.5 | 0.0 | 0.0 |

①, ⋯, ④ represent the statistics *hhg.sc*, *hhg.sl*, *hhg.mc*, *hhg.ml*, respectively. ①∼④ stands for the *fusion* of statistics ① to statistic ④.

For Model **M0**, where $X$ and $Y$ are independent, Table 4 contains the empirical sizes of all test statistics. All methods maintain reasonable control over the

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type-I error. For Models **M1**–**M6**, their power is given in Table 5. In the univariate case, the *fused* statistic based on ①∼④ consistently delivers high power across all four models, whereas each of its six competitors has strengths and weakness; for example, both HSIC and DC are powerless in detecting the dependency in **M4**. As for the multivariate case, HSIC and DC become unreliable for **M6**. As for the four HHG-type statistics, the two maximum-type statistics, ③ and ④, perform better with **M6** than with **M5**, and vice versa for the two summation-type statistics ① and ②. Again, our *fused* of the four HHG statistics, that is, ①∼④, maintains satisfactory power for both models, supporting our claim that when testing against an unknown alternative, the *fused* statistic is, in general, a better choice than any individual statistic.

## 7. Real-data examples

Genome-wide association studies (GWAS) identify risk genetic variants for major human diseases by genotyping millions of single nucleotide polymorphisms (SNPs) in large cohorts. With data collected by the Wellcome Trust Case Control Consortium (WTCCC), we apply the two-sample mean comparison procedures of Section 3 to analyze the association between the SNPs and two diseases: type-2 diabetes (T2D), and rheumatoid arthritis (RA). In the case of T2D, there are 1,952 observations with 307,089 SNPs, and for RA, there are 1,969 observations with 305,394 SNPs. For either disease, the data are split into two groups: individuals with the disease ($X$), and individuals without the disease ($Y$). If the means of these two groups are different, then this indicates an association between the said disease and the SNPs. The $p$-values of the existing methods mentioned in Section 3 are all highly significant, suggesting an overwhelmingly strong association that it could be picked up by any valid tests, regardless of whether the test is sparse or dense sensitive.

In order for the data to be suitable for assessing the competitiveness of different tests, we need to first reduce the strength of the signals by thinning out the SNPs. This is realized through the following steps. First, calculate the p-value of each SNP, as in the case of a univariate mean-comparison problem, and rank the SNPs according to their p-values in ascending order. The now ordered SNPs are then divided into 1000 roughly equal-sized groups, with about 300 SNPs in each group. Randomly select one SNP from each group to obtain a total of 1000 SNPs. Finally, calculate the p-values of all competing methods using data on these 1000 randomly selected SNPs. Repeat this procedure 200 times. The boxplot of the 200 p-values for each method is depicted in Figure 2, with the left panel occupied by those related to T2D, and the right panel by RA.

The first thing revealed by these plots is that the pattern related to the power of the various methods is largely in line with what we have seen in the simulation studies. These plots also highlight the potential use of the fusion statistic to choose between recommendations made by different testing methods. Specifically, for example, in the case of T2D, with a significance level set anywhere between 5% and 1%, the two statistics $T_{n,1}$ and $T_{n,p}$ make opposite recommendations for a majority of of the 200 occasions, with $T_{n,p}$ recommending rejection, and $T_{n,1}$ suggesting otherwise. In these occasions, the *fused* statistic can then be used to decide which recommendation is more likely to be correct.

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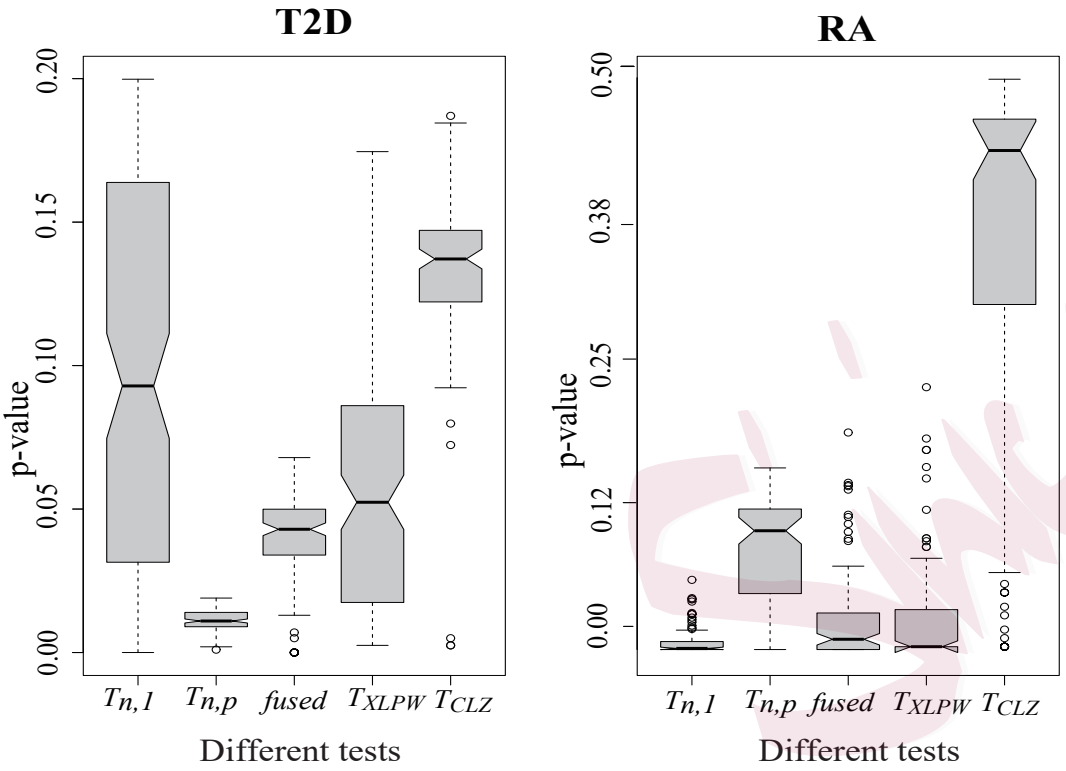


Figure 2: Boxplots of p-values for different statistics; the horizontal gray dashed line is the significance level.

## Appendix: Assumptions and Proofs

### A.1 Further notations and regularity conditions for Sections 2 and 3

For any $\nu = (v_1, \cdots, v_p) \in R^p$, let $|\nu|_\infty$ denote the supremum norm and $|\nu|_1 = (|v_1| + \cdots + |v_p|)/p$, the $L_1$ norm.

For ease of exposition, suppose there exists some sequence of constants $B_n \geq 1$, such that $|X|_\infty \leq B_n$, $i = 1, \cdots, n$, $k = 1, \cdots, p$, with probability one. Moreover, for any $p-$dim vector with at most $s_n$ nonzero elements being either 1 or $-1$, standardize it so that it has unit $L_1$ norm; let $\mathcal{C}(p, s_n)$ denote the collection of all such $p-$dim vectors, obviously with a cardinality no more than $(2p)^{s_n}$.

(C1) The diagonal elements of $\Sigma^X$ are bounded both from below and above. The minimum eigenvalue of $\Sigma^X$ is bounded from below by some constant $c_3 > 0$.

(C2) there exist finite constants $c_{n,1} > 0$ such that for any $\nu \in \mathcal{C}(p, s_n)$,

$$E\{\exp(|\nu^\top X|/c_{n,1})\} \leq 2, \quad E[|\nu^\top X|^{2+k}] \leq c_{n,1}^k, \ k = 1, 2. \tag{A.24}$$

(C3) $s_n = o(p)$, and $B_n s_n \log p = o(n^{1/7})$.

Conditions (C1)–(C3) could be found in Chernozhukov et al. (2017) so that the high-dimensional central limit theorem holds for simple convex sets; see also Kong et al. (2022). Among them, (C3) dictates how large $s_n$ and $P$ could get relative to $n$.

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### A.2 Proof of Theorem 1

Let $D = \text{diag}(\Sigma) = (\sigma_j^2)_{j=1,\cdots,p}$, where $\sigma_j^2 = Var(X^j)$. For a random variable $Z$, and any $r > 0$, let $|Z|_r = [E(|Z|^r)]^{1/r}$, and its Orlicz norm be defined as

$$|Z|_\psi = \inf\{C > 0 : E\psi(|Z/C|) \le 1\}, \quad \text{where } \psi(t) = e^t - 1.$$

A useful inequality is that $|Z|_r \le r!|Z|_\psi$. Condition (C2) implies that $|X^j|_\psi \le c_{n1}$, for all $j = 1, \cdots, p$. Then by Lemma 2.2.2 of van der Vaart and Wellner (1996), $|\max_{j=1,\cdots,p} X^j|_\psi \le c_{n1} \log p$. Consequently, $|\max_{j=1,\cdots,p} X^j|_4 \le c_{n1} \log p$, and based on Lemma D.3 of Chernozhukov et al. (2019), we have for any $c \in (0, 1)$ ,

$$\text{P}(\max_{j=1,\cdots,p} |\hat{\sigma}_{nj}/\sigma_j - 1| \ge n^{-(1-c)/2} c_{n1}^2 \log^3 p) \le n^{-c},$$

whence $a_n = \sup_j |\hat{\sigma}_{nj} - \sigma_j| = o_p((\log p)^{-1})$. Let $\tilde{\delta}_n = D^{-1/2}\bar{X}_n$ . Then for any $\epsilon > 0$, and $k = 1, \cdots, K$,

$$\text{P}(T_{n,k}(\delta_n) \le t) \le \text{P}(T_{n,k}(\bar{X}_n) \le t + \epsilon) + \text{P}(|\bar{X}_n|_\infty \ge \epsilon/a_n), \quad \text{(A.25)}$$
$$\text{P}(T_{n,k}(\delta_n) \le t) \ge \text{P}(T_{n,k}(\bar{X}_n) \le t - \epsilon) + \text{P}(|\bar{X}_n|_\infty \ge \epsilon/a_n). \quad \text{(A.26)}$$

Note that $I(T_{n,k}(\bar{X}_n)) \le t) \Leftrightarrow I(n^{1/2}\bar{X}_n \in A)$, for some $m - generated$ set $A$, namely a set generated by the intersection of $m-$half spaces (Chernozhukov et al., 2017), where the half spaces are defined via vectors belonging to $\mathcal{C}(p, s_n)$, whence $m \le (2p)^{s_n}$. To see this is case, note that for any $p-$dim vector $\mu$, $T_{n,k}(\mu) \le t$ is equivalent to: for any $\nu \in \mathcal{C}(p, s_n)$, $\mu^\top \nu \le t$, i.e. the intersection of half-spaces defined via vectors in $\mathcal{C}(p, s_n)$.

The terms on the RHS of (A.25) and (A.26) concerning $T_{n,k}(\bar{X}_n)$ could then be dealt with through similar arguments used in proving Theorem 3 of Kong et al. (2022), mostly involving high-dimensional Gaussian approximation, i.e., Proposition 2.2 of Chernozhukov et al. (2017), followed by anti-concentration inequalities. The probability to the RHS of (A.25) or (A.26) concerning $|\bar{X}_n|_\infty$ is $o_p(1)$, and could be similarly proved by making use of the fact that $a_n = o_p((\log p)^{-1})$.

The bootstrapped sample has mean $\bar{X}_n$ and variance matrix $\hat{\Sigma}_n = n^{-1}\sum_i (X_i - \bar{X}_n)(X_i - \bar{X}_n)^\top$. Thus the convergence of the bootstrap distribution could be proved through similar arguments in conjunction with Proposition 4.3 of Chernozhukov et al. (2017). □

### A.3 Proof of Theorem 2

Similar to the arguments below (A.26), with $T_{n,k}(.)$ as defined in (2.6), we have

$$I\Big(\bigcap_{k=1}^{K} \{T_{n,k}(Z_\pi^N) \le t_k\}\Big) = I(n^{1/2}\delta_n(Z_\pi^N) \in A),$$

where $A \subset R^p$ is some $m - generated$ set with $m \le (2p)^{s_n}$. Through arguments similar to those used in proving Theorem 3 of Kong et al. (2022), we have

$$\sup_A |\text{P}^*(n^{1/2}\delta_n(Z_\pi^N) \in A) - \text{P}(N(0, \Sigma^X + \Sigma^Y) \in A)| \to 0, \text{ in probability}$$
$$\sup_A |\text{P}(n^{1/2}\delta_n(Z^N) \in A) - \text{P}(N(0, \Sigma^X + \Sigma^Y) \in A)| \to 0,$$

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where the supremum is taken over all $m-generated$ set with $m \leq (2p)^{s_n}$, while the probability $P^*$ is taken conditional on $Z^N$, with respect to $\pi$ uniformly distributed on $G_N$. □

### A.4 Proof of Theorem 3

Let $a = (a_k,\, k = 1, \cdots, K)^\top$, $d = (d_k,\, k = 1, \cdots, K)^\top$, where $a_k = E(a_k(X))$, $d_k = E(d_k(Y))$. $\bar{a}_n = (\bar{a}_n^{(k)}, k = 1, \cdots, K)^\top$; and $\bar{d}_n = (\bar{d}_n^{(k)}, k = 1, \cdots, K)^\top$. Let $(Z_1, \cdots, Z_k) \sim N(0, \Sigma)$, the $K-$dim Gaussian with covariance matrix $\Sigma = [\sigma_{k,l} s_{k,l}]$, where $\sigma_{k,l} = \mathrm{Cov}(a_k(X), a_l(X))$, $s_{k,l} = \mathrm{Cov}(d_k(Y), d_l(Y))$.

The proof of Theorem 3 is broken down into the following two lemmas, which deals with the (joint) null distribution and the joint permutation distribution, respectively.

**Lemma 1.**

$$\max_{k=1,\cdots,K} \sup_{t_k \in R} |F_{n,k}(t_k) - \mathrm{P}(Z_k \leq t_k)| = o(1),$$

$$\sup_{t_1,\cdots,t_K \in R} \Big| F_n(t_1, \cdots, t_{s_n}) - \mathrm{P}\Big( \bigcap_{k=1}^{K} \{Z_k \leq t_k\} \Big) \Big| = o(1),$$

*Proof of Lemma 1.* For fixed $K$, the assertion is simply the multivariate CLT. Here, we prove these two statements under a more general set-up where $K = s_n$, the number of statistics, is allowed to grow as $n$ increases, while the function $a_k(X)$ and $d_k(Y)$, $k = 1, \cdots, s_n$, could be any measurable functions satisfying the moment conditions (A1)-(A3) below.

(A1) $\inf_{k=1,\cdots,s_n} E[(a_k(X)d_k(Y))^2] > 0.$

(A2) There exists some sequence of constants $B_n \geq 1$, possibly growing to infinity as $n \to \infty$, such that for all $i = 1, \cdots, n$, and $k = 1, \cdots, s_n$,

$$E\{\exp(|a_k(X)d_k(Y)|/B_n)\} \leq 2, \quad E[|a_k(X)d_k(Y)|^{2+l}] \leq B_n^l,\ l = 1, 2. \tag{A.27}$$

(A3) $B_n^{1/3}\{\log(ns_n)\}^{7/6} = o(1)$.

For ease of exposition, write $T_{n,k} := T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^n)$, and

$$T_{n,k} = S_{n,k} - n^{1/2}(\bar{a}_n^{(k)} - a_k)(\bar{b}_n^{(k)} - d_k),\ S_{n,k} = n^{-1/2} \sum_i (a_{n,i}^{(k)} - a_k)(d_{n,i}^{(k)} - d_k).$$

For any $t_k \in R$, $k = 1, \cdots, s_n$, and $\epsilon > 0$

$$\mathrm{P}(T_{n,k} \leq t) \leq \mathrm{P}(S_{n,k} \leq t + \epsilon^2) + \mathrm{P}(n^{1/2}|(\bar{a}_n - a)|_\infty \geq n^{1/4}\epsilon) \tag{A.28}$$

$$+\mathrm{P}(n^{1/2}|(\bar{d}_n - d)|_\infty \geq n^{1/4}\epsilon) \tag{A.29}$$

$$\mathrm{P}(n^{1/2}|(\bar{a}_n - a)|_\infty \geq n^{1/4}\epsilon) = \mathrm{P}(|W_1|_\infty \geq n^{1/4}\epsilon) + o(1) \tag{A.30}$$

$$= O(n^{-1/4}(\log s_n)^{1/2}/\epsilon) + o(1), \tag{A.31}$$

$$\mathrm{P}(n^{1/2}|(\bar{d}_n - d)|_\infty \geq n^{1/4}\epsilon) = \mathrm{P}(|W_2|_\infty \geq n^{1/4}\epsilon) + o(1) \tag{A.32}$$

$$= O(n^{-1/4}(\log s_n)^{1/2}/\epsilon) + o(1), \tag{A.33}$$

$$\sup_{t \in R} |\mathrm{P}(S_{n,k} \leq t + \epsilon^2) - \mathrm{P}(Z_k \leq t + \epsilon^2)| = O(n^{-1/2}B_n^{3/2}) \tag{A.34}$$

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where $W_1$ (or $W_2$) is $s_n-$dim zero-mean Gaussian vector with covariance matrix identical to that of $n^{1/2}\bar{a}_n$ ( or $n^{1/2}\bar{d}_n$), while $Z_k$ is $N(0, \sigma_{k,k}s_{k,k})$; here (A.31) and (A.33) follow from Proposition 2.1 of Chernozhukov et al. (2017), Lemma D.3 of Chernozhukov et al. (2015) and the Chebyshev inequality, while (A.34) is a result of the Berry-Esseen Bounds and (A.27).

Reverse the direction of the inequality in (A.29), we have

$$\begin{aligned}\mathrm{P}(T_{n,k} \le t) \ge \mathrm{P}(S_{n,k} \le t - \epsilon^2) - \mathrm{P}(n^{1/2}|(\bar{a}_n - a)|_\infty \ge n^{1/4}\epsilon) \\ -\mathrm{P}(n^{1/2}|(\bar{d}_n - d)|_\infty \ge n^{1/4}\epsilon);\end{aligned}$$

for the three terms to the RHS, results parallel to (A.31)-(A.34) could be similarly proved. Thus

$$\max_{k=1,\cdots,s_n} \sup_{t\in R} |\mathrm{P}(T_{n,k} \le t) - \mathrm{P}(Z_k \le t)| = O(\epsilon^2 + n^{-1/2}B_n^{3/2} + n^{-1/4}(\log s_n)^{1/2}/\epsilon) + o(1),$$

where the right hand side is $o(1)$, if $n^{-1/4}(\log s_n)^{1/2} = o(1)$. This proves the first assertion on the (null) marginal distribution.

As for the joint (null) distribution, first note that similar to (A.31),

$$\begin{aligned}\mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{T_{n,k} \le t_k\}\Big) \le \mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{S_{n,k} \le t + \epsilon^2\}\Big) + \mathrm{P}(n^{1/2}|(\bar{a}_n - a)|_\infty \ge n^{1/4}\epsilon) \\ +\mathrm{P}(n^{1/2}|(\bar{d}_n - d)|_\infty \ge n^{1/4}\epsilon).\end{aligned}$$

We could then again apply Proposition 2.1 of Chernozhukov et al. (2017) and Nazarov's inequality (Nazarov, 2003) to see that

$$\sup_{t_1,\cdots,t_{s_n}\in R} \Big|\mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{S_{n,k} \le t_k\}\Big) - \mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{Z_k \le t_k\}\Big)\Big| = O((B_n^2 \log^7(ns_n)/n)^{1/6} = o(1)$$

$$\sup_{t_1,\cdots,t_{s_n}\in R} \Big|\mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{Z_k \le t_k\}\Big) - \mathrm{P}\Big(\bigcap_{k=1}^{s_n}\{Z_k \le t_k + \epsilon^2\}\Big)\Big| \le C\epsilon^2(\log s_n)^{1/2}.$$

The proof is thus complete if $\epsilon$ could be chosen such that $\epsilon = o(n^{-1/4}(\log s_n)^{1/2})$ and $\epsilon = o((\log s_n)^{-1/4})$. □

**Lemma 2.** With probability one,

$$\sup_{t_1,\cdots,t_K\in R} \Big|R_n(t_1,\cdots,t_K|\mathbf{X}_1^n, \mathbf{Y}_1^n) - \mathrm{P}\Big(\bigcap_{k=1}^{K}\{Z_k \le t_k\}\Big)\Big| = o(1).$$

*Proof of Lemma 2* For ease of exposition, the conclusion will be proved for the case where $\{d^{(k)}(.),\ k = 1,\cdots,K\}$ are all binary. The proof could be trivially adapted for the more general cases, where $k = 1,\cdots,K$, $d^{(k)}(.)$ is categorical taking a finite number of values.

For $k = 1,\cdots,K$, and $i = 1,\cdots,n$, write

$$a_{n,i}^{(k)} = a_k(X_i),\ c_{n,i}^{(k)} = n^{-1/2}(a_{n,i}^{(k)} - \bar{a}_n^{(k)}),\ d_{n,i}^{(k)} = d^k(Y_i).$$

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Re-arrange the $n$ observations $\{(X_i, Y_i) : i = 1, \cdots, n\}$ via the following steps: firstly, move the rows with $d_{n,i}^{(1)} = 0$ ahead of those rows with $d_{n,i}^{(1)} = 1$; secondly, for rows with the same value of $d_{n,i}^{(1)}$, sort them according to the value of $\{d_{n,i}^{(2)}, i = 1, \cdots, n\}$ (again in ascending order); repeat this process until the last step where the rows with the same value of $d_{n,i}^{(k)}$, for all $k = 1, \cdots, K-1$, are sorted according to their respective value of $d_{n,i}^{(K)}$. To illustrate, in the case of $K = 3$, there are eight possibilities for the rows of $n \times 3$ matrix, and they are arranged in the following order:

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| (1) | 0 | 0 | 0 | (5) | 1 | 0 | 0 |
| (2) | 0 | 0 | 1 | (6) | 1 | 0 | 1 |
| (3) | 0 | 1 | 0 | (7) | 1 | 1 | 0 |
| (4) | 0 | 1 | 1 | (8) | 1 | 1 | 1 |

For the re-arranged observations, without loss of generality, we still use $c_{n,i}^{(k)}$ and $d_{n,i}^{(k)}$ $i = 1, \cdots, n$, $k = 1, \cdots, K$, to denote the corresponding 'coefficients' and 'scores'. As a result of the strong law of large numbers (SLLN), there exist square integrable functions $\phi_k(.)$, $k = 1, \cdots, K$, on (0,1), such that

$$\sup_{n\to\infty} \int_0^1 \left\{\phi_k(u) - d_{n,1+[nu]}^{(k)}\right\}^2 du = 0, \quad k = 1, \cdots, K. \tag{A.35}$$

For illustration purposes, here we only give the specific forms for $\psi_1(.)$ and $\psi_2(.)$; the explicit form of other $\phi_k(.)$ could be derived through similar arguments. Let $B_1 = \{y \in R^q : d^1(Y) = 0\}$, $B_2 = \{y \in R^q : d^2(Y) = 0\}$, $q_1 = \Pr(Y \in B_1)$, $q_2 = \Pr(Y \in B_2)$, $q_{1,2} = \Pr(Y \in B_1 \cap B_2)$. Then $\psi_1(.)$ and $\psi_2(.)$ could be defined as:

$$\phi_1(u) = \begin{cases} 0, & u \in (0, q_1) \\ 1, & o.w. \end{cases}, \quad \phi_2(u) = \begin{cases} 0, & u \in (0, q_{1,2}) \\ 1, & u \in [q_{1,2}, q_1) \\ 0, & u \in [q_1, q_1 + q_2 - q_{1,2}) \\ 1, & u \in [q_1 + q_2 - q_{1,2}, 1). \end{cases}$$

For these 'score' functions, it holds that for any $k, l = 1, \cdots, K$,

$$\bar{\psi}_k := \int_0^1 \psi_k(u)du = 1 - q_k, \quad \int_0^1 \phi_k(u)\psi_l(u)du = 1 - q_k - q_l + q_{k,l}, \ k \neq l.$$

In view of (A.35), when $\pi$ is uniformly distributed on $S_n$, so that $\pi(i)$ is the rank of $U_i$, with $U_1, \cdots, U_n$ i.i.d. $U(0,1)$, we could apply Theorem 6.1.6.1 of Hajek et al. (1999) and claim that for all $k = 1, \cdots, K$,

$$T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{n,\pi}) = \sum_i c_{n,i}^{(k)} d_{n,\pi(i)}^{(k)} = \sum_i c_{n,i}^{(k)} (\psi_k(U_i) - \bar{\psi}_k) + o_p(1). \tag{A.36}$$

Thus conditional on $(\mathbf{X}_1^n, \mathbf{Y}_1^n)$, $\{T_{n,k}(\mathbf{X}_1^n, \mathbf{Y}_1^{n,\pi}), k = 1, \cdots, K\}$ are jointly normal with covariance matrix given by

$$\mathrm{Cov}\Big[\sum_i c_{n,i}^{(k)} \psi_k(U_i), \sum_i c_{n,i}^{(l)} \psi_l(U_i)\Big] = \sum_i c_{n,i}^{(k)} c_{n,i}^{(l)} (q_{k,l} - q_k q_l).$$

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Moreover, by SLLN, with probability one,

$$\sum_i c_{n,i}^{(k)} c_{n,i}^{(l)} = \frac{1}{n}\sum_i (a_{n,i}^{(k)} - \bar{a}_n^{(k)})(a_{n,i}^{(l)} - \bar{a}_n^{(l)}) \to \sigma_{k,l},$$

and the proof is thus complete. □

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Efang Kong
School of Mathematical Sciences
University of Electronic Science and Technology of China, China
E-mail: (kongefang@uestc.edu.cn)
Yu Liu
School of Mathematical Sciences
University of Electronic Science and Technology of China, China
E-mail: (liuyuchina123@gmail.com)
Yingcun Xia
Department of Statistics and Data Science
National University of Singapore, Singapore
E-mail: (staxyc@nus.edu.sg)