How Many Entries of A Typical Orthogonal Matrix Can Be Approximated By Independent Normals?

Short title: Normals Approximate Matrix Entries

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Abstract We solve an open problem of Diaconis that asks what are the largest orders of p_n and q_n such that Z_n, the $p_n \times q_n$ upper left block of a random matrix $\mathbf{\Gamma}_n$ which is uniformly distributed on the orthogonal group $O(n)$, can be approximated by independent standard normals? This problem is solved by two different approximation methods.

First, we show that the *variation distance* between the joint distribution of entries of Z_n and that of p_nq_n independent standard normals goes to zero provided $p_n = o(\sqrt{n})$ and $q_n = o(\sqrt{n})$. We also show that the above variation distance does not go to zero if $p_n = [x\sqrt{n}]$ and $q_n = [y\sqrt{n}]$ for any positive numbers x and y. This says that the largest orders of p_n and q_n are $o(n^{1/2})$ in the sense of the above approximation.

Second, suppose $\mathbf{\Gamma}_n = (\gamma_{ij})_{n\times n}$ is generated by performing the Gram-Schmidt algorithm on the columns of $\mathbf{Y}_n = (y_{ij})_{n\times n}$ where $\{y_{ij}; 1 \le i, j \le n\}$ are i.i.d. standard normals. We show that $\epsilon_n(m) := \max_{1\le i\le n, 1\le j\le m} |\sqrt{n}\gamma_{ij} - y_{ij}|$ *goes to zero in probability* as long as $m = m_n = o(n/\log n)$. We also prove that $\epsilon_n(m_n) \to 2\sqrt{\alpha}$ in probability when $m_n = [n\alpha/\log n]$ for any $\alpha > 0$. This says that $m_n = o(n/\log n)$ is the largest order such that the entries of the first m_n columns of $\mathbf{\Gamma}_n$ can be approximated simultaneously by independent standard normals.

1 Introduction

Let $\mathbf{\Gamma}_n = (\gamma_{ij})$ be a random orthogonal matrix which is uniformly distributed on the orthogonal group $O(n)$. Let Z_n be the $p_n \times q_n$ upper left block of $\mathbf{\Gamma}_n$, where p_n and q_n are two positive integers. The open problem in section 6.3 from Diaconis [10] is as follows:

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what are the largest orders of p_n and q_n such that the variation distance between the joint distribution of the entries of Z_n and that of $p_n q_n$ independent standard normals goes to zero as $n \to \infty$. We answer this question here. Before stating the results formally, let's first review some history of this problem.

In studying "Equivalence of Ensembles" in statistical mechanics, Borel [5] showed that

$$P(\sqrt{n}\gamma_{11} \le x) \to \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{x} e^{-t^2/2}\, dt \tag{1.1}$$

as $n \to \infty$ for any real number x. For more information about this formula, one is referred to Poincaré [27], p. 197 in McKean [26], p. 412 in Letac [23], p. 342 in Billingsley [4], Diaconis and Freedman [11], and Maxwell [24] and [25].

Similar results for fixed m are derived through Brownian motion by Gallardo [16] and Yor [32]. Let $\boldsymbol{\gamma}_1$ be the first column of $\mathbf{\Gamma}_n$. Stam [30] proved that d_m, the variation distance between the distribution of the first m coordinates of $\boldsymbol{\gamma}_1$ and the distribution of m independent standard normals, goes to zero provided $m = o(\sqrt{n})$ as $n \to \infty$. He applied this result to a geometric probability problem.

In studying a finite representation theorem of the de Finetti type, Diaconis and Freedman [11] showed that the above d_m goes to zero as $n \to \infty$ provided $m = o(n)$. On the other hand, in studying a de Finetti type theorem on a finite sequence of orthogonal invariant random vectors, Diaconis, Eaton and Lauritzen [14] proved the following.

THEOREM A.1 *For each $n \ge 1$, let Z_n be the $p_n \times q_n$ upper left block of a random matrix $\mathbf{\Gamma}_n$ which is uniformly distributed on the orthogonal group $O(n)$. Let also δ_n be the variation distance between the distribution of the $p_n q_n$ entries of Z_n and the joint distribution of $p_n q_n$ independent standard normals. Then $\delta_n \to 0$ if $p_n = o(n^\alpha)$ and $q_n = o(n^\alpha)$ for $\alpha = 1/3$.*

Since the publication of [14], there have been various speculations on the maximum value α to make the variation distance go to zero. Here are three major ones: (a) $p_n = O(n^{1/3})$ and $q_n = O(n^{1/3})$; (b) $p_n = o(n^{1/2})$ and $q_n = o(n^{1/2})$; (c) $p_n = o(n)$ and $q_n = o(n)$. Recently Collins [7] showed that the variation distance in Theorem A.1 goes to zero when $p_n = O(n^{1/3})$ and $q_n = O(n^{1/3})$.

Attempts to improve on the orders of p_n and q_n are partly motivated by the following reasons. First, it is well known that the above $\mathbf{\Gamma}_n$ is close to $\mathbf{\Gamma}'_n$, an $n \times n$ matrix with independent normals as entries. Mathematically, it is interesting to know in what sense they are close. Diaconis and Shahshahani [12], Diaconis and Evans [13] and Rains [28] characterized relationships between the traces of $\mathbf{\Gamma}_n$ and those of $\mathbf{\Gamma}'_n$ in terms of expectations; Johansson [20] obtained the speed of convergence of traces of $\mathbf{\Gamma}_n$ to a normal random variable;

D'Aristotile, Diaconis and Newman [8] showed that the linear combination of entries of $\mathbf{\Gamma}_n$ also converges weakly to a normal distribution. Second, improving the orders of p_n and q_n has a lot of applications; see Diaconis, Eaton and Lauritzen [14] and Jiang [19]. The last paper also proved the following coupling result.

THEOREM A.2 *For each $n \geq 2$, there exists matrices $\mathbf{\Gamma}_n = (\gamma_{ij})_{1\leq i,j\leq n}$ and $\mathbf{\Gamma}'_n = (\gamma'_{ij})_{1\leq i,j\leq n}$ whose $2n^2$ elements are random variables defined on the same probability space such that*

(i) the law of $\mathbf{\Gamma}_n$ is the normalized Haar measure on the orthogonal group O_n;

(ii) $\{\gamma'_{ij}; 1 \leq i, j \leq n\}$ are independent standard normals;

(iii) set $\epsilon_n(m) = \max_{1\leq i\leq n, 1\leq j\leq m} |\sqrt{n}\gamma_{ij} - \gamma'_{ij}|$ for $m = 1, 2, \cdots, n$. Then

$$\epsilon_n(m_n) \to 0 \text{ in probability}$$

as $n \to \infty$ provided $m_n = o(n/(\log n)^2)$.

It says that $n^2/(\log n)^2$ elements of $\mathbf{\Gamma}_n$ can be approximated by the corresponding elements of $\mathbf{\Gamma}'_n$ in terms of convergence in probability, which is weaker than the convergence in variation norm.

This theorem highlights the interest in improving the orders of p_n and q_n. It seems to suggest that Theorem A.1 holds for much larger p_n and q_n. This is why people conjectured that the maximum orders of p_n and q_n are $o(n)$. At the same time it would be interesting to know the largest order of m_n such that Theorem A.2 holds.

In this paper we prove that the maximum value of α as in Theorem A.1 is actually $1/2$, and the largest order of m_n such that $\epsilon_n(m_n) \to 0$ in probability is $o(n/\log n)$, where $\epsilon_n(m_n)$ is as in Theorem A.2. To state our results formally, let's recall the definition of variation distance first.

Let μ and ν be two probability measures on $(\mathbb{R}^m, \mathcal{B})$, where $\mathcal{B}$ is the Borel σ-algebra. The variation distance between μ and ν, denoted by $\|\mu - \nu\|$, is equal to

$$\|\mu - \nu\| = 2 \cdot \sup_{A\in\mathcal{B}} |\mu(A) - \nu(A)| = \int_{\mathbb{R}^m} |f(x) - g(x)|\, dx_1 dx_2 \cdots dx_m. \tag{1.2}$$

provided μ and ν have density functions $f(x)$ and $g(x)$ with respect to the Lesbegue measure, respectively. For each $n \geq 1$, suppose that Z_n is the $p_n \times q_n$ upper left block of a random matrix $\mathbf{\Gamma}_n$ which is uniformly distributed on the orthogonal group $O(n)$. Let G_n be the joint distribution of $p_n q_n$ independent standard normals. We use $\mathcal{L}(\sqrt{n}Z_n)$ to represent the joint probability distribution of the $p_n q_n$ random entries of $\sqrt{n}Z_n$. It is not difficult to see that $\|\mathcal{L}(\sqrt{n}Z_n) - G_n\|$ is non-decreasing in p_n and q_n, respectively.

THEOREM 1 *If $p_n = o(\sqrt{n})$ and $q_n = o(\sqrt{n})$ as $n \to \infty$ then*

$$\lim_{n\to\infty} \|\mathcal{L}(\sqrt{n}Z_n) - G_n\| = 0.$$

As usual, the notation $[a]$ stands for the integer part of a positive integer a.

THEOREM 2 *Let $x > 0$ and $y > 0$ be two numbers and $p_n = [xn^{1/2}]$ and $q_n = [yn^{1/2}]$. Then*

$$\liminf_{n\to\infty} \|\mathcal{L}(\sqrt{n}Z_n) - G_n\| \geq \phi(x, y) > 0,$$

where $\phi(x, y) := E\left|\exp\left(-\frac{x^2y^2}{8} + \frac{xy}{4}\xi\right) - 1\right| \in (0, 1)$ and ξ is a standard normal.

One can see that $\phi(0, 0) = 0$, which roughly reflects the flavor of Theorem 1. This is rigorously true if the conclusion in Theorem 2 is replaced by that $\lim_{n\to\infty} \|\mathcal{L}(\sqrt{n}Z_n) - G_n\| = \phi(x, y)$. A further analysis shows that the inequality in the theorem is actually strict.

Why are the maximum orders of p_n and q_n equal to $o(n^{1/2})$ as shown in Theorems 1 and 2?

There are two reasons. First, Diaconis and Freedman [11] showed that the variation distance between the distribution of the $o(n)$ entries of the first column of $\mathbf{\Gamma}_n$ and that of independent normals goes to zero. We know that Z_n, a p_n by q_n sub-matrix of $\mathbf{\Gamma}_n$, has p_nq_n elements. One can guess that the number of approximated entries are fixed (loosely speaking). So the largest α in $p_n = o(n^\alpha)$ and $q_n = o(n^\alpha)$ must be 1/2. Second, we can see this mathematically. Let $f_n(z)$ and $g_n(z)$ be the density functions of $\sqrt{n}Z_n$ and G_n, respectively. By (1.2)

$$\|\mathcal{L}(\sqrt{n}Z_n) - G_n\| = \int \left|\frac{f_n(z)}{g_n(z)} - 1\right| g_n(z)\, dz = E\left|\frac{f_n(X_n)}{g_n(X_n)} - 1\right| \tag{1.3}$$

where the integration region in the first integral is $\mathbb{R}^{p_nq_n}$, and the p_nq_n entries of matrix X_n are independent standard normals. The term $f(X_n)/g(X_n)$, as will be shown later, converges weakly to a lognormal distribution when both p_n and q_n are of order $n^{1/2}$; $f(X_n)/g(X_n)$ converges to one when both p_n and q_n are of order $o(n^{1/2})$.

Now we consider the approximation method as in Theorem A.2.

Let $\mathbf{Y}_n = (y_{ij})_{1\leq i,j\leq n}$, where y_{ij}'s are independent standard normals. Let also $\mathbf{\Gamma}_n = (\gamma_{ij})_{1\leq i,j\leq n}$ be the orthogonal matrix obtained from performing the Gram-Schmidt procedure on the columns of $\mathbf{Y}_n$ (the procedure is briefly reviewed at the beginning of Section 3). Define

$$\epsilon_n(m) = \max_{1\leq i\leq n, 1\leq j\leq m} |\sqrt{n}\gamma_{ij} - y_{ij}|.$$

We have the following theorem.

THEOREM 3 *Let $\{m_n < n;\ n \geq 1\}$ be a sequence of positive integers. Then*
(i) the matrix $\mathbf{\Gamma}_n$ is Haar invariant on the orthogonal group $O(n)$;
(ii) $\epsilon_n(m_n) \to 0$ in probability provided $m_n = o(n/\log n)$ as $n \to \infty$;
(iii) for any $\alpha > 0$, we have that $\epsilon_n([n\alpha/\log n]) \to 2\sqrt{\alpha}$ in probability as $n \to \infty$.

This theorem tells us that the maximum order of m_n such that $\epsilon_n(m_n) \to 0$ in probability is that $m_n = o(n/\log n)$, where the typical orthogonal matrix $\mathbf{\Gamma}_n$ is obtained through performing the Gram-Schmidt procedure for a matrix whose elements are independent standard normals.

We prove Theorems 1 and 2 in Section 2. Theorem 3 is proved in Section 3. Technical lemmas used in Sections 2 and 3 are given in Section 4. At last, a couple of of known results needed for the proof of Theorem 3 are listed in Section 5.

2 The Proofs of Theorems 1 and 2

First we list some lemmas needed for the proofs of Theorems 1 and 2. The proofs of these lemmas are listed in Section 4.1.

LEMMA 2.1 *Let $\Gamma(x),\ x > 0$ be the standard Gamma function. Then*

$$(i) \quad 1 - \frac{1}{6n} < \frac{\Gamma(n + (1/2))}{\sqrt{n}\,\Gamma(n)} < 1 \quad \textit{for all} \quad n \geq 1;$$

$$(ii) \quad \left| \frac{\Gamma((n+1)/2)}{\sqrt{n/2}\,\Gamma(n/2)} - 1 \right| < \frac{3}{5n} \ \textit{for all} \quad n \geq 1.$$

LEMMA 2.2 *Let $f(u, v)$ be a real-valued function. Suppose the three second-order derivatives of f exist and bounded below and above by $-M$ and M, respectively, over $[a, b] \times [c, d]$. Then*

$$\begin{aligned} \frac{1}{n^2} \sum_{j=j_1}^{j_2} \sum_{i=i_1}^{i_2} f\left(\frac{i}{n}, \frac{j}{n}\right) &= \int_{j_1/n}^{(j_2+1)/n} \int_{i_1/n}^{(i_2+1)/n} f(x, y)\, dx\, dy \\ &- \frac{1}{2n^3} \sum_{j=j_1}^{j_2} \sum_{i=i_1}^{i_2} f'_x\left(\frac{i}{n}, \frac{j}{n}\right) - \frac{1}{2n^3} \sum_{j=j_1}^{j_2} \sum_{i=i_1}^{i_2} f'_y\left(\frac{i}{n}, \frac{j}{n}\right) + \epsilon, \end{aligned}$$

where $|\epsilon| \leq (i_2 - i_1)(j_2 - j_1)M/n^4$ for any i_1, i_2, j_1 and j_2 such that $na \leq i_1 < i_2 \leq nb - 1$ and $nc \leq j_1 < j_2 \leq nd - 1$.

We will use the following setting a couple of times.

Let $X = (x_{ij})$ be a p by q matrix, where $\{x_{ij},\ 1 \leq i \leq p; 1 \leq j \leq q\}$ are i.i.d. standard normals. Let $\lambda_1, \lambda_2, \cdots, \lambda_q$ be the eigenvalues of $X'X$. (2.1)

A sequence $\{X_n; n \geq 1\}$ will be studied, where X_n is of the above setting for each n. We still use notation X for X_n sometimes when there is no confusion.

The next lemma is a standard result when using the moment method to show weak convergence of certain functions of eigenvalues of matrices with independent and identically distributed random variables as entries. It is can be seen from, e.g., (2.15) and (2.16) in [3].

LEMMA 2.3 *Let $\{p_n; n \geq 1\}$ and $\{q_n; n \geq 1\}$ be two sequences of positive integers such that $p_n \to \infty$ and $p_n/q_n \to \eta \in (0, \infty)$. For each n, assume the setting in (2.1) with $p = p_n$ and $q = q_n$. The following two statements hold. For each integer $k \geq 1$,*

$$(i) \qquad E\left(tr(X_n'X_n)^k\right) \sim p_n^k q_n \sum_{r=0}^{k-1} \frac{1}{r+1}\left(\frac{q_n}{p_n}\right)^r \binom{k}{r}\binom{k-1}{r}$$

as $n \to \infty$.

(ii)

$$\frac{tr\left((X_n'X_n)^k\right)}{q_n^{k+1}} \to \sum_{r=0}^{k-1} \frac{\eta^{k-r}}{r+1}\binom{k}{r}\binom{k-1}{r}$$

in probability as $n \to \infty$.

LEMMA 2.4 *Let $\epsilon > 0$. Let $\{p_n; n \geq 1\}$ and $\{q_n; n \geq 1\}$ be two sequences of positive integers such that $\epsilon \leq p_n/q_n \leq \epsilon^{-1}$ for all $n \geq 1$. For each n, assume the setting in (2.1) with $p = p_n$ and $q = q_n$. Assume $p_n \to \infty$ as $n \to \infty$. Then*

(i) $Var\left(tr((X_n'X_n)^2)\right) \sim p_n^2 q_n^2 + 8p_n q_n (p_n + q_n)^2$ *as $n \to \infty$;*

(ii) $Cov(tr(X_n'X_n), tr((X_n'X_n)^2)) \sim 4p_n q_n (p_n + q_n)$ *as $n \to \infty$.*

The following lemma is Proposition 2.1 from Diaconis, Eaton and Lauritzen [14] or Proposition 7.3 from Eaton[15]. This is the starting point of the proofs of Theorems 1 and 2.

LEMMA 2.5 *Let U be a n by n random matrix which is uniformly distributed on the orthogonal group O_n and let Z be the upper left $p \times q$ corner block of U. If $p + q \leq n$ and $q \leq p$ then the joint density function of entries of Z is*

$$f(z) = (\sqrt{2\pi})^{-pq} \frac{\omega(n-p, q)}{\omega(n, q)} \left\{det(I_q - z'z)^{(n-p-q-1)/2}\right\} I_0(z'z) \tag{2.2}$$

where $I_0(z'z)$ is the indicator function of the set that all q eigenvalues of $z'z$ are in $(0, 1)$, and $\omega(\cdot, \cdot)$ is the Wishart constant defined by

$$\frac{1}{\omega(r, s)} = \pi^{s(s-1)/4} 2^{rs/2} \prod_{j=1}^{s} \Gamma\left(\frac{r-j+1}{2}\right).$$

Here s is a positive integer and r is a real number, $r > s-1$. When $p \le q$, the density of Z is obtained by interchanging p and q in the above Wishart constant.

To simplify notation, when there is no confusion, we write p for p_n and q for q_n.

Let $g(z)$ be the joint density function of entries of $X = (x_{ij})_{p\times q}$, where x_{ij}'s are independent standard normals. So, $g(z) = (2\pi)^{-pq/2}\exp(-tr(z'z)/2)$, where z is a p by q matrix. We need to understand the ratio $f(z)/g(z)$ in later proofs. Assuming the pq entries of z are independent standard normals, then $f(z)/g(z)$ can be written as a product of a constant part and a random part. They are analyzed in the following two lemmas.

Lemma 2.6 *Given $x > 0$ and $y > 0$, let $p = p_n = [xn^{1/2}]$ and $q = q_n = [yn^{1/2}]$. Set*

$$K_n = \left(\frac{2}{n}\right)^{pq/2}\prod_{j=1}^{q}\frac{\Gamma((n-j+1)/2)}{\Gamma((n-p-j+1)/2)}.$$

Then

$$K_n = \exp\left\{-\left(\frac{p^2q+pq^2}{4n}+\frac{xy}{4}+\frac{2x^3y+2xy^3+3x^2y^2}{24}\right)+o(1)\right\} \tag{2.3}$$

as n is sufficiently large.

Proof. Suppose $p = 2k$. Using the fact that $\Gamma(x+1) = x\Gamma(x)$, we have that

$$\begin{aligned} K_n &= \left(\frac{2}{n}\right)^{pq/2}\prod_{j=1}^{q}\left\{\left(\frac{2}{n}\right)^{-p/2}\prod_{i=1}^{k}\left(1-\frac{2i+j-1}{n}\right)\right\} \\ &= \prod_{j=1}^{q}\prod_{i=1}^{k}\left(1-\frac{2i+j-1}{n}\right) := e^{B_n} \end{aligned} \tag{2.4}$$

where

$$B_n := \sum_{j=0}^{q-1}\sum_{i=1}^{k}\log\left(1-\frac{2i+j}{n}\right).$$

Let $f(s,t) = \log(1-2s-t)$ with $2s+t < 1$. Then $f'_s(s,t) = -2/(1-2s-t) = -2 + O(n^{-1/2})$, $f'_t(s,t) = -1/(1-2s-t) = -1 + O(n^{-1/2})$ and

$$\left|\frac{\partial f^2}{\partial s^2}\right| = \left|\frac{-4}{(1-2s-t)^2}\right| \le 5, \quad \left|\frac{\partial f^2}{\partial t^2}\right| = \left|\frac{-1}{(1-2s-t)^2}\right| \le 5 \text{ and}$$
$$\left|\frac{\partial f^2}{\partial s\partial t}\right| = \left|\frac{-2}{(1-2s-t)^2}\right| \le 5$$

for all $(s,t) \in [0,p/n] \times [0,q/n]$ as n is sufficiently large. By Lemma 2.2,

$$\begin{aligned}
B_n &= n^2 \int_0^{q/n} \int_{1/n}^{(k+1)/n} \log(1-2s-t)\, ds\, dt + \frac{3kq}{2n} + O\left(\frac{1}{\sqrt{n}}\right) \\
&= \frac{n^2}{2} \int_0^{v} \int_0^{u} \log(1+s+t)\, ds\, dt - \frac{n^2}{2} \int_0^{v} \int_0^{-2/n} \log(1+s+t)\, ds\, dt + \frac{3xy}{4} + O\left(\frac{1}{\sqrt{n}}\right)
\end{aligned} \tag{2.5}$$

as n is sufficiently large, where $u = -(p+2)/n,\ v = -q/n$. We now estimate the above integral. By Taylor's expansion there exists $\delta > 0$ such that

$$\left|\log(1+s+t) - \left((s+t) - \frac{(s+t)^2}{2}\right)\right| \le (s+t)^3$$

for all s and t such that $s+t \in (0,\delta)$. Thus,

$$\begin{aligned}
&\left|\int_0^{v} \int_0^{u} \log(1+s+t)\, ds\, dt - \left[\int_0^{v} \int_0^{u} (s+t)\, ds\, dt - \frac{1}{2}\int_0^{v} \int_0^{u} (s+t)^2\, ds\, dt\right]\right| \\
\le\ & \int_0^{v} \int_0^{u} (s+t)^3\, ds\, dt
\end{aligned} \tag{2.6}$$

as both u and v are in $(0,\delta/2)$. It is trivial to verify that

$$\int_0^{v} \int_0^{u} (s+t)^k\, ds\, dt = \frac{1}{(k+1)(k+2)} \left((u+v)^{k+2} - u^{k+2} - v^{k+2}\right)$$

for $k \ge 0$. Plugging this into (2.6), we obtain

$$\int_0^{v} \int_0^{u} \log(1+s+t)\, ds\, dt = \left[\frac{u^2v+uv^2}{2} - \frac{1}{12}(2uv^3+2u^3v+3u^2v^2)\right] + O((u+v)^5)$$

as $n \to \infty$. (The actual formula for the integral is

$$\begin{aligned}
&\int_0^{v} \int_0^{u} \log(1+s+t)\, ds\, dt \\
=\ & \frac{1}{2}(1+u+v)^2\log(1+u+v) - \frac{1}{2}(1+u)^2\log(1+u) - \frac{1}{2}(1+v)^2\log(1+v) - \frac{3}{2}uv.)
\end{aligned}$$

Now substituting $u = -(p+2)/n$ and $v = -q/n$ back into the two integrals in (2.5), we have that

$$\begin{aligned}
&\frac{n^2}{2} \int_0^{v} \int_0^{u} \log(1+s+t)\, ds\, dt \\
=\ & -\left[\frac{p^2q+pq^2}{4n} + xy + \frac{y^2}{2} + \frac{2xy^3+2x^3y+3x^2y^2}{24}\right] + O\left(\frac{1}{\sqrt{n}}\right)
\end{aligned} \tag{2.7}$$

and

$$\frac{n^2}{2} \int_0^{v} \int_0^{-2/n} \log(1+s+t)\, ds\, dt = -\frac{y^2}{2} + O\left(\frac{1}{\sqrt{n}}\right) \tag{2.8}$$

as n is sufficiently large. Combining (2.4),(2.5), (2.7) and (2.8), we obtain

$$K_n = \exp\left\{-\left(\frac{p^2q+pq^2}{4n}+\frac{xy}{4}+\frac{2x^3y+2xy^3+3x^2y^2}{24}\right)+O\left(n^{-1/2}\right)\right\} \tag{2.9}$$

as n is sufficiently large.

Now, suppose $p = 2k-1$. Let

$$C_n = \prod_{j=1}^{q} \frac{\Gamma((n-j-p+1)/2)}{\Gamma((n-j-p)/2)\sqrt{(n-j-p)/2}}.$$

By Lemma 2.1, the j-th term in the product, say, $C_{n,j}$, has the following property

$$1-\frac{1}{n-p-q} \le C_{n,j} \le 1+\frac{1}{n-p-q}$$

for all $j = 1, 2, \cdots, q$ as long as $p+q \le n-3$. Therefore,

$$\left(1-\frac{1}{n-p-q}\right)^q \le C_n \le \left(1+\frac{1}{n-p-q}\right)^q.$$

Since $(1+x_n)^{k_n} = 1+O(k_nx_n)$ as $x_n \to 0$, $k_n \to \infty$ and $k_nx_n \to 0$. It follows that $C_n = 1+O(n^{-1/2})$ provided $p = O(\sqrt{n})$ and $q = O(\sqrt{n})$. So

$$\begin{aligned} K_n &= \frac{1}{C_n}\left(\frac{2}{n}\right)^{pq}\prod_{j=1}^{q}\frac{\Gamma((n-j+1)/2)}{\Gamma((n-j-2k+1)/2)\sqrt{(n-j-2k+1)/2}} \\ &\sim \left\{\prod_{j=1}^{q}\prod_{i=1}^{k}\frac{n-2i-j+1}{n}\right\}\cdot\left\{\prod_{j=1}^{q}\frac{n-j-2k+1}{n}\right\}^{-1/2} := K_n'\cdot K_n'', \end{aligned}$$

where the fact $\Gamma(x+1) = x\Gamma(x)$ is used in the second step. Now

$$\begin{aligned} \log K_n'' = -\frac{1}{2}\sum_{j=1}^{q}\log\left(1-\frac{j+2k-1}{n}\right) &= \frac{1}{2n}\sum_{j=1}^{q}(j+2k-1)+O\left(\frac{1}{\sqrt{n}}\right) \\ &= \frac{y^2+2xy}{4}+O\left(\frac{1}{\sqrt{n}}\right) \end{aligned} \tag{2.10}$$

as $n \to \infty$. In notation, K_n' is identical to K_n in (2.4). Keeping in mind that the k in (2.4) is equal to $p/2$; but the k in the definition of K_n' is equal to $(p+1)/2$. Apply (2.9) to K_n' to obtain

$$\begin{aligned} -\log K_n' &= \frac{(p+1)^2q+(p+1)q^2}{4n}+\frac{xy}{4}+\frac{2x^3y+2xy^3+3x^2y^2}{24}+O\left(n^{-1/2}\right) \\ &= \frac{p^2q+pq^2}{4n}+\frac{3xy+y^2}{4}+\frac{2x^3y+2xy^3+3x^2y^2}{24}+O\left(n^{-1/2}\right). \end{aligned}$$

This together with (2.10) thus yields (2.3). ■

Lemma 2.7 *Suppose $x > 0$ and $y > 0$. For each $n \geq 1$, assume the setting in (2.1) with $p = p_n = [x\sqrt{n}]$ and $q = q_n = [y\sqrt{n}]$. Define*

$$L_n = \left\{\prod_{i=1}^{q}\left(1 - \frac{\lambda_i}{n}\right)\right\}^{(n-p-q-1)/2} \exp\left(\frac{1}{2}\sum_{i=1}^{q}\lambda_i\right) I(0 < \lambda_1, \lambda_2, \cdots, \lambda_q < n).$$

Then, $e^{-a_n}L_n$ converges weakly to the distribution of $e^{\sigma\xi}$ where ξ is a standard normal, and

$$a_n = \frac{p^2q + pq^2}{4n} + \frac{3xy + x^3y + xy^3}{12} \text{ and } \sigma = \frac{xy}{4}.$$

Proof. Set

$$f(x) = \begin{cases} \frac{x}{2} + \frac{n-p-q-1}{2}\log\left(1 - \frac{x}{n}\right), & \text{if } 0 \leq x < n; \\ -\infty, \text{ otherwise.} \end{cases} \tag{2.11}$$

Then, $L_n = \exp(\sum_{i=1}^{q} f(\lambda_i))$. For any $x \in (0, n)$, by Taylor's expansion, there exists $\xi = \xi_x \in (0, x)$ such that

$$\log\left(1 - \frac{x}{n}\right) = 1 - \frac{x}{n} - \frac{x^2}{2n^2} - \frac{x^3}{3n^3} - \frac{x^4}{4} \cdot \frac{1}{(\xi - n)^4}.$$

Then

$$f(x) = \frac{p+q+1}{2n}x - \frac{n-p-q-1}{4n^2}x^2 - \frac{n-p-q-1}{6n^3}x^3 + g_n(x)\frac{x^4}{n^3}, \; x \in (0, n), \tag{2.12}$$

where $g_n(x) = -n^3(n-p-q-1)/(8(\xi - n)^4)$. It is trivial to see that $\sup_{0 \leq x \leq \alpha n}|g_n(x)| \leq (1-\alpha)^{-4}$ for any $\alpha \in (0, 1)$. Recall that $\lambda_1, \lambda_2, \cdots, \lambda_q$ are eigenvalues of $X_n'X_n$, where the entries of the $p \times q$ matrix X_n are independent standard normals. Note that $p \sim x\sqrt{n}$ and $q \sim y\sqrt{n}$. By the Theorem from [17] or Theorem 3.1 from [31], there exists a constant $c(x, y) \in (0, \infty)$ such that

$$\frac{\max_{1 \leq i \leq q}\lambda_i}{\sqrt{n}} \to c(x, y) \tag{2.13}$$

in probability as $n \to \infty$. Define $\Omega_n := \{\max_{1 \leq i \leq q}\lambda_i \leq (c(x, y) + 1)\sqrt{n}\}$. Then

$$P(\Omega_n^c) \to 0 \tag{2.14}$$

as $n \to \infty$. Now on Ω_n, by (2.12),

$$\begin{aligned} \sum_{i=1}^{q} f(\lambda_i) &= \frac{p+q+1}{2n}tr\left(X'X\right) - \frac{n-p-q-1}{4n^2}tr\left((X'X)^2\right) \\ &- \frac{n-p-q-1}{6n^3}tr\left((X'X)^3\right) + \tilde{g}_n\frac{tr\left((X'X)^4\right)}{n^3}, \end{aligned} \tag{2.15}$$

where $|\tilde{g}_n| \in [0, 2)$ as n is sufficiently large. Note that $tr\left((X'X)^i\right)$ are well defined random variables which do not depend on Ω_n. Easily, $E\left(tr(X'X)\right) = pq$. By Lemma 2.3,

$$Etr\left((X'X)^3\right) \sim pq(p^2+q^2+3pq), \text{ and } Etr\left((X'X)^4\right) \le C(x,y)q^5$$

for some constant $C(x, y)$. It is easy to check that

$$\begin{aligned} & tr((X'X)^2) \\ = & \sum_{j=1}^{q}\sum_{i=1}^{p} x_{ij}^4 + \sum_{j=1}^{q}\sum_{i\neq l=1}^{p} x_{ij}^2 x_{lj}^2 + \sum_{i=1}^{p}\sum_{j\neq k=1}^{q} x_{ij}^2 x_{ik}^2 + \sum_{i\neq l,\, j\neq k} x_{ij}x_{ik}x_{lk}x_{lj}. \end{aligned}$$

Then $Etr\left((X'X)^2\right) = pq(p+q+1)$ (this is sharper than the one corresponding to the case $k = 2$ in (i) of Lemma 2.3). Now set $h_i = tr(X'X)^i - E\left(tr(X'X)^i\right)$ for $i = 1, 2, 3$. By simple algebra, we have from (2.15) that

$$\begin{aligned} \sum_{i=1}^{q} f(\lambda_i) &= \frac{p^2q+pq^2}{4n} + \frac{3xy+x^3y+xy^3}{12} + O\left(\frac{1}{\sqrt{n}}\right) \\ &+ \frac{p+q+1}{2n}h_1 - \frac{n-p-q-1}{4n^2}h_2 - \frac{n-p-q-1}{6n^3}h_3 + \tilde{g}_n\frac{h_4}{n^3} \end{aligned}$$

on Ω_n as $n \to \infty$. Recall that $L_n = \exp(\sum_{i=1}^{q} f(\lambda_i))$. By (ii) of Lemma 2.3, both h_3/n^2 and h_4/n^3 go to zero in probability. By (2.14), to prove the lemma, it suffices to show that

$$W_n := \frac{p+q+1}{2n}h_1 - \frac{n-p-q-1}{4n^2}h_2 \text{ converges to } N(0,\sigma^2) \text{ weakly} \tag{2.16}$$

where σ is as in the statement of the lemma. Since, $tr(X'X) = \sum_{i,j} x_{ij}^2$, which is a sum of independent and identically distributed random variables, $Var(h_1) = Var(tr(X'X)) = 2pq$. Therefore, by Lemma 2.4, $Var(h_2)/n^2$ converges to a positive constant. By Theorem 4.1 from Jonsson [21], $(h_1/\sqrt{Var(h_1)}, h_2/\sqrt{Var(h_2)})$ converges weakly to a normal distribution with mean zero. It follows that W_n converges weakly to a normal distribution with mean zero. We only need to calculate variance σ^2. Now,

$$\begin{aligned} Var(W_n) &= \frac{(p+q+1)^2}{4n^2}Var\left(tr(X'X)\right) + \frac{(n-p-q-1)^2}{16n^4}Var\left(tr\left((X'X)^2\right)\right) \\ &-\frac{(p+q+1)(n-p-q-1)}{4n^3}\cdot Cov\left(tr(X'X), tr\left((X'X)^2\right)\right). \end{aligned}$$

Since $Var(tr(X'X)) = 2pq$ as calculated earlier, by Lemma 2.4 again, the above yields

$$Var(W_n) \to \frac{x^2y^2}{16}$$

as $n \to \infty$. Therefore, $\sigma^2 = \lim_{n\to\infty} Var(W_n) = x^2y^2/16$. The proof is completed. ■

COROLLARY 2.1 *For $x > 0$ and $y > 0$, let $p_n = [xn^{1/2}]$ and $q_n = [yn^{1/2}]$. Let $f_n(z)$ be the joint probability density function of Z_n as in Theorem 1 and $g_n(z)$ be the joint probability density function of p_nq_n independent standard normals. Then as $n \to \infty$*

$$\frac{f_n(X_n)}{g_n(X_n)} \text{ converges weakly to } \exp\left(-\frac{x^2y^2}{8} + \frac{xy}{4}\xi\right)$$

where ξ and all the entries of X_n are independent standard normals.

Proof. Without loss of generality, we assume $y \le x$. Hence $q_n \le p_n$ for any $n \ge 1$. By Lemma 2.5, the density function of $\sqrt{n}Z_n$ is

$$f_n(z) := (\sqrt{2\pi})^{-pq}n^{-pq/2}\frac{\omega(n-p,q)}{\omega(n,q)}\left\{det\left(I_q - \frac{z'z}{n}\right)^{(n-p-q-1)/2}\right\} I_0(z'z/n).$$

Obviously, $g_n(z) := (\sqrt{2\pi})^{-pq}e^{-tr(z'z)/2}$. Let $\lambda_1, \lambda_2, \cdots, \lambda_q$ be the eigenvalues of $X_n'X_n$. Then

$$\frac{f_n(X_n)}{g_n(X_n)} = K_n \cdot L_n$$

where

$$K_n = \left(\frac{2}{n}\right)^{pq/2}\prod_{j=1}^{q}\frac{\Gamma((n-j+1)/2)}{\Gamma((n-p-j+1)/2)}, \tag{2.17}$$

$$L_n = \left\{\prod_{i=1}^{q}\left(1-\frac{\lambda_i}{n}\right)\right\}^{(n-p-q-1)/2} \exp\left(\frac{1}{2}\sum_{i=1}^{q}\lambda_i\right) \tag{2.18}$$

if all λ_i's are in $(0, n)$, and L_n is zero otherwise. The desired conclusion immediately follows from Lemmas 2.6 and 2.7 on K_n and L_n, respectively, ■

Proof of Theorem 2. First, we show that the lower bound is strictly between zero and one. Recall $\phi(x,y) = E\left|\exp\left(-(x^2y^2/8) + (xy\xi/4)\right) - 1\right|$. Then $\phi(x,y) > 0$ because ξ is an non-degenerate random variable. Second, by Hölder's inequality,

$$\phi(x,y) \le \left\{E\left[\exp\left(-\frac{x^2y^2}{8} + \frac{xy}{4}\xi\right) - 1\right]^2\right\}^{1/2}.$$

By expanding the square and using the fact that $E\exp(t\xi) = \exp(t^2/2)$ for any $t \in \mathbb{R}$, we have that

$$\phi(x,y)^2 \le e^{-x^2y^2/8} - 2e^{-3x^2y^2/32} + 1.$$

Let $\varphi(t) = e^{-t/8} - 2e^{-3t/32} + 1$ for $t \in \mathbb{R}$. Then $\varphi(0) = 0$, $\varphi(+\infty) = 1$ and $\varphi'(t) = (3/16)e^{-t/8}(e^{t/32} - (2/3)) > 0$ for any $t > 0$. Thus $\phi(x, y) < 1$ for any $x > 0$ and $y > 0$.

Now we prove the remaining part of Theorem 2.

Let's continue to use the notation in Corollary 2.1. First,

$$d(\mathcal{L}(\sqrt{n}Z), G_n) = \int_{R^{pq}} \left| \frac{f_n(z)}{g_n(z)} - 1 \right| g_n(z)\, dz = E\left| \frac{f_n(X_n)}{g_n(X_n)} - 1 \right|, \tag{2.19}$$

where X_n has the density function $g_n(z)$, i.e., the pq entries of X_n are independent standard normals. Second, by Corollary 2.1,

$$\frac{f_n(X_n)}{g_n(X_n)} \text{ converges weakly to } \exp\left(-\frac{x^2y^2}{8} + \frac{xy}{4}\xi\right)$$

where ξ is a standard normal. Then, applying Fatou's lemma to (2.19),

$$\liminf_{n\to\infty} d(\mathcal{L}(\sqrt{n}Z), G_n) \geq E\left|\exp\left(-\frac{x^2y^2}{8} + \frac{xy}{4}\xi\right) - 1\right|.$$

The proof is completed. ■

Proof of Theorem 1. Let $p_n' = q_n' = p_n + q_n + [n^{1/4}]$. For an n by n random orthogonal matrix U which has the normalized Haar measure, let $Z_{p,q}$ denote the upper left p by q block of U, $1 \leq p,\ q \leq n$. Thus, Z_{p_n,q_n} is a sub-block of $Z_{p_n',q_n'}$. As a consequence, the joint density function of entries of Z_{p_n,q_n} is a marginal density function of that of $Z_{p_n',q_n'}$. Therefore, by formula (1.2)

$$\|\mathcal{L}(\sqrt{n}Z_{p_n,q_n}) - G_{p_nq_n}\| \leq \|\mathcal{L}(\sqrt{n}Z_{p_n',q_n'}) - G_{p_n'q_n'}\|, \tag{2.20}$$

where G_{pq} is the joint distribution of pq standard normal distributions (one can verify this by choosing $B = A \times \mathbb{R}^{p_n'q_n' - p_nq_n}$ for any Borel set $A \in \mathbb{R}^{p_nq_n}$ and then plugging them into definition (1.2)).

So, to prove the theorem, without loss of generality, we assume $p_n = q_n$ for all $n \geq 1$, $p_n \to \infty$ and $p_n = o(\sqrt{n})$.

As in the proof of Theorem 2,

$$\|\mathcal{L}(\sqrt{n}Z_{p_n,q_n}) - G_{p_nq_n}\| = E\left|K_n \cdot L_n - 1\right|,$$

where K_n and L_n are as in (2.17) and (2.18). By following the proof of Lemma 2.6 step by step, we obtain that

$$K_n = \exp\left\{-\frac{p^2q + pq^2}{4n} + o(1)\right\} \tag{2.21}$$

as $n \to \infty$. We claim that

$$e^{-(p^2q+pq^2)/4n} L_n \to 1 \tag{2.22}$$

in probability as $n \to \infty$. If this is true, then $K_n \cdot L_n \to 1$ in probability as $n \to \infty$. Note that $K_n \cdot L_n \geq 0$ and it is easy to see that $E(K_n \cdot L_n) = \int_{\mathbb{R}^{pq}} f_n(x)\, dx = 1$. These three facts imply that $\{K_n \cdot L_n\}$ is uniformly integrable, that is, $\limsup_{t\to+\infty} \limsup_{n\to\infty} E(K_n L_n I_{\{K_n L_n \geq t\}}) = 0$. It follows that $E|K_n L_n - 1| \to 0$ as $n \to \infty$. The proof is then complete.

Now we prove claim (2.22). Let's go back to the proof of Lemma 2.7. Since $p_n = q_n = o(\sqrt{n})$, the term $c(x, y)$ in (2.13) is equal to zero. So, correspondingly, $\Omega_n = \{\max_{1\leq i\leq q} \lambda_i \leq \sqrt{n}\}$ and $P(\Omega_n^c) \to 0$ as $n \to \infty$. Recall the definition of $f(x)$ in (2.11) and $L_n = \exp(\sum_{i=1}^{q} f(\lambda_i))$. On Ω_n, similar to (2.15),

$$\begin{aligned}\sum_{i=1}^{q} f(\lambda_i) &= \frac{p+q+1}{2n} tr\left(X'X\right) - \frac{n-p-q-1}{4n^2} tr\left((X'X)^2\right) + \tilde{g}_n \frac{tr\left((X'X)^3\right)}{n^2} \\ &= \frac{p^2q+pq^2}{4n} + \frac{p+q+1}{2n} \cdot h_1 - \frac{n-p-q-1}{4n^2} \cdot h_2 + \tilde{g}_n \frac{tr\left((X'X)^3\right)}{n^2}, \end{aligned} \tag{2.23}$$

where $\tilde{g}_n$ is a random variable satisfying $|\tilde{g}_n| \in [0, 2)$ as n is sufficiently large, and $h_i = tr(X'X)^i - E(tr(X'X)^i)$. Obviously, h_i is well-defined on the same probability space as those of x_{ij}'s which does not depend on Ω_n. Note that $p = q = o(\sqrt{n})$. Then

$$\frac{p}{n} h_1 = \frac{p^2}{n} \cdot \frac{\sum_{i=1}^{p} \sum_{i=1}^{q} (x_{ij}^2 - 1)}{p} \to 0 \tag{2.24}$$

in probability as $n \to \infty$ by the classical Central Limit Theorem of independent and identically distributed random variables. We will show next that the third term on the right hand side of (2.23) also goes to zero in probability. Indeed,

$$P\left(\frac{|h_2|}{n} \geq \epsilon\right) \leq \frac{Var\left(tr((X'X)^2)\right)}{n^2\epsilon^2} = O\left(\frac{(pq)^2 + 8pq(p+q)^2}{n^2}\right) \to 0$$

by (i) of Lemma 2.4. This says that

$$\frac{n-p-q-1}{4n^2} \cdot h_2 \to 0 \tag{2.25}$$

in probability as $n \to \infty$. Lastly,

$$\frac{tr\left((X'X)^3\right)}{n^2} = \frac{p^4}{n^2} \cdot \frac{tr\left((X'X)^3\right) - E\left(tr\left((X'X)^3\right)\right)}{p^4} + \frac{E\left(tr\left((X'X)^3\right)\right)}{n^2}.$$

By (ii) of Lemma 2.3, the first term on the right hand side goes to zero in probability. By (i) of Lemma 2.3, $Etr\left((X'X)^3\right) \sim pq(p^2 + q^2 + 3pq)$ as $n \to \infty$. So the second term on the right hand side goes to zero. Consequently

$$\frac{tr\left((X'X)^3\right)}{n^2} \to 0 \tag{2.26}$$

in probability. Combining (2.23)-(2.26), we obtain

$$\sum_{i=1}^{q} f(\lambda_i) - \frac{p^2q + pq^2}{4n} \to 0$$

in probability, which together with the fact that $P(\Omega_n^c) \to 0$, implies (2.22). ■

3 The Proof of Theorem 3

The main tool of proving Theorem 3 is the Gram-Schmidt algorithm. Let's briefly review it first.

Suppose $\{\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_n\}$ is a sequence of $n \times 1$ vectors. Set $\mathbf{w}_1 = \mathbf{y}_1$ and

$$\mathbf{w}_j = \mathbf{y}_j - \sum_{i=1}^{j-1} \frac{\mathbf{y}_j^T \mathbf{w}_i}{\|\mathbf{w}_i\|^2} \mathbf{w}_i, \qquad j = 2, 3, \cdots, n, \tag{3.1}$$

where $\|\mathbf{w}_j\|^2 = \mathbf{w}_j^T \mathbf{w}_j$ $(j = 1, 2, \cdots, n)$. Then, $\{\mathbf{w}_j, 1 \le j \le n\}$ are orthogonal, that is, $\mathbf{w}_i^T \mathbf{w}_j = 0$ for any $1 \le i < j \le n$. Let $\boldsymbol{\gamma}_j = (1/\|\mathbf{w}_j\|)\mathbf{w}_j$, $j = 1, 2, \cdots, n$. Then the matrix $\mathbf{\Gamma}_n = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_n)$ is orthonormal. So (3.1) can be rewritten as follows:

$$\mathbf{w}_j = \mathbf{y}_j - \sum_{i=1}^{j-1} (\mathbf{y}_j^T \boldsymbol{\gamma}_i)\boldsymbol{\gamma}_i, \qquad j = 2, 3, \cdots, n. \tag{3.2}$$

The reader is referred to Section A.5 on page 603 from [1] and p.15 from [18] for further details.

Define

$$\mathbf{\Delta}_1 = \mathbf{0},\ \mathbf{\Delta}_j = \sum_{i=1}^{j-1} (\mathbf{y}_j^T \boldsymbol{\gamma}_i)\boldsymbol{\gamma}_i \text{ and } L_j = \left| \sqrt{\frac{n}{\|\mathbf{w}_j\|^2}} - 1 \right|,\ j = 1, 2, \cdots, n. \tag{3.3}$$

Note $\mathbf{y}_j^T \boldsymbol{\gamma}_i \in \mathbb{R}^1$, rewrite $(\mathbf{y}_j^T \boldsymbol{\gamma}_i)\boldsymbol{\gamma}_i = (\boldsymbol{\gamma}_i \boldsymbol{\gamma}_i^T)\mathbf{y}_j$. It is easy to check that

$$\mathbf{w}_j = (\mathbf{I}_n - \mathbf{\Gamma}_{n,j}\mathbf{\Gamma}_{n,j}^T)\mathbf{y}_j,\ \mathbf{\Delta}_j = \mathbf{\Gamma}_{n,j}\mathbf{\Gamma}_{n,j}^T \mathbf{y}_j \text{ and } \boldsymbol{\gamma}_j = \frac{\mathbf{y}_j}{\sqrt{n}} - \frac{\mathbf{\Delta}_j}{\sqrt{n}} + \mathbf{u}_j \tag{3.4}$$

where $\mathbf{\Gamma}_{n,j} = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_{j-1})$ and $\mathbf{u}_j = (1 - n^{-1/2}\|\mathbf{w}_j\|)\boldsymbol{\gamma}_j$.

One repeatedly used fact in later proofs is that if the n^2 elements of $\mathbf{Y} = (\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_n)$ are i.i.d. standard normals, then $\mathbf{\Gamma}_n = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_n)$ follows the normalized Haar measure on the orthogonal group $O(n)$. In particular, $\boldsymbol{\gamma}_i$'s are identically distributed and

$$\mathcal{L}(\boldsymbol{\gamma}_i) = \mathcal{L}\left(\frac{\mathbf{y}_1}{\|\mathbf{y}_1\|}\right) \tag{3.5}$$

for any $i = 1, 2, \cdots, n$.

For any $n \times n$ orthogonal matrix $\boldsymbol{G}$, observe that $\mathcal{L}(\boldsymbol{G}\boldsymbol{\Gamma}_n^{-1}) = \mathcal{L}((\boldsymbol{\Gamma}_n \boldsymbol{G}^T)^{-1}) = \mathcal{L}(\boldsymbol{\Gamma}_n^{-1})$ by the invariance property of Haar measures. Also, $\boldsymbol{\Gamma}_n^{-1} = \boldsymbol{\Gamma}_n^T$. From the uniqueness of Haar measures, we obtain another useful fact that

$$\mathcal{L}(\boldsymbol{\Gamma}_n) = \mathcal{L}(\boldsymbol{\Gamma}_n^T). \tag{3.6}$$

We will use the following notation. Let $A = (a_{ij})$ be an p by q matrix. Then

$$|||A||| := \max_{1 \le i \le p, 1 \le j \le q} |a_{ij}|. \tag{3.7}$$

The following definition will also be used.

$$\epsilon_n(m) = \max_{1 \le i \le n, 1 \le j \le m} |\sqrt{n}\gamma_{ij} - y_{ij}| \ \text{ and } \ n_\alpha = \left[\frac{n}{\log n - (5/4)\log(\log n)}\alpha\right] \tag{3.8}$$

for $\alpha > 0$ and $n \ge 2$.

The following says that, to prove part (iii) of Theorem 3, we only needs to work on $\max_{2 \le j \le m} |||\boldsymbol{\Delta}_j|||$.

Lemma 3.1 *Let $\epsilon_n(m)$ and n_α be as in (3.8). Then*

$$P\left(\left|\epsilon_n(n_\alpha) - \max_{2 \le j \le n_\alpha} |||\boldsymbol{\Delta}_j|||\right| \ge \delta\right) \to 0$$

as $n \to \infty$ for any $\alpha > 0$ and $\delta > 0$.

The following lemma is the key in the proof of Theorem 3. A recursive inequality is derived. It implies that all $\boldsymbol{\Delta}_j$'s are almost independent when $j \le n_\alpha$.

Lemma 3.2 *Let ξ be a standard normal. Given $\alpha > 0$ and $t > 0$, define*

$$f_n^+(k) = P\left(|\xi| > t\left(\sqrt{\frac{n}{k}} + \frac{(\log n)^8}{\sqrt{n}}\right)\right), \ k = 1, 2, \cdots, n,$$

and $f_n^-(k)$ as the probability above when "$+$" on the right hand side is replaced by "$-$". Then there exists a constant $C = C_{\alpha,t} > 0$ such that $P(\max_{2 \le j \le k+1} |||\boldsymbol{\Delta}_j||| \le t)$ is bounded below and above, respectively, by

$$(1 - nf_n^-(k))P(\max_{2 \le j \le k} |||\boldsymbol{\Delta}_j||| \le t) - \frac{(\log n)^C}{n^{(t^2/\alpha)-2}} \ \textit{and}$$
$$(1 - nf_n^+(k))P(\max_{2 \le j \le k} |||\boldsymbol{\Delta}_j||| \le t) + \frac{(\log n)^C}{n^{(t^2/\alpha)-2}}$$

uniformly on $n/(\log n)^3 \le k \le n_\alpha$ as n is sufficiently large, where n_α is as in (3.8).

Proof of Theorem 3. Part (i) is obvious. As for (ii), take $r = 1/\log n$, $s = (\log n)^{3/4}$, $t = t$, $m = m_n' = [\delta n/\log n]$ for some $\delta < \min\{1/4, t^2/100\}$ in Lemma A.4. Trivially, $t^2/(3(m+\sqrt{n})) \geq t^2(\log n)/(6n\delta)$ and $1/s \leq 1$ as n is sufficiently large. We obtain that

$$P(\epsilon_n(m_n') \geq 3t) \leq 4ne^{-n/(4\log n)^2} + 3n^2 e^{-(\log n)^{3/2}/2} + \frac{3n^2}{t}\left(1 + \frac{t^2}{6\delta}\frac{\log n}{n}\right)^{-n/2} \to 0$$

as $n \to \infty$ by the choice of δ.

Now we prove (iii). To simplify notation, set $m = n_\alpha$. We actually will show that

$$P\left(\max_{2\leq j\leq m} \|\boldsymbol{\Delta}_j\| \leq t\right) \to \begin{cases} 1, & \text{if } t > 2\sqrt{\alpha}; \\ e^{-Kt^2}, & \text{if } t = 2\sqrt{\alpha}; \\ 0, & \text{if } t \in (\sqrt{3\alpha}, 2\sqrt{\alpha}), \end{cases} \tag{3.9}$$

where $K = (8\sqrt{2\pi})^{-1}$. Since $P\left(\max_{2\leq j\leq m} \|\boldsymbol{\Delta}_j\| \leq t\right)$ is increasing in t, the above implies that the left hand side above goes to zero for any $t \in (0, 2\sqrt{\alpha})$. This together with (3.9) implies that $\max_{2\leq j\leq m} \|\boldsymbol{\Delta}_j\|$ converges to $2\sqrt{\alpha}$ in probability. Lemma 3.1 says that $\epsilon_n(n_\alpha) - \max_{2\leq j\leq n_\alpha} \|\boldsymbol{\Delta}_j\|$ converges to zero in probability as $n \to \infty$. It follows that

$$\epsilon_n(n_\alpha) \to 2\sqrt{\alpha} \tag{3.10}$$

in probability as $n \to \infty$. We next show that this implies that $\epsilon_n([n\alpha/\log n]) \to 2\sqrt{\alpha}$ as $n \to \infty$. Indeed, set $k_\alpha = [n\alpha/\log n]$. For any $\delta \in (0, \sqrt{\alpha})$, choose α_1 such that

$$\left(\sqrt{\alpha} - \frac{\delta}{4}\right)^2 < \alpha_1 < \alpha.$$

Then $n_{\alpha_1} < k_\alpha \leq n_\alpha$ as n is sufficiently large. It follows from the definition of $\epsilon_n(m)$ that $\epsilon_n(n_{\alpha_1}) \leq \epsilon_n(k_\alpha) \leq \epsilon_n(n_\alpha)$ as n is sufficiently large. Therefore

$$\begin{aligned} P(|\epsilon_n(k_\alpha) - 2\sqrt{\alpha}| > \delta) &\leq P(\epsilon_n(k_\alpha) > 2\sqrt{\alpha} + \delta) + P(\epsilon_n(k_\alpha) < 2\sqrt{\alpha} - \delta) \\ &\leq P\left(\epsilon_n(n_\alpha) > 2\sqrt{\alpha} + \delta\right) + P\left(\epsilon_n(n_{\alpha_1}) < 2\sqrt{\alpha_1} - \frac{\delta}{2}\right) \end{aligned}$$

as n is sufficiently large. The above two terms go to zero as $n \to \infty$ by (3.10). Then (iii) follows.

Now we show (3.9).

We continue to use the notation in Lemma 3.2. Set

$$\begin{aligned} &A_k = P(\max_{2\leq j\leq k} \|\boldsymbol{\Delta}_j\| \leq t),\ b_k^+ = 1 - nf_n^+(k),\ b_k^- = 1 - nf_n^-(k), \\ &c_n = \frac{(\log n)^C}{n^{(t^2/\alpha)-2}} \ \text{ and } m' = \left[\frac{n}{(\log n)^3}\right] + 2. \end{aligned}$$

By Lemma A.1, $P(|\xi| \geq x) \sim (2/(\sqrt{2\pi}\, x)) \exp(-x^2/2)$ as $x \to +\infty$ for a standard normal ξ. Here and later, the notation "$f(x) \sim g(x)$ as $x \to +\infty$" means that $\lim_{x\to+\infty} f(x)/g(x) = 1$. The same interpretation applies to $\alpha_n \sim \beta_n$ as $n \to \infty$. It is easy to check that

$$\text{both } f_n^+(k) \text{ and } f_n^-(k) \sim \frac{2}{t\sqrt{2\pi}} \left(\frac{k}{n}\right)^{1/2} e^{-(t^2/2)(n/k)} \tag{3.11}$$

uniformly on $m' \leq k \leq m$ as $n \to \infty$, and also that

$$1 > \max\{b_i^+, b_i^-;\ m' \leq i \leq m\} \to 1 \tag{3.12}$$

as $n \to \infty$ provided $t > \sqrt{2\alpha}$. By Lemma 3.2,

$$b_k^- A_{k-1} - c_n \leq A_k \leq b_k^+ A_{k-1} + c_n$$

for all $m' \leq k \leq m$ as n is sufficiently large. By iteration, we obtain

$$A_m \geq \left(\prod_{j=m'}^{m} b_j^-\right) A_{m'-1} - c_n \sum_{j=0}^{m-m'+2} \left[\max_{m'\leq i\leq m} \{b_i^-\}\right]^j. \tag{3.13}$$

By (3.12) the second term on the right hand side is no larger than $nc_n \leq (\log n)^C / n^{(t^2/\alpha)-3}$ as n is sufficiently large. Further, applying the same argument in (3.13) to the "+" case, we obtain

$$\left(\prod_{j=m'}^{m} b_j^-\right) A_{m'-1} - \frac{(\log n)^C}{n^{(t^2/\alpha)-3}} \leq A_m \leq \left(\prod_{j=m'}^{m} b_j^+\right) A_{m'-1} + \frac{(\log n)^C}{n^{(t^2/\alpha)-3}} \tag{3.14}$$

as n is sufficiently large. By definition, $A_k = P\left(\max_{2\leq j\leq k} \|\mathbf{\Delta}_j\| \leq t\right)$. From the proved (ii) we know that $A_{m'-1} \to 1$ as $n \to \infty$ for any $t > 0$. Evidently, $(\log n)^C n^{3-(t^2/\alpha)} \to 0$ provided $t > \sqrt{3\alpha}$. So to prove (3.9) we only need to show that

$$\text{both } \prod_{j=m'}^{m} b_j^- \text{ and } \prod_{j=m'}^{m} b_j^+ \to \begin{cases} 1, & \text{if } t > 2\sqrt{\alpha}; \\ e^{-Kt^2}, & \text{if } t = 2\sqrt{\alpha}; \\ 0, & \text{if } t \in (\sqrt{3\alpha}, 2\sqrt{\alpha}) \end{cases} \tag{3.15}$$

as $n \to \infty$. Recall $b_j^+ = 1 - nf_n^+(k)$ and $b_j^- = 1 - nf_n^-(k)$. Since $|\log(1+x) - x| \leq x^2$ for x small enough. By (3.11) and (3.12),

$$\prod_{j=m'}^{m} b_j^+ \leq \exp\left(-n \sum_{k=m'}^{m} f_n^+(k)\right) \cdot \exp\left(+n^2 \sum_{k=m'}^{m} f_n^+(k)^2\right)$$
$$\prod_{j=m'}^{m} b_j^- \geq \exp\left(-n \sum_{k=m'}^{m} f_n^-(k)\right) \cdot \exp\left(-n^2 \sum_{k=m'}^{m} f_n^-(k)^2\right)$$

as n is sufficiently large. Also, the fact $f_n^+(k) \le f_n^-(k)$ implies that $b_j^+ \ge b_j^-$. So (3.15) is reduced to show that

$$n^2 \sum_{k=m'}^{m} f_n^+(k)^2 \to 0, \quad \text{and} \quad n \sum_{k=m'}^{m} f_n^+(k) \to \begin{cases} 0, & \text{if } t > 2\sqrt{\alpha}; \\ Kt^2, & \text{if } t = 2\sqrt{\alpha}; \\ +\infty, & \text{if } t \in (\sqrt{3\alpha}, 2\sqrt{\alpha}), \end{cases} \tag{3.16}$$

and that the above is also true if $f_n^+(k)$ is replaced by $f_n^-(k)$.

By (3.11) again, $n^2 \sum_{k=m'}^{m} f_n^+(k)^2 \le (\log n)^C n^{3-(t^2/\alpha)} \to 0$ as $n \to \infty$ provided $t > \sqrt{3\alpha}$. Similarly, $n^2 \sum_{k=m'}^{m} f_n^-(k)^2 \to 0$ for $t > \sqrt{3\alpha}$. Let

$$g(x) = \frac{2}{t\sqrt{2\pi}} x^{1/2} e^{-t^2/(2x)}$$

for $x > 0$. By the uniform convergence of $f_n^+(k)/g(k/n)$ and $f_n^-(k)/g(k/n)$ as $n \to \infty$ over $k \in [m', m]$ as in (3.11), to prove the second part in (3.16), it is enough to show

$$n \sum_{k=m'}^{m} g\left(\frac{k}{n}\right) \quad \text{goes to the second limit in (3.16)} \tag{3.17}$$

as $n \to \infty$. Note that $g(x)$ is non-negative and increasing in x over $[0, +\infty)$, it is elementary to see that

$$\left| \frac{1}{n} \sum_{k=m'}^{m} g\left(\frac{k}{n}\right) - \int_0^{m/n} g(x)\, dx \right| \le \int_{m/n}^{(m+1)/n} g(x)\, dx + \int_0^{m'/n} g(x)\, dx.$$

Use $\sqrt{x} e^{-t^2/(2x)} \le e^{-t^2/(2x)}$ on $x \in [0,1]$, the first integral on the right hand side is bounded by $(1/n)\exp(-nt^2/(2m+2)) \le n^{-1-(t^2/(2\alpha))}(\log n)^C$ as n is sufficiently large; the second one is bounded by $\exp(-(\log n)^2)$ as n is large because $m' \sim n(\log n)^{-3}$ by definition. Hence

$$\frac{1}{n} \sum_{k=m'}^{m} g\left(\frac{k}{n}\right) - \int_0^{m/n} g(x)\, dx = o\left(\frac{1}{n^2}\right) \tag{3.18}$$

as $n \to \infty$ if $t > \sqrt{2\alpha}$. Now we evaluate the integral.

Write $\sqrt{x}\exp(-t^2/(2x))\, dx = (2t^{-2}x^{5/2})d(e^{-t^2/(2x)})$. By integration by parts,

$$I_n := \int_0^{m/n} \sqrt{x} e^{-t^2/(2x)}\, dx = \frac{2}{t^2}\left(\frac{m}{n}\right)^{5/2} e^{-nt^2/(2m)} - \frac{5}{t^2} \int_0^{m/n} \sqrt{x^3} e^{-t^2/(2x)}\, dx.$$

Note that $\sqrt{x^3} \le (m/n)\sqrt{x}$ on $[0, m/n]$. The last integral is less than or equal to $(m/n)I_n$. But $m/n \to 0$, thus

$$I_n \sim \frac{2}{t^2}\left(\frac{m}{n}\right)^{5/2} e^{-nt^2/(2m)}.$$

By the definition of m, $nt^2/(2m) = (t^2/(2\alpha))(\log n - (5/4)\log_2 n) + O(n^{-1}(\log n)^2)$ as $n \to \infty$. It follows that

$$I_n \sim \frac{2\alpha^{5/2}}{t^2} \cdot \frac{1}{n^{t^2/(2\alpha)}} (\log n)^{5t^2/(8\alpha)-(5/2)}. \tag{3.19}$$

From (3.18)

$$n \sum_{k=m'}^{m} g\left(\frac{k}{n}\right) \sim n^2 \int_0^{m/n} g(x)\,dx = \frac{2n^2}{\sqrt{2\pi}t} \cdot I_n \sim \frac{4\alpha^{5/2}}{\sqrt{2\pi}t^3} \cdot \frac{1}{n^{t^2/(2\alpha)-2}} \cdot (\log n)^{5t^2/(8\alpha)-(5/2)}$$

provided $t > \sqrt{3\alpha}$. Recall $K = (8\sqrt{2\pi})^{-1}$. The above implies (3.17). ■

4 Technical Lemmas

Now we prove the lemmas used in the previous sections. To see them clearly, we break them into two subsections.

4.1 The Proofs of Lemmas Used in Section 2

Proof of Lemma 2.1. (i) First, when $n = 1$, $\Gamma(n + (1/2))/(\sqrt{n}\Gamma(n)) = \sqrt{\pi}/2 \in (5/6, 1)$. So (i) is true for $n = 1$. Now assume $n \geq 2$.

Using the fact that $\Gamma(x + 1) = x\Gamma(x)$ for any $x > 0$ and $\Gamma(1/2) = \sqrt{\pi}$, we have that

$$\frac{\Gamma(n + (1/2))}{\Gamma(n)} = \frac{\sqrt{\pi}n}{2^{2n}} \cdot \frac{(2n)!}{(n!)^2}.$$

By Stirling's formula (see, e.g., Lemma 1 on p.45 from [6]), $n! = \sqrt{2\pi n}n^n e^{-n+\frac{\theta_n}{12n}}$ for all $n \geq 2$, where

$$\frac{n}{n + \frac{1}{12}} < \theta_n < 1. \tag{4.1}$$

It is easily checked that

$$\frac{\Gamma(n + (1/2))}{\sqrt{n}\,\Gamma(n)} = \exp\left(\frac{\theta_n - 4\theta_n'}{24n}\right) \tag{4.2}$$

for some θ_n corresponding to $2n$ and θ_n' corresponding to n in (4.1). Evidently, $(\theta_n - 4\theta_n')/24 \in (-1/6, 0)$ for all $n \geq 2$. Then the desired result follows by using the inequality $e^x > 1 + x$ for all $x \neq 0$.

(ii) A direct verification shows that (ii) is true for $n = 1$. Now assume $n \geq 2$. If $n = 2k$ for some integer $k \geq 1$, then (ii) follows from (i). Now suppose $n = 2k + 1$ for $k \geq 1$. Trivially,

$$\frac{\Gamma((n + 1)/2)}{\sqrt{n/2}\,\Gamma(n/2)} = \left(\frac{\Gamma(k + (1/2))}{\sqrt{k}\,\Gamma(k)}\right)^{-1} \cdot \sqrt{\frac{2k}{2k + 1}}\,.$$

By (i), the above ratio is between $\sqrt{2k/(2k+1)}$ and $(1-(6k)^{-1})^{-1}$. By a simple calculation, $\sqrt{2k/(2k+1)} \geq 1-(3/5n)$ and $(1-(6k)^{-1})^{-1} \leq 1+(5k)^{-1}$ for all $k \geq 1$. So (ii) follows. $\blacksquare$

Proof of Lemma 2.2. By the multivariate Taylor's expansion formula (see p. 361 from [2] and p. 172 from [22]),

$$f(x,y) = f\left(\frac{i}{n}, \frac{j}{n}\right) + f'_x\left(\frac{i}{n}, \frac{j}{n}\right)\left(x - \frac{i}{n}\right) + f'_y\left(\frac{i}{n}, \frac{j}{n}\right)\left(y - \frac{j}{n}\right) + \delta_{ij}(\xi, \eta),$$

for some $\xi \in [i/n, x]$ and $\eta \in [j/n, y]$, where

$$\delta_{ij}(x,y) = \frac{1}{2}\left((x-\frac{i}{n})^2\frac{\partial^2 f}{\partial x^2} + 2(x-\frac{i}{n})(y-\frac{j}{n})\frac{\partial^2 f}{\partial x \partial y} + (y-\frac{j}{n})^2\frac{\partial^2 f}{\partial y^2}\right). \tag{4.3}$$

By the given condition,

$$|\delta_{ij}(x,y)| \leq \frac{M}{2}\left((x-\frac{i}{n}) + (y-\frac{j}{n})\right)^2 \leq M\left((x-\frac{i}{n})^2 + (y-\frac{j}{n})^2\right).$$

Then

$$\int_{j/n}^{(j+1)/n}\int_{i/n}^{(i+1)/n} f(x,y)\,dx\,dy = \frac{1}{n^2}f\left(\frac{i}{n}, \frac{j}{n}\right) + \frac{1}{2n^3}f'_x\left(\frac{i}{n}, \frac{j}{n}\right) + \frac{1}{2n^3}f'_y\left(\frac{i}{n}, \frac{j}{n}\right) + \delta'_{ij},$$

where

$$|\delta'_{ij}| = |\int_{j/n}^{(j+1)/n}\int_{i/n}^{(i+1)/n} \delta_{ij}(\xi,\eta)\,dx\,dy| \leq M\int_0^{1/n}\int_0^{1/n}(x^2+y^2)\,dx\,dy = \frac{2M}{3n^4}$$

since $|\delta_{ij}(\xi,\eta)| \leq M((x-i/n)^2 + (y-j/n)^2)$ by (4.3). The desired result follows by taking the sum over i from i_1 to i_2, and j from j_1 to j_2. $\blacksquare$

Proof of Lemma 2.4. (i) It is not difficult to check that

$$\begin{aligned}
& tr(X'X) = \sum_{j=1}^{q}\sum_{i=1}^{p} x_{ij}^2; \\
& tr((X'X)^2) \\
= \quad & \sum_{j=1}^{q}\sum_{i=1}^{p} x_{ij}^4 + \sum_{j=1}^{q}\sum_{i\neq l=1}^{p} x_{ij}^2 x_{lj}^2 + \sum_{i=1}^{p}\sum_{j\neq k=1}^{q} x_{ij}^2 x_{ik}^2 + \sum_{i\neq l,\, j\neq k} x_{ij}x_{ik}x_{lk}x_{lj}.
\end{aligned} \tag{4.4}$$

Let

$$B_1 = \sum_{j=1}^{q}\sum_{i=1}^{p}(x_{ij}^4 - 3), \quad B_2 = \sum_{j=1}^{q}\sum_{i\neq l=1}^{p}(x_{ij}^2-1)(x_{lj}^2-1),$$

$$B_3 = \sum_{i=1}^{p}\sum_{j\neq k=1}^{q}(x_{ij}^2-1)(x_{ik}^2-1), \quad B_4 = \sum_{i\neq l,\, j\neq k} x_{ij}x_{ik}x_{lk}x_{lj}.$$

By a simple algebra,

$$tr((X'X)^2) = \left(\sum_{i=1}^{4} B_i\right) + 2(p+q-2)tr(X'X) + C_{p,q}, \tag{4.5}$$

where $C_{p,q}$ is a constant on p and q. It is easy to check that $EB_i = 0$ for $1 \le i \le 4$, $Cov(B_i, B_j) = 0$ for all $1 \le i \ne j \le 4$, and $Cov(B_i, tr(X'X)) = 0$ for $i = 2, 3, 4$. Also, each B_i is a sum of uncorrelated random variables. Therefore,

$$Var\left(tr((X'X)^2)\right) = \left(\sum_{i=1}^{4} Var(B_i)\right) + 4(p+q-2)^2 Var(tr(X'X)) + 2Cov(B_1, tr(X'X)).$$

Now it is easy to verify that $Cov(B_1, tr(X'X)) = O(p^2)$ and $Var(B_i) = O(p^3)$ for $i = 1, 2, 3$ as $p \to \infty$. Moreover, $Var(B_4) = pq(p-1)(q-1)$ and $Var(tr(X'X)) = 2pq$. Combining these quantities together, we obtain (i).

(ii) By (4.5) again,

$$\begin{aligned} Cov(tr(X'X), tr((X'X)^2)) &= Cov(tr(X'X), B_1) + 2(p+q-2) \cdot Var(tr(X'X)) \\ &\sim 4pq(p+q) \end{aligned}$$

as $n \to \infty$. ■

4.2 The Proofs of Lemmas Used in Section 3

Before the proof of these lemmas, we need some preliminary results for a preparation.

Lemma 4.1 *Let E_i, $i = 0, 1, 2, \cdots, n$ be events in a probability space $(\Omega, \mathcal{F}, P)$. Then*

$$\left| P\left(\cap_{i=0}^{n} E_i\right) - P(E_0) + \sum_{i=1}^{n} P\left(E_0 \backslash E_i\right) \right| \le \sum_{1 \le i < j \le n} P\left(E_i^c E_j^c\right).$$

Proof. First, $P(E_0) - P\left(\cap_{i=0}^{n} E_i\right) = P\left(\cup_{i=1}^{n} E_0 \backslash E_i\right)$. By Bonferoni's inequality, it is bounded above and below, respectively, by

$$\sum_{i=1}^{n} P(E_0 \backslash E_i) \quad \text{and} \quad \sum_{i=1}^{n} P(E_0 \backslash E_i) - \sum_{1 \le i < j \le n} P((E_0 \backslash E_i) \cap (E_0 \backslash E_j)).$$

Note that $(E_0 \backslash E_i) \cap (E_0 \backslash E_j) \subset E_i^c E_j^c$. The desired conclusion follows. ■

Lemma 4.2 *Let $\{\xi_i; i \ge 1\}$ be a sequence of i.i.d. random variables with the standard normal distribution. Set $S_k = \sum_{i=1}^{k} \xi_i^2$. Then*

$$P\left(\left|\frac{S_n}{S_m} - \frac{n}{m}\right| \ge x\right) \le 6 \exp\left(-\frac{m^4 x^2}{48 n^3}\right)$$

for any $m \ge 1$, $n \ge 1$ and $x > 0$ satisfying $m \le n/2$ and $x \le n/m$.

Proof. Write

$$\frac{S_n}{S_m} - \frac{n}{m} = \frac{(m-n)(S_m - m) + m[(S_n - S_m) - (n-m)]}{mS_m}.$$

Then

$$\left|\frac{S_n}{S_m} - \frac{n}{m}\right| \le \frac{n}{mS_m} \max\{|S_m - m|,\ |(S_n - S_m) - (n-m)|\}.$$

Since the distribution of $S_n - S_m$ is equal to that of S_{n-m}, we have that

$$\begin{aligned} & P\left(\left|\frac{S_n}{S_m} - \frac{n}{m}\right| \ge x\right) \\ \le\ & P\left(S_m \le \frac{m}{2}\right) + P\left(|S_m - m| > \frac{m^2 x}{2n}\right) + P\left(|S_{n-m} - (n-m)| > \frac{m^2 x}{2n}\right). \end{aligned} \quad (4.6)$$

Let P_1, P_2 and P_3 stand for the previous three probabilities in order. Define $I(x) := \sup_{\theta\in\mathbb{R}}\{\theta x - \log(E\exp(\theta\xi_1^2))\}$ for $x \in \mathbb{R}$. It is not difficult to verify that

(i) $I(x) = (x - 1 - \log x)/2$ for $x > 0$; $I(x) = +\infty$ for $x \le 0$;

(ii) $I(x)$ is increasing on $[1, \infty)$ and decreasing on $(0, 1)$.

The above two facts can be also seen in Lemma 3.2 from [19]. By (i) of Lemma A.3,

$$P_1 \le 2e^{-mI(1/2)} \le 2\exp(-(\log 4 - 1)m/4) \le 2\exp(-m/12).$$

Define $\eta(x) = x - \log(1+x) - (x^2/3)$ for $x > -1$. Then $\eta(0) = 0$ and $\eta'(x) = x(1-2x)(1+x)^{-1}/3$. Hence $\eta'(x) \ge 0$ for $x \in [0, 1/2]$ and $\eta'(x) < 0$ for $x \in [-1/2, 0)$. It follows that $x - \log(1+x) \ge x^2/3$ for $|x| < 1/2$. Therefore,

$$\begin{aligned} P_2 &\le 2\exp\left\{-m \cdot \max\left\{I\left(1 + \frac{mx}{2n}\right),\ I\left(1 - \frac{mx}{2n}\right)\right\}\right\} \\ &\le 2e^{-m^3x^2/(24n^2)} \end{aligned}$$

provided $x \le n/m$, where property (ii) of $I(x)$ above is used. Similarly,

$$\begin{aligned} P_3 &\le P\left(\left|\frac{S_{n-m}}{n-m} - 1\right| > \frac{m^2 x}{2n^2}\right) \\ &\le 2\exp\left\{-(n-m) \cdot \max\left\{I\left(1 + \frac{m^2x}{2n^2}\right),\ I\left(1 - \frac{m^2x}{2n^2}\right)\right\}\right\} \\ &\le 2e^{-m^4x^2/(48n^3)} \end{aligned}$$

provided $m \le n/2$ and $x \le n^2/m^2$, where the fact that $n - m \ge n/2$ is used in the last step. Thus,

$$P_1 + P_2 + P_3 \le 6\exp\left(-\min\left\{\frac{m}{12}, \frac{m^3x^2}{24n^2}, \frac{m^4x^2}{48n^3}\right\}\right)$$

if $m \le n/2$ and $x \le n/m$. By a simple verification, the minimum above is actually $m^4x^2/(48n^3)$. This together with (4.6) proves the lemma. ■

Proof of Lemma 3.1. Write $m = n_\alpha$ for simplification. By (3.4), we know that

$$\max_{1\le j\le m} \|\sqrt{n}\boldsymbol{\gamma}_j - \mathbf{y}_j + \boldsymbol{\Delta}_j\| \le \max_{1\le j\le m} \|\sqrt{n}\mathbf{u}_j\|,$$

where $\mathbf{u}_j = (1 - n^{-1/2}\|\mathbf{w}_j\|)\boldsymbol{\gamma}_j$. By the triangle inequality,

$$\left|\epsilon_n(m) - \max_{2\le j\le m} \|\boldsymbol{\Delta}_j\|\right| \le \max_{1\le j\le m} \|\sqrt{n}\mathbf{u}_j\| \le \left\{\max_{1\le j\le n} \|\sqrt{n}\boldsymbol{\gamma}_j\|\right\} \cdot \max_{1\le j\le m} \left|1 - \frac{\|\mathbf{w}_j\|^2}{n}\right|,$$

where the inequality $|1-\sqrt{x}| \le |1-x|$ is used in the last step. Proposition 1 from [19] implies that

$$\sqrt{\frac{n}{\log n}} \max_{1\le j\le n} \|\boldsymbol{\gamma}_j\| \xrightarrow{P} 2$$

as $n \to \infty$. To prove the lemma, it suffices to show that

$$B_n := \sqrt{\log n} \max_{1\le j\le m} \left|1 - \frac{\|\mathbf{w}_j\|^2}{n}\right| \to 0 \tag{4.7}$$

in probability as $n \to \infty$. By orthogonality, $(I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T)^2 = I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T$. This says that $I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T$ is an idempotent matrix. So by (3.4), $\mathbf{w}_j \sim N_n(\mathbf{0}, I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T)$ conditioning on $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_{j-1}$, where $\boldsymbol{\Gamma}_{n,j} = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots \boldsymbol{\gamma}_{j-1})$. In this context, "$\sim$" means that both sides of "$\sim$" have the same probability distribution. It also follows that $\mathrm{rank}(I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T) = \mathrm{trace}(I_n - \boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T) = \mathrm{trace}(I_n) - \mathrm{trace}(\boldsymbol{\Gamma}_{n,j}\boldsymbol{\Gamma}_{n,j}^T) = n - j + 1$. By Lemma A.2, $\|\mathbf{w}_j\|^2 \sim \chi^2(n-j+1)$. Obviously, $2tn/\sqrt{\log n} - j \ge tn/\sqrt{\log n}$ for all $1 \le j \le m$ as n is sufficiently large. Let $\{\xi_1, \xi_2, \cdots, \xi_n\}$ be independent standard normals. Then

$$\begin{aligned} P\left(\left|1 - \frac{\|\mathbf{w}_j\|^2}{n}\right| \ge 2t(\log n)^{-1/2}\right) &\le P\left(\left|\sum_{k=1}^{n-j+1} (\xi_k^2 - 1)\right| \ge \frac{tn}{\sqrt{\log n}}\right) \\ \le\ & P\left(\frac{1}{(n-j+1)^{1/2}}\left|\sum_{k=1}^{n-j+1} (\xi_k^2 - 1)\right| \ge n^{1/3}\right) \\ \le\ & \exp(-n^{1/3}) \end{aligned} \tag{4.8}$$

uniformly for $1 \le j \le m$ as n is sufficiently large, where Lemma A.3 is used in the last inequality (heuristically, since $\sum_{k=1}^{n-j+1}(\xi_k^2 - 1)$ is a sum of i.i.d. random variables with mean zero and variance equal to two, one can think of $\sum_{k=1}^{n-j+1}(\xi_k^2-1)/\sqrt{n-j+1}$ as a normal. Then the last inequality above is intuitive). By the union bound,

$$P(B_n \ge 2t) \le n \cdot \max_{1\le j\le m} P\left(\left|1 - \frac{\|\mathbf{w}_j\|^2}{n}\right| \ge 2t(\log n)^{-1/2}\right) \le n \cdot \exp(-n^{1/3}) \to 0$$

as $n \to \infty$. So (4.7) follows. $\blacksquare$

We need the following two lemmas for the proof of Lemma 3.2.

LEMMA 4.3 *Let $\mathbf{\Delta}_j$ be as in (3.3) and n_α in (3.8). Write $\mathbf{\Delta}_j = (\Delta_{1j}, \Delta_{2j}, \cdots, \Delta_{nj})^T \in \mathbb{R}^n$. Then, for any $t > 0$,*

$$P\left(|\Delta_{1j}| \geq t,\ |\Delta_{2j}| \geq t\right) \leq e^{-t^2 n/j} + e^{-(\log n)^2/11}$$

uniformly on $j \in (n/(\log n)^3, n_\alpha)$ as n is sufficiently large.

Proof. Again, write $m = n_\alpha$. By (3.4), $\mathbf{\Delta}_j = \mathbf{\Gamma}_{n,j}\mathbf{\Gamma}_{n,j}^T \mathbf{y}_j$, where $\mathbf{\Gamma}_{n,j} = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_{j-1})$ and $\mathbf{y}_j = (y_{1j}, y_{2j}, \cdots, y_{nj})^T \in \mathbb{R}^n$. It is easy to see from the orthogonality of the γ_i's, and the independence between $\mathbf{y}_j$ and $\mathbf{\Gamma}_{n,j}$ that

$$\mathbf{\Delta}_j \stackrel{d}{=} \mathbf{\Gamma}_{n,j}(y_{1j}, y_{2j}, \cdots y_{j-1\,j})^T. \tag{4.9}$$

Here and later, the notation "$\stackrel{d}{=}$" means that the distributions of both sides are identical. Thus

$$(\Delta_{1j}, \Delta_{2j})^T \stackrel{d}{=} \left(\sum_{k=1}^{j-1} \gamma_{1k} y_{kj}, \sum_{k=1}^{j-1} \gamma_{2k} y_{kj}\right)^T. \tag{4.10}$$

Observe that $\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_{j-1}$ are functions of $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_{j-1}$. We know from (4.10) that $(\Delta_{1j}, \Delta_{2j})^T \sim N_2(\boldsymbol{\mu}, \mathbf{\Sigma})$ conditioning on $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_{j-1}$. Easily, $\boldsymbol{\mu} = 0$ and $\mathrm{Var}(\Delta_{pj}) \sim \sum_{k=1}^{j-1} \gamma_{pk}^2$ for $p = 1, 2$, and the correlation coefficient of Δ_{1j} and Δ_{2j} is

$$\rho_j := \frac{\sum_{k=1}^{j-1} \gamma_{1k}\gamma_{2k}}{\sqrt{\sum_{k=1}^{j-1} \gamma_{1k}^2}\sqrt{\sum_{k=1}^{j-1} \gamma_{2k}^2}}. \tag{4.11}$$

Therefore there exists two independent standard normals ξ and η such that the conditional distribution of Δ_{1j} and Δ_{2j} given $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_{j-1}$ is the same as that of $(\sum_{k=1}^{j-1} \gamma_{1k}^2)^{1/2}\xi$ and $(\sum_{k=1}^{j-1} \gamma_{2k}^2)^{1/2}(\rho_j \xi + \sqrt{1-\rho_j^2}\eta)$. It follows that

$$\begin{aligned} & P\left(|\Delta_{1\,j+1}| \geq t,\ |\Delta_{2\,j+1}| \geq t | \mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_j\right) \\ \leq\ & P\left(|\xi| \geq t(\sum_{k=1}^{j} \gamma_{1k}^2)^{-1/2},\ |\eta| \geq t(\sum_{k=1}^{j} \gamma_{2k}^2)^{-1/2} - |\rho_{j+1}\xi|\ |\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_j\right). \end{aligned} \tag{4.12}$$

Now, by (3.5) and (3.6), there exists a sequence of i.i.d. standard normals $\psi_1, \psi_2, \cdots, \psi_n$ such that $\mathcal{L}(\sum_{k=1}^{j} \gamma_{pk}^2) = \mathcal{L}(S_j/S_n)$ for $p = 1, 2$, where $S_j = \sum_{l=1}^{j} \psi_l^2$. By Lemma 4.2,

$$\max_{n/(\log n)^3 \leq j \leq m} P\left(\left|\frac{S_n}{S_j} - \frac{n}{j}\right| \geq n^{-1/5}\right) \leq 6 \max_{n/(\log n)^3 \leq j \leq m} \left\{\exp\left(-\frac{j^4 n^{-2/5}}{48 n^3}\right)\right\} \leq e^{-\sqrt{n}}$$

as n is sufficiently large. By (4.12),

$$\begin{aligned} & P\left(|\Delta_{1\,j+1}| \geq t,\ |\Delta_{2\,j+1}| \geq t\right) \\ \leq\ & P\left(|\xi| \geq t\sqrt{(n/j) - n^{-1/5}},\ |\eta| \geq t\sqrt{(n/j) - n^{-1/5}} - |\rho_{j+1}\xi|\right) + 2e^{-\sqrt{n}}. \quad (4.13) \end{aligned}$$

Since $P(|\xi| \geq x) \leq (1/x)\exp(-x^2/2)$ for any $x > 0$, by Lemma 4.4 below,

$$P(|\rho_{j+1}\xi| \geq (\log n)^7/n^{1/4}) \leq P\left(|\rho_{j+1}| \geq \frac{(\log n)^6}{\sqrt{n}}\right) + P(|\xi| \geq \log n) \leq 2e^{-(\log n)^2/10}$$

for sufficiently large n. Thus, combining this with (4.13), we obtain from the independence of ξ and η that $P\left(|\Delta_{1\,j+1}| \geq t,\ |\Delta_{2\,j+1}| \geq t\right)$ is bounded above by

$$\begin{aligned} & P(|\xi| \geq \underbrace{t\sqrt{(n/j) - n^{-1/5}}}_{A},\ |\eta| \geq \underbrace{t\sqrt{(n/j) - n^{-1/5}} - n^{-1/4}(\log n)^7}_{B}) + 3e^{-(\log n)^2/10} \\ \leq\ & 2e^{-t^2 n/j} + e^{-(\log n)^2/11} \end{aligned}$$

uniformly on $j \in (n/(\log n)^3, m)$ as n is sufficiently large, where A and B are essentially $t\sqrt{n/j}$ when using Lemma A.1 in the last step. ■

Now we measure how fast the correlation coefficient ρ_j goes to zero. The idea behind the proof is that we view γ_{ij}'s in the expression of ρ_j in (4.11) as independent normals with mean zero and standard deviation $n^{-1/2}$. This intuition will be carried out rigorously by using Lemma A.4.

LEMMA 4.4 *Let ρ_j be as in (4.11). Then*

$$P(|\rho_{j+1}| \geq (\log n)^6/n^{1/4}) \leq e^{-(\log n)^2/10}$$

uniformly on $j \in (n/(\log n)^3, n_\alpha)$ for sufficiently large n.

Proof. Write $m = n_\alpha$ for simplification. Note that $(\gamma_{11}, \gamma_{12}, \cdots, \gamma_{1n})$ has the same distribution as that of $(\gamma_{21}, \gamma_{22}, \cdots, \gamma_{2n})$ because of the Haar invariance of $\mathbf{\Gamma} = (\boldsymbol{\gamma}_1, \boldsymbol{\gamma}_2, \cdots, \boldsymbol{\gamma}_n)$. For any $a > 0$

$$P(|\rho_{j+1}| \geq a) \leq P\left(\left|\sum_{k=1}^{j} \gamma_{1k}\gamma_{2k}\right| \geq \frac{aj}{2n}\right) + 2P\left((\sum_{k=1}^{j} \gamma_{1k}^2)^{-1} \geq \frac{2n}{j}\right). \quad (4.14)$$

By (3.5) and (3.6), the sum appearing in the last probability in (4.14) is equal to S_j/S_n in law as in Lemma 4.2. By this Lemma,

$$\begin{aligned} P\left(\left|(\sum_{k=1}^{j} \gamma_{1k}^2)^{-1} - \frac{n}{j}\right| \geq \frac{n}{j}\right) = P\left(\left|\frac{S_n}{S_j} - \frac{n}{j}\right| \geq \frac{n}{j}\right) \ & \leq\ 6\exp\left(-\frac{j^4}{48n^3}\left(\frac{n}{j}\right)^2\right) \\ & \leq\ e^{-\sqrt{n}} \quad (4.15) \end{aligned}$$

uniformly on $j \in (n/(\log n)^3, m)$ for n sufficiently large. Recall (3.6) again. Choosing $m = 2,\ t = n^{-1/4}\log n, s = \log n$ and $r = (\log n)^2/\sqrt{n}$ in Theorem A.4, by (3.6), we have $2n^2$ i.i.d. standard normals $\{y_{ij}; 1 \le i \le 2,\ 1 \le j \le n\}$ such that

$$\begin{aligned} & P\left(\epsilon_n(2) \ge \frac{(\log n)^2}{n^{1/4}}\right) \\ \le\ & 4n^2 \exp\left(-\frac{(\log n)^4}{16}\right) + 3n^2 e^{-(\log n)^2/2} + 3n^{5/4}\left(1 + \frac{(\log n)^2}{3\sqrt{n}(\sqrt{n}+2)}\right)^{-n/2} \\ \le\ & e^{-(\log n)^2/9} \end{aligned} \tag{4.16}$$

for n large enough, where $\epsilon_n(2) = \max_{1\le i\le 2,\ 1\le j\le n} |\sqrt{n}\gamma_{ij} - y_{ij}|$. Notice that

$$n\left|\sum_{k=1}^{j} \gamma_{1k}\gamma_{2k}\right| \le \left|\sum_{k=1}^{j} y_{1k}y_{2k}\right| + \frac{(\log n)^2}{n^{1/4}} \sum_{i=1}^{2}\sum_{k=1}^{k} |y_{ik}| + \frac{2j(\log n)^4}{\sqrt{n}} \tag{4.17}$$

on $\{\epsilon_n(2) \le (\log n)^2/n^{1/4}\}$. Note that $E\exp(|y_{11}y_{21}|/8) < \infty$ and $E|y_{11}| \le 1$. By Lemma A.3, there exists a universal constant $C > 0$ such that

$$P\left(\sum_{i=1}^{2}\sum_{k=1}^{j} |y_{ik}| \ge 3j\right) \le e^{-Cj} \quad \text{and} \quad P\left(\left|\sum_{k=1}^{j} y_{1k}y_{2k}\right| \ge \sqrt{j}\log j\right) \le e^{-(\log n)^2/3} \tag{4.18}$$

uniformly on $j \in (n/(\log n)^3, m)$, where the first one comes from (i) of Lemma A.3 and the second is obtained by (ii) of Lemma A.3 in the same way as in (4.8). If neither of the events in the above two probabilities occurs and $\epsilon_n(2) \le (\log n)^2/n^{1/4}$, then from (4.17)

$$n\left|\sum_{k=1}^{j} \gamma_{1k}\gamma_{2k}\right| \le \sqrt{j}\log j + \frac{3j(\log n)^2}{n^{1/4}} + \frac{2j(\log n)^4}{\sqrt{n}} < 5n^{3/4}(\log n)^2$$

uniformly on $j \in (n/(\log n)^3, m)$ for n sufficiently large n. Thus, from (4.16) and (4.18)

$$P\left(\left|\sum_{k=1}^{j} \gamma_{1k}\gamma_{2k}\right| \ge \frac{5(\log n)^2}{n^{1/4}}\right) \le 2e^{-(\log n)^2/9}$$

as n is sufficiently large. Choose $a = (\log n)^6/n^{1/4}$ in (4.14). Then, $aj/(2n) \ge 5(\log n)^2/n^{1/4}$ for all $j \in (n(\log n)^{-3}, m)$ as n is sufficiently large. It follows from the above that

$$P\left(\left|\sum_{k=1}^{j} \gamma_{1k}\gamma_{2k}\right| \ge \frac{aj}{2n}\right) \le 2e^{-(\log n)^2/9} \tag{4.19}$$

uniformly on $j \in (n/(\log n)^3, m)$ as n is sufficiently large. It is easy to see that the last probability in (4.14) is bounded by the first probability in (4.15). Combining (4.14), (4.15) and (4.19) together, we obtain that

$$P(|\rho_{j+1}| \ge (\log n)^6/n^{1/4}) \le 2e^{-(\log n)^2/9} + 2e^{-\sqrt{n}} \le e^{-(\log n)^2/10}$$

as n is sufficiently large. $\blacksquare$

Proof of Lemma 3.2. Write $m = n_\alpha$. Rewrite $\mathbf{\Delta}_{k+1} = (\Delta_{1\,k+1}, \Delta_{2\,k+1}, \cdots, \Delta_{n\,k+1})^T \in \mathbb{R}^n$. By (4.9) and (4.10), $\mathcal{L}(\Delta_{i\,k+1}) = \mathcal{L}(\sum_{l=1}^k \gamma_{il} y_{l\,k+1})$, so conditioning on $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k$,

$$\Delta_{i\,k+1} \sim N\left(0, \sum_{l=1}^{k} \gamma_{il}^2\right). \tag{4.20}$$

Let $E_0 = \{\max_{2\le j\le k} \|\mathbf{\Delta}_j\| \le t\}$ and $E_i = \{|\Delta_{i\,k+1}| \le t\}$. Although each E_i depends on n and k, we would rather use the notation E_i for simplification. This will not cause confusion in the context. Evidently,

$$\left\{\max_{2\le j\le k+1} \|\mathbf{\Delta}_j\| \le t\right\} = \bigcap_{i=0}^{n} E_i. \tag{4.21}$$

To apply Lemma 4.1 we now calculate $P(E_0 \backslash E_i)$. Define

$$\delta_n = \max_{(i,l)\in\Omega_n} \left| (\sum_{j=1}^{l} \gamma_{ij}^2)^{-1/2} - \sqrt{\frac{n}{l}} \right|,$$

where

$$\Omega_n = \left\{(i,l);\ 1 \le i \le n,\ n/(\log n)^3 \le l \le m\right\}.$$

Recall (4.20). Let S_j be as in Lemma 4.2, then by the lemma and the fact that $|\sqrt{a} - \sqrt{b}| \le |a-b|$ if $a \ge 1$,

$$P\left(\delta_n \ge \frac{(\log n)^8}{\sqrt{n}}\right) \le n^2 \max P\left(\left|\frac{S_n}{S_l} - \frac{n}{l}\right| \ge \frac{(\log n)^8}{\sqrt{n}}\right) \le e^{-(\log n)^2} \tag{4.22}$$

for sufficiently large n, where the max above is taken over all l such that $n/(\log n)^3 \le l \le m$. By (4.20), for some standard normal ξ, we have $\Delta_{i,k+1} \sim (\sum_{j=1}^k \gamma_{ij}^2)^{1/2}\xi$ conditioning on $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k$. Thus $P(E_i^c|\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k) = P(|\xi| > (\sum_{j=1}^k \gamma_{ij}^2)^{-1/2} t \mid \mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k)$. It follows that on $\{\delta_n \le (\log n)^8/\sqrt{n}\}$,

$$\begin{aligned} f_n^+(k) &= P\left(|\xi| > t\left(\sqrt{\frac{n}{k}} + \frac{(\log n)^8}{\sqrt{n}}\right)\right) \\ &\le P(E_i^c|\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k) \le P\left(|\xi| > t\left(\sqrt{\frac{n}{k}} - \frac{(\log n)^8}{\sqrt{n}}\right)\right) = f_n^-(k) \end{aligned} \tag{4.23}$$

uniformly on $(i,k) \in \Omega_n$. The key observation for this proof is that the above conditional probability is bounded above and below by unconditional probabilities. Obviously, E_0 is a set in the σ-algebra generated by $\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k$. By (4.22) and (4.23)

$$P(E_0 \backslash E_i) \;=\; E\left\{I_{E_0}\left(P(E_i^c|\mathbf{y}_1, \mathbf{y}_2, \cdots, \mathbf{y}_k)\right)\right\} \le P(E_0) f_n^-(k) + e^{-(\log n)^2}$$

for all $(i,k) \in \Omega_n$ when n is sufficiently large. Similarly, use the first step above to obtain

$$P(E_0 \backslash E_i) \geq P(E_0 \cap F_n) \cdot f_n^+(k) \geq P(E_0) \cdot f_n^+(k) - e^{-(\log n)^2},$$

for all $(i,k) \in \Omega_n$, where $F_n := \{\delta_n \leq (\log n)^8/\sqrt{n}\}$. Therefore,

$$nP(E_0) \cdot f_n^+(k) - ne^{-(\log n)^2} \leq \sum_{i=1}^n P(E_0 \backslash E_i) \leq nP(E_0) \cdot f_n^-(k) + ne^{-(\log n)^2} \tag{4.24}$$

uniformly on $n/(\log n)^3 \leq k \leq m$ as n is sufficiently large.

Finally, note that $e^{-t^2 n/j}$ is increasing in j. By Lemma 4.3, $P(E_1^c E_2^c) \leq n^{-t^2/\alpha}(\log n)^C$ for some constant $C > 0$ as n is sufficiently large. Also, the n random variables in $(\Delta_{1,k+1}, \Delta_{2,k+1}, \cdots, \Delta_{n,k+1})$ are exchangeable by the Haar-invariance. Hence

$$\sum_{1 \leq i < j \leq n} P(E_i^c E_j^c) \leq \frac{n^2}{2} P(E_1^c E_2^c) \leq \frac{(\log n)^C}{n^{t^2/\alpha - 2}} \tag{4.25}$$

as n is sufficiently large. By (4.24), the quantity $P(E_0) - \sum_{i=1}^n P(E_0 \backslash E_i)$ is bounded above and below respectively by

$$(1 - nf_n^+(k))P(E_0) + ne^{-(\log n)^2} \text{ and } (1 - nf_n^-(k))P(E_0) - ne^{-(\log n)^2}.$$

This together with (4.25) yields the desired conclusion via Lemma 4.1. ■

5 Appendix

The following is a standard result. It can be found in, e.g., Lemma 3 on page 49 from [6].

Lemma A.1 *Suppose $X \sim N(0,1)$. Then*

$$\frac{1}{\sqrt{2\pi}} \cdot \frac{x}{1+x^2} e^{-x^2/2} \leq P(X > x) \leq \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{x} e^{-x^2/2}$$

for all $x > 0$.

The following lemma is part (ii) on p.186 from [29].

Lemma A.2 *Suppose $\mathbf{y}$ is a $\mathbb{R}^n$-valued random vector with multi-normal distribution with mean $\mathbf{0}$ and covariance matrix $\mathbf{\Sigma}$ of rank r. If $\mathbf{\Sigma}^2 = \mathbf{\Sigma}$, then there exists a sequence of independent standard normals $\{\xi_j;\ j = 1, 2, \cdots, n\}$ such that $\|\mathbf{y}\|^2$ has the same distribution as that of $\sum_{j=1}^r \xi_j^2$, that is, $\|\mathbf{y}\|^2 \sim \chi^2(r)$.*

For $A \subset \mathbb{R}$, the interior and the closure of A in $\mathbb{R}$ are denoted by A° and $\bar{A}$, respectively. The following are Chernoff's bound and a moderate deviation result. They can be found from, e.g., (c) of Remarks on page 27 from [9] and Theorem 3.7.1 on page 109 from [9].

LEMMA A.3 *Let $\{X, X_i, i = 1, 2, \cdots\}$ be a sequence of i.i.d. random variables. Let $S_n = \sum_{i=1}^n X_i, n \geq 1$. Then*

(i) For any $A \subset \mathbb{R}$ and $n \geq 1$,

$$P(S_n/n \in A) \leq 2e^{-nI(A)},$$

where $I(x) = \sup_{t\in\mathbb{R}}\{tx - \log E(e^{tX})\}$ and $I(A) = \inf_{x\in A} I(x)$.

(ii) Assume further that $EX = 0$, $var(X) = \sigma^2 > 0$ and $Ee^{t_0 X} < \infty$ for some $t_0 > 0$. Let $\{a_n; n = 1, 2, \cdots\}$ be a sequence of positive numbers such that $a_n \to 0$ and $na_n \to \infty$ as $n \to \infty$. Then

$$\lim_{n\to\infty} a_n \log P\left(\sqrt{\frac{a_n}{n}} S_n \in A\right) = -\inf_{x\in A}\left\{\frac{x^2}{2\sigma^2}\right\}$$

for any subset $A \subset \mathbb{R}$ such that $\inf\{|x|; x \in A^{\circ}\} = \inf\{|x|; x \in \bar{A}\}$.

The following lemma is Theorem 5 from [19].

LEMMA A.4 *For each $n \geq 2$, there exists matrices $\mathbf{\Gamma}_n = (\gamma_{ij})_{1\leq i,j\leq n}$ and $\mathbf{Y}_n = (y_{ij})_{1\leq i,j\leq n}$ whose $2n^2$ elements are random variables defined on the same probability space such that*

(i) the law of $\mathbf{\Gamma}_n$ is the normalized Haar measure on the orthogonal group O_n;

(ii) $\{y_{ij}; 1 \leq i, j \leq n\}$ are i.i.d. random variables with the standard normal distribution;

(iii) set $\epsilon_n(m) = \max_{1\leq i\leq n, 1\leq j\leq m} |\sqrt{n}\gamma_{ij} - y_{ij}|$ for $m = 1, 2, \cdots, n$. Then

$$P(\epsilon_n(m) \geq rs + 2t) \leq 4me^{-nr^2/16} + 3mn\left(\frac{1}{s}e^{-s^2/2} + \frac{1}{t}\left(1 + \frac{t^2}{3(m+\sqrt{n})}\right)^{-n/2}\right)$$

for any $r \in (0, 1/4)$, $s > 0$, $t > 0$, and $m \leq (r/2)n$.

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