RUNS TEST FOR A CIRCULAR DISTRIBUTION AND A TABLE OF PROBABILITIES*)

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Summary

A method is suggested for testing whether two samples observed on a circle are drawn from the same distribution. The proposed test is a modification of the well-known Wald-Wolfowitz runs test for a distribution on a straight line. The primary advantage of the proposed test is that it minimizes the number of assumptions on the theoretical distribution.

1. Introduction

Circular statistical problems arise in many scientific fields such as research on orientation of animals (see for instance Schmidt-Koenig [13]), time period analysis for biological clocks, and rock magnetism in geology.

As Curray [3] pointed out, for very large samples the two-sample problem can be treated by the use of the χ^2-test. There is, however, a great need for a test that can be used when, due to the small size of the samples, the χ^2-test is not applicable.

In 1956 Watson and Williams proposed several two-sample tests based on the von Mises distribution (the so-called circular normal distribution). These tests, however, are all parametric. In applications there is not always evidence of the circular normal distribution.

There exist also some non-parametric two-sample tests. One of them, proposed by Kuiper [8] [9], is a modification of the Kolmogorov-Smirnov test for a circle. Another such test is due to Watson [21] who applies

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a similar procedure to a test suggested by Smirnov. At present the usefulness of these tests is limited since tables for the significant values of the test statistic are only partly available. Finally, a modification of the Mann-Whitney-Cochran test for a circle has been studied by Batschelet. The result is still unpublished.

The purpose of this paper is to propose a runs test for a circular distribution in the two-sample case which will be applicable when the sample size is small and which will involve a minimum number of assumptions on the theoretical distribution. This at first appeared to be only a matter of extending the considerations of the ordinary theory of runs on a line as proposed by Stevens [15], Wald and Wolfowitz [17], Mood [11], Swed and Eisenhart [16], and Wolfowitz [18]. But it soon became evident that further investigations were needed. The rotatable symmetry for the circle changes the mathematical treatment essentially. When two separate sets of observations are combined in all the various possible ways and rotatable symmetry is considered, the resulting arrangements were sometimes identical with other cases already obtained. Hence, we must reduce the number of cases by the number of arrangements found to be identical with one already obtained.

We suppose that the merit and the properties of this test are quite similar to those of the ordinary runs test studied previously for points on a line. For practical applications the runs test is extremely simple and fast. The theoretical treatment of the runs test has the advantage that no discussion is necessary to justify the independence of the starting point. Research on the power of the circular runs test has not yet begun.

The numerical table of the distribution function of the test statistic was computed on an IBM 1620.

2. Probability function for the number of runs on a circle

Given two sets of samples on a circle, we wish to determine the probability function for the number of runs obtainable by combining these two sets of samples. As a preliminary step we consider the following partition problem.

Suppose that there are k intervals on a circle and that in each interval there are n_i elements of the first sample, where the n_i's are ordered as follows:

$$n_1 \geqq n_2 \geqq \cdots \geqq n_k > 0\,, \qquad \text{for } 1 \leqq k \leqq N\,, \tag{2.1}$$

where $\sum_{i=1}^{k} n_i = N$ and N is now fixed. After the consideration of all possible arrangements of such k partitioned integers on a circle, we will consider how to combine the second sample among these k partitioned integers of the first sample.

Let

$$S_{(k)}=\{n_1, n_2, \cdots, n_k \mid n_i \geqq n_{i+1}, \sum_i n_i = N\} \tag{2.2}$$

denote the set or sets of ordered integers determined by the sample size N and the partition size k; e.g., for $N=4$ we have $S_{(1)}=\{4\}$, $S_{(2)}=\{3, 1\}, \{2, 2\}$, $S_{(3)}=\{2, 1, 1\}$, $S_{(4)}=\{1, 1, 1, 1\}$. Thus the set $\{S_{(k)}\}$ $k=1, 2, \cdots, N$ contains all the possible partitions for the integer N.

We now proceed to determine the number of rotatable symmetries generated from arranging these k partitioned integers on a circle.

If we introduce g_j such that

$$g_j \equiv (\text{the number of } i\text{'s} \mid n_i = q,\ i=1, 2, \cdots, k) \quad \text{for } j=1, 2, \cdots, t, \tag{2.3}$$

where $n_k \leqq q \leqq n_1 \leqq N$, $1 \leqq t \leqq k$, we can characterize each element in the set $\{S_{(k)}\}$ $k=1, 2, \cdots, N$. Then, corresponding to each element in $S_{(k)}$, we obtain a new set $G_{(k)}$ given by

$$G_{(k)}=\{g_1, g_2, \cdots, g_t\}. \tag{2.4}$$

Furthermore, let the common divisors, including one, of such $g_1, g_2, \cdots, g_t$ be $d_1, d_2, \cdots, d_p$, where we put $d_1=1<d_2< \cdots <d_p$ and $1 \leqq p \leqq t$.

If we omit repeated identical arrangement, then the number of circular permutations of the k integers is given by

$$\begin{aligned} &\Phi(n_1, n_2, \cdots, n_k \mid N) \\ &= \frac{1}{k} \sum_{i=1}^{p} \phi(d_i) \left(\frac{k}{d_i}\right)! \Big/ \left(\frac{g_1}{d_i}\right)! \left(\frac{g_2}{d_i}\right)! \cdots \left(\frac{g_t}{d_i}\right)! \end{aligned} \tag{2.5}$$

where Euler's function $\phi(d_i)$, the number of positive integers less than d_i and prime to d_i, is given by

$$\phi(d_i) = d_i\left(1-\frac{1}{p_1}\right)\left(1-\frac{1}{p_2}\right) \cdots$$

and $p_1, p_2, \cdots$ are the different prime factors of d_i, with the exception that $\phi(0) \equiv \phi(1) \equiv 1$. This corresponds to Barton and David [1], [2].

Similarly, the number $\Psi(n_1, n_2, \cdots, n_k \mid d_i, N)$ of symmetrical cases generated by $\left(\frac{d_i}{k}\right)$-rotation*) is obtained in the following way.

*) The notation $\left(\frac{d_i}{k}\right)$-rotation means a rotation of $\left(360 \times \frac{d_i}{k}\right)^0$.

Let $m_1, m_2, \cdots, m_t$ denote the integers $\frac{g_1}{d_i}, \frac{g_2}{d_i}, \cdots, \frac{g_t}{d_i}$, respectively, and let $\Phi(m_1, m_2, \cdots, m_t \mid d_i, N)$ be given by

$$\text{(2.7)} \qquad \Phi(m_1, m_2, \cdots, m_t \mid d_i, N) = \frac{1}{t}\sum_{d^*} \phi(d^*)\left(\frac{t}{d^*}\right)! \Big/ \left(\frac{m_1}{d^*}\right)! \left(\frac{m_2}{d^*}\right)! \cdots \left(\frac{m_t}{d^*}\right)!,$$

where the d^*'s denote the common divisors of $m_1, m_2, \cdots, m_t$, including one, and $\phi(d^*)$ is Euler's function, with the exception that $\phi(0)\equiv\phi(1)\equiv 1$.

Then the value of $\Psi(n_1, n_2, \cdots, n_k \mid d_i, N)$ is given by

$$\text{(2.8)} \qquad \Psi(n_1, n_2, \cdots, n_k \mid d_i, N) = \Phi(m_1, m_2, \cdots, m_t \mid d_i, N) - \sum_{p\geq j\geq i+1}^{*} \Psi(n_1, n_2, \cdots, n_k \mid d_j, N),$$

where $\sum^*$ means a summation over all multiples of d_i among $d_1, d_2, \cdots, d_p$. Naturally, as a result of (2.3), we obtain

$$\text{(2.9)} \qquad \Psi(n_1, n_2, \cdots, n_k \mid d_i=1, N)=0.$$

Now, on the basis of the above results, let us consider the probability function for the number of runs obtained by arranging simultaneously two different sets of observations on a circle.

Let N_1 and N_2 be the sizes of the first and second sample, respectively, where we assume $N_1 \leq N_2$ without any loss of generality.

First, the number $I(N_1, N_2)$ of all possible runs observable on a circle is obtained by using Euler's function again as follows:

$$\text{(2.10)} \qquad I(N_1, N_2) = \frac{1}{N_1+N_2}\sum_{d} \phi(d)\left(\frac{N_1+N_2}{d}\right)! \Big/ \left(\frac{N_1}{d}\right)! \left(\frac{N_2}{d}\right)!,$$

where the summation is over all divisors, including one, of the greatest common divisor of N_1 and N_2. This number will be the denominator in the determination of the probabilities.

Second, in order to give the probability function for an arbitrary "$2k$ runs", $1\leq k\leq N_1$, let us determine the number of possibilities that $2k$ runs will be observed. Let $n_1^{(s)}, n_2^{(s)}, \cdots, n_k^{(s)}$ be partitioned integers for N_s, $s=1, 2$. Then the enumerators of both non-symmetrical arrangements for N_1 and N_2 on a circle are given by

$$\text{(2.11)} \qquad \Phi(n_1^{(s)}, n_2^{(s)}, \cdots, n_k^{(s)} \mid N_s) - \sum_{i=1}^{p} \Psi(n_1^{(s)}, n_2^{(s)}, \cdots, n_k^{(s)} \mid d_i^{(s)}, N)$$

for $s=1, 2$, respectively, where $d_i^{(s)}$ indicates the d_i defined previously for the sth sample.

Hence, the number of arrangements obtainable by combining both non-symmetrical circular permutations for N_1 and N_2 is

$$I_1 \equiv k \prod_{s=1}^{2} \{\Phi(n_1^{(s)}, n_2^{(s)}, \cdots, n_k^{(s)} \mid N_s) - \sum_{i=1}^{p} \Psi(n_1^{(s)}, n_2^{(s)}, \cdots, n_k^{(s)} \mid d_i^{(s)}, N)\} . \tag{2.12}$$

Furthermore, when the symmetrical circular permutations of k integers for N_1 are combined with the non-symmetrical circular permutations for N_2, the number of possible arrangements is given by

$$I_2 \equiv \left\{ \sum_{d_i^{(1)}} \left(\frac{k}{d_i^{(1)}}\right) \Psi(n_1^{(1)}, n_2^{(1)}, \cdots, n_k^{(1)} \mid d_i^{(1)}, N_1) \right\} \cdot \left\{ \Phi(n_1^{(2)}, n_2^{(2)}, \cdots, n_k^{(2)} \mid N_2) - \sum_{i=1}^{p} \Psi(n_1^{(2)}, n_2^{(2)}, \cdots, n_k^{(2)} \mid d_i^{(2)}, N_2) \right\} . \tag{2.13}$$

Similarly, reversing the roles of N_1 and N_2, we obtain

$$I_3 \equiv \left\{ \sum_{d_i^{(2)}} \left(\frac{k}{d_i^{(2)}}\right) \Psi(n_1^{(2)}, n_2^{(2)}, \cdots, n_k^{(2)} \mid d_i^{(2)}, N_2) \right\} \cdot \left\{ \Phi(n_1^{(1)}, n_2^{(1)}, \cdots, n_k^{(1)} \mid N_1) - \sum_{i=1}^{p} \Psi(n_1^{(1)}, n_2^{(1)}, \cdots, n_k^{(1)} \mid d_i^{(1)}, N_1) \right\} . \tag{2.14}$$

Finally, when both symmetrical circular permutations for N_1 and N_2 are combined, the number of possible arrangements is given by

$$I_4 \equiv \sum_{d_i^{(1)}} \sum_{d_j^{(2)}} \text{G. C. D.} \left(\frac{k}{d_i^{(1)}}, \frac{k}{d_j^{(2)}}\right) \Psi\left(n_1^{(1)}, n_2^{(1)}, \cdots, n_k^{(1)} \mid d_i^{(1)}, N_1\right) \cdot \Psi(n_1^{(2)}, n_2^{(2)}, \cdots, n_k^{(2)} \mid d_j^{(2)}, N_2) , \tag{2.15}$$

where G. C. D. $\left(\frac{k}{d_i^{(1)}}, \frac{k}{d_j^{(2)}}\right)$ indicates the greatest common divisor of $\frac{k}{d_i^{(1)}}$ and $\frac{k}{d_j^{(2)}}$.

Thus putting

$$I(N_1, N_2, k) = \sum_{\{S_{(k)}^{(1)}\}} \sum_{\{S_{(k)}^{(2)}\}} \sum_{u=1}^{4} I_u \tag{2.16}$$

we obtain the probability function of observing $2k$ runs by arranging simultaneously N_1 and N_2 observations on a circle, where $\{S_{(k)}^{(s)}\}$ indicates the set $S_{(k)}$ defined by (2.2) for $s=1, 2$. This function is given by

(2.17) $P(k \mid N_1, N_2)=I(N_1, N_2, k) / I(N_1, N_2) \quad \text{for } 1 \leqq k \leqq N_1 .$

3. Distribution function and the table

Now we can easily obtain the distribution function for the number of runs on a circle by using (2.17).

If $2k$ is defined to be the number of runs, then the probability of an arrangement yielding $2r$ or fewer runs is

$$P\{2k \leqq 2r\}=\sum_{k=1}^{r} P\{k \mid N_1, N_2\} . \tag{3.1}$$

The following table has been prepared for use in testing whether or not two sets of observations are from the same population. The Table gives $P\{2k \leqq 2r\}$ to 5 decimal places for $N_1 \leqq N_2 \leqq 20$ with a range of N_1 from 2 to 20.

4. Numerical example

To illustrate the use of the numerical table in testing for randomness of an arrangement under the null hypothesis that two sets of observations are from the same distribution, let us consider the following example. Watson [21] studied a problem related to the migration of birds. In his data the measurements are given only to the nearest 5°, as follows:

Control group ($N_1=12$): 50, 290, 300, 300, 305, 320, 330, 330, 335, 340, 340, 355

Experimental group ($N_2=14$): 70, 155, 190, 195, 215, 235, 235, 240, 255, 260, 290, 300, 300, 300.

In this example, unfortunately, due to grouping some ties occur between values from the two different sets of observations. However, breaking up the ties we can give upper and lower bounds for the number of ties in favor or against the null hypothesis.

Following Watson, let us first change 290, 300, 300 of the control group into 285, 295, 295. Then the number of runs observed is 6. From the Table we find $P(2r \leqq 6)=0.0040$ such that the two samples are significantly different at an often-used level of 0.01.

Second, it is easy to see that for various ways in breaking up the ties the lower bound is 4 runs, the upper bound 8 runs. Thus we obtain

$$P\{2r \leqq 4\}=0.0002 \leqq P\{2r \leqq \text{ the actual number of runs}\} \leqq P\{2r \leqq 8\}=0.0357.$$

TABLE of $P(2r \leq 2k)$, where $2r$ is the number of runs.

N_2	k	$N_1=2$	$N_1=3$	$N_1=4$	$N_1=5$	$N_1=6$	$N_1=7$	$N_1=8$	$N_1=9$
2	1	.5							
	2	1.							
3	1	.5	.25						
	2	1.	.75						
	3		1.						
4	1	.33333	.2	.1					
	2	1.	.8	.6					
	3		1.	.9					
	4			1.					
5	1	.33333	.14286	.07143	.03846				
	2	1.	.71429	.50000	.34615				
	3		1.	.92857	.80769				
	4			1.	.96154				
	5				1.				
6	1	.25	.1	.04545	.02381	.01250			
	2	1.	.6	.40909	.26190	.17500			
	3		1.	.86364	.73810	.60000			
	4			1.	.97619	.92500			
	5				1.	.98750			
	6					1.			
7	1	.25	.08333	.03333	.01515	.00758	.00407		
	2	1.	.58333	.33333	.19697	.06897	.07724		
	3		1.	.83333	.65152	.50000	.38211		
	4			1.	.95455	.87879	.78862		
	5				1.	.99242	.97154		
	6					1.	.99593		
	7						1.		
8	1	.2	.06666	.02326	.01010	.00461	.00233	.00124	
	2	1.	.53333	.27907	.15152	.08756	.05128	.03218	
	3		1.	.76744	.57576	.41014	.29604	.21411	
	4			1.	.92930	.82028	.70396	.59406	
	5				1.	.98157	.94872	.89728	
	6					1.	.99767	.99010	
	7						1.	.99876	
	8							1.	
9	1	.2	.05263	.01818	.00699	.00299	.00140	.00070	.00037
	2	1.	.47368	.23636	.11889	.06269	.03497	.02028	.01224
	3		1.	.74545	.51049	.34328	.23077	.15734	.10612
	4			1.	.90210	.76119	.62238	.50000	.41233
	5				1.	.97015	.91608	.84266	.76067
	6					1.	.99441	.97972	.95510
	7						1.	.99930	.99667
	8							1.	.99963
	9								1.

Table of P{2r ≤ 2k} (continued).

N_2	k	$N_1=2$	$N_1=3$	$N_1=4$	$N_1=5$	$N_1=6$	$N_1=7$	$N_1=8$	$N_1=9$
10	1	.16667	.04545	.01370	.00498	.00198	.00086	.00041	.00021
	2	1.	.45455	.20548	.09453	.04762	.02405	.01354	.00761
	3		1.	.69863	.45274	.28571	.17869	.11738	.07672
	4			1.	.87065	.70635	.53952	.42133	.31859
	5				1.	.95635	.86426	.78460	.68141
	6					1.	.98969	.96344	.92328
	7						1.	.99794	.99238
	8							1.	.99979
	9								1.
	10								
11	1	.16667	.03846	.01099	.00366	.00137	.00057	.00025	.00012
	2	1.	.42308	.17582	.07692	.03571	.01753	.00905	.00488
	3		1.	.67033	.40659	.24176	.14480	.08824	.05489
	4			1.	.84615	.65385	.48416	.35219	.25494
	5				1.	.94231	.84050	.72172	.60503
	6					1.	.98303	.94344	.88509
	7						1.	.99623	.98512
	8							1.	.99940
	9								1.
	10								
	11								
12	1	.14286	.03226	.00862	.00275	.00096	.00041	.00016	.00007
	2	1.	.38710	.15517	.06314	.02788	.01377	.00626	.00317
	3		1.	.62931	.36538	.20481	.12353	.06657	.03938
	4			1.	.81868	.60288	.37667	.29339	.20210
	5				1.	.92019	.77764	.65523	.52754
	6					1.	.97327	.92058	.84524
	7						1.	.99326	.97542
	8							1.	.99866
	9								1.
	10								
	11								
	12								
13	1	.14286	.02857	.00714	.00210	.00070	.00026	.00010	.00004
	2	1.	.37143	.13571	.05252	.02171	.00955	.00444	.00217
	3		1.	.60714	.32983	.17577	.09469	.05212	.02726
	4			1.	.79202	.56092	.37848	.25077	.16379
	5				1.	.09756	.76161	.60836	.47097
	6					1.	.96594	.89443	.79863
	7						1.	.98978	.96246
	8							1.	.99756
	9								1.
	10								
	11								
	12								
	13								

Table of P{2r ≤ 2k} (continued)

N_2	k	N_1=10	N_1=11	N_1=12	N_1= 13	N_1=14	N_1=15
10	1	.00011					
	2	.00454					
	3	.05123					
	4	.24233					
	5	.58560					
	6	.87224					
	7	.98119					
	8	.99892					
	9	.99989					
	10	1.					
11	1	.00006	.00003				
	2	.00274	.00159				
	3	.03489	.02264				
	4	.18492	.13491				
	5	.50000	.40997				
	6	.81508	.74004				
	7	.96511	.93651				
	8	.99726	.99264				
	9	.99994	.99966				
	10	1.	.99997				
	11		1.				
12	1	.00003	.00002	.00001			
	2	.00171	.00094	.00053			
	3	.02382	.01477	.00923			
	4	.14006	.09772	.06795			
	5	.41863	.33001	.25568			
	6	.75864	.66999	.59091			
	7	.94436	.90228	.85373			
	8	.99427	.98523	.97118			
	9	.99980	.99906	.99727			
	10	1.	.99998	.99990			
	11		1.	.99999			
	12			1.			
13	1	.00002	.00001	.00000	.00000		
	2	.00111	.00059	.00032	.00018		
	3	.01703	.01011	.00614	.00381		
	4	.10991	.07356	.04977	.03406		
	5	.36068	.27346	.20682	.15657		
	6	.69505	.59328	.50000	.41791		
	7	.91796	.85981	.79318	.72281		
	8	.98961	.97403	.95023	.91882		
	9	.99956	.99783	.99386	.98688		
	10	1.	.99994	.99968	.99898		
	11		1.	1.	1.		
	12			1.	1.		
	13				1.		

Table of $P\{2r \leq 2k\}$ (continued)

N_2	k	$N_1=2$	$N_1=3$	$N_1=4$	$N_1=5$	$N_1=6$	$N_1=7$	$N_1=8$	$N_1=9$
14	1	.12500	.25000	.00581	.00163	.00051	.00018	.00006	0.00003
	2	1.00000	.35000	.12209	.04412	.01749	.00722	.00299	.00149
	3		1.00000	.57558	.29902	.15123	.07765	.03768	.02207
	4			1.	.76634	.52058	.33586	.19696	.13483
	5				1.	.88837	.72319	.51496	.41688
	6					1.	.95558	.87718	.75421
	7						1.	.98621	.94762
	8							1.	.99597
	9								1.
	10								
	11								
	12								
	13								
	14								
15	1	.12500	.02174	.00490	.00129	.00039	.00013	.00005	.00002
	2	1.	.32609	.10784	.03737	.01392	.00555	.00238	.00105
	3		1.	.55392	.27191	.13148	.06426	.03273	.01665
	4			1.	.74098	.48337	.29910	.18450	.11018
	5				1.	.87046	.68632	.51837	.36739
	6					1.	.94465	.83647	.71039
	7						1.	.97956	.93086
	8							1.	.99385
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
16	1	.11111	.01961	.00408	.00103	.00029	.00009	.00003	.00001
	2	1.	.31373	.09796	.03199	.01147	.00424	.00176	.00075
	3		1.	.52653	.24871	.11445	.05258	.02573	.01274
	4			1.	.71827	.45013	.28050	.15574	.09069
	5				1.	.85173	.65761	.46731	.32454
	6					1.	.93416	.81038	.66752
	7						1.	.97359	.91251
	8							1.	.99125
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
	16								

Table of P{2r ≤ 2k} (continued)

N_2	k	N_1=10	N_1=11	N_1=12	N_1=13	N_1=14	N_1=15	N_1=16
14	1	.00001	.00000	.00000	.00000	.00000		
	2	.00073	.00037	.00020	.00011	.00006		
	3	.01218	.00693	.00404	.00242	.00148		
	4	.08572	.05505	.03574	.02359	.01567		
	5	.30612	.22348	.16249	.11887	.08661		
	6	.63690	.52665	.42873	.34755	.27817		
	7	.88879	.81539	.73292	.65245	.57002		
	8	.98336	.95975	.92526	.88113	.83131		
	9	.99911	.99584	.98863	.97641	.95899		
	10	1.	.99985	.99921	.99758	.99448		
	11		1.	.99998	.99989	.99964		
	12			1.	1.00000	.99999		
	13				1.	1.		
	14					1.		
15	1	.00001	.00000	.00000	.00000	.00000	.00000	
	2	.00049	.00024	.00012	.00006	.00003	.00002	
	3	.00889	.00483	.00272	.00156	.00092	.00055	
	4	.06765	.04158	.02605	.01653	.01065	.00696	
	5	.26156	.18306	.12873	.09064	.06417	.04572	
	6	.57964	.46602	.36857	.28826	.22674	.17491	
	7	.85665	.76919	.67661	.58470	.50000	.42407	
	8	.97537	.94243	.89664	.83878	.77526	.70882	
	9	.99845	.99296	.98221	.96229	.93583	.90261	
	10	1.	.99969	.99840	.99523	.98935	.98012	
	11		1.	.99995	.99972	.99908	.99774	
	12			1.	.99999	.99997	.99987	
	13				1.	1.	1.	
	14					1.	1.	
	15						1.	
16	1	.00000	.00000	.00000	.00000	.00000	.00000	.00000
	2	.00034	.00016	.00008	.00004	.00002	.00001	.00000
	3	.00650	.00342	.00185	.00103	.00058	.00034	.00020
	4	.05330	.03169	.01913	.01172	.00729	.00461	.00295
	5	.22163	.15023	.10204	.06947	.04750	.03277	.02277
	6	.53034	.41148	.31487	.23886	.18022	.13598	.10269
	7	.82425	.72249	.61888	.52117	.43300	.35717	.29296
	8	.96604	.92242	.86321	.79341	.71867	.64283	.56942
	9	.99753	.98907	.97178	.94465	.90828	.86402	.81406
	10	1.	.99943	.99713	.99170	.98199	.96723	.94726
	11		1.	.99989	.99940	.99807	.99539	.99085
	12			1.	1.	.99990	.99966	.99911
	13				1.	1.	1.	.99996
	14					1.	1.	1.
	15						1.	1.
	16							1.

Table of P{2r ≤ 2k} (continued)

N_2	k	$N_1=2$	$N_1=3$	$N_1=4$	$N_1=5$	$N_1=6$	$N_1=7$	$N_1=8$	$N_1=9$
17	1	.11111	.01754	.00351	.00084	.00023	.00007	.00002	.00001
	2	1.	.29824	.08772	.02757	.00934	.00340	.00132	.00046
	3		1.	.50877	.22807	.10048	.04500	.02073	.00843
	4			1.	.69591	.41946	.23917	.13399	.06421
	5				1.	.83413	.61778	.42847	.39051
	6					1.	.92067	.78185	.68055
	7						1.	.96695	.90844
	8							1.	.98983
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
	16								
	17								
18	1	.10000	.01563	.00299	.00068	.00018	.00005	.00002	.00001
	2	1.	.28125	.08060	.02392	.00783	.00270	.00101	.00040
	3		1.	.48657	.20984	.08861	.03807	.01685	.00771
	4			1.	.67464	.39181	.21487	.11593	.06255
	5				1.	.81530	.58617	.39306	.25450
	6					1.	.90806	.75357	.58722
	7						1.	.95944	.87239
	8							1.	.98442
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
	16								
	17								
	18								

Table of $P\{2r \le 2k\}$ (continued)

N_2	k	$N_1=10$	$N_1=11$	$N_1=12$	$N_1=13$	$N_1=14$	$N_1=15$	$N_1=16$	$N_1=17$	$N_1=18$
17	1	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	
	2	.00023	.00011	.00005	.00002	.00001	.00001	.00000	.00000	
	3	.00484	.00245	.00128	.00068	.00038	.00021	.00012	.00007	
	4	.04248	.02436	.01419	.00832	.00506	.00309	.00192	.00121	
	5	.18927	.12403	.08131	.05300	.03548	.02371	.01598	.01087	
	6	.48284	.36323	.26926	.19600	.14501	.10615	.07781	.05720	
	7	.79039	.67648	.56461	.45817	.37450	.30047	.23974	.19067	
	8	.95515	.90023	.82831	.73906	.66136	.57808	.50000	.42902	
	9	.99634	.98413	.96016	.91461	.87650	.82098	.76026	.69716	
	10	1.	.99905	.99532	.97703	.97212	.95053	.92219	.88784	
	11		1.	.99980	.99888	.99646	.99175	.98402	.97278	
	12			1.	.99997	.99978	.99925	.99808	.99595	
	13				1.	1.	.99997	.99988	.99966	
	14					1.	1.	1.	.99999	
	15						1.	1.	1.	
	16							1.	1.	
	17								1.	
18	1	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
	2	.00017	.00008	.00003	.00002	.00001	.00000	.00000	.00000	.00000
	3	.00365	.00190	.00090	.00047	.00025	.00014	.00007	.00004	.00003
	4	.03413	.02009	.01063	.00609	.00355	.00210	.00126	.00078	.00048
	5	.16208	.10926	.06511	.04150	.02665	.01726	.01122	.00746	.00498
	6	.43936	.34110	.23038	.16427	.11675	.08296	.05871	.04226	.03030
	7	.75618	.67231	.51367	.40980	.32268	.25189	.19437	.15146	.11712
	8	.94294	.86831	.79193	.69919	.60584	.51735	.44039	.36595	.30445
	9	.99480	.97674	.94651	.90015	.84180	.77544	.70687	.63407	.56500
	10	1.	.99842	.99289	.98053	.95978	.93029	.89341	.84856	.79950
	11		1.	.99964	.99807	.99411	.98660	.97481	.95776	.93594
	12			1.	.99993	.99957	.99854	.99640	.99256	.98658
	13				1.	.99999	.99992	.99972	.99924	.99827
	14					1.	1.	.99999	.99996	.99987
	15						1.	1.	1.	1.
	16							1.	1.	1.
	17								1.	1.
	18									1.

Table of P{2r ≤ 2k} (continued).

N_2	k	$N_1=2$	$N_1=3$	$N_1=4$	$N_1=5$	$N_1=6$	$N_1=7$	$N_1=8$	$N_1=9$
19	1	.10000	.01429	.00260	.00056	.00014	.00004	.00001	.00000
	2	1.	.27143	.07273	.02089	.00649	.00217	.00078	.00030
	3		1.	.47013	.19368	.07849	.03241	.01384	.00608
	4			1.	.65443	.36646	.19368	.09840	.05240
	5				1.	.79842	.55652	.35955	.22607
	6					1.	.89518	.72517	.55025
	7						1.	.95150	.85128
	8							1.	.98029
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
	16								
	17								
	18								
	19								
20	1	.09091	.01299	.00224	.00047	.00011	.00003	.00001	.00000
	2	1.	.25974	.06726	.01834	.00524	.00176	.00061	.00022
	3		1.	.45067	.17921	.06617	.02776	.01139	.00484
	4			1.	.63500	.37781	.17507	.08781	.04413
	5				1.	.79217	.52861	.33216	.20126
	6					1.	.88215	.69883	.51552
	7						1.	.94317	.82978
	8							1.	.97568
	9								1.
	10								
	11								
	12								
	13								
	14								
	15								
	16								
	17								
	18								
	19								
	20								

Table of $P\{2r \leq 2k\}$ (continued)

N_2	k	N_1=10	N_1=11	N_1=12	N_1=13	N_1=14	N_1=15	N_1=16	N_1=17	N_1=18	N_1=19	N_1= 20
19	1	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	
	2	.00012	.00005	.00002	.00001	.00000	.00000	.00000	.00000	.00000	.00000	
	3	.00278	.00131	.00064	.00032	.00017	.00009	.00005	.00003	.00001	.00001	
	4	.02759	.01475	.00800	.00445	.00252	.00145	.00085	.00050	.00031	.00020	
	5	.13923	.08533	.05221	.03236	.02015	.01267	.00805	.00517	.00335	.00236	
	6	.39974	.28296	.19663	.13655	.09422	.06503	.04502	.03129	.02186	.01648	
	7	.72227	.58881	.46484	.36228	.27763	.21088	.15944	.12021	.09057	.07330	
	8	.92961	.85096	.75569	.65251	.55274	.46092	.38012	.31077	.25254	.14595	
	9	.99296	.97111	.93130	.87422	.80493	.72832	.64984	.57278	.50000	.39148	
	10	1.	.99782	.98984	.97275	.94504	.90685	.85963	.80568	.74746	.66429	
	11		1.	.99942	.99694	.99089	.97978	.96261	.93907	.90943	.86518	
	12			1.	.99987	.99923	.99746	.99382	.98758	.97814	.96258	
	13				1.	.99998	.99984	.99942	.99846	.99665	.99318	
	14					1.	1.	.99997	.99989	.99969	.99923	
	15						1.	1.	1.	.99999	.99995	
	16							1.	1.	1.	1.	
	17								1.	1.	1.	
	18									1.	1.	
	19										1.	
20	1	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000	.00000
	2	.00010	.00004	.00002	.00001	.00000	.00000	.00000	.00000	.00000	.00000	.00000
	3	.00237	.00097	.00046	.00022	.00011	.00006	.00003	.00002	.00001	.00001	.00000
	4	.02495	.01162	.00613	.00327	.00181	.00102	.00057	.00033	.00019	.00012	.00007
	5	.13329	.07121	.04239	.03251	.01541	.00947	.00578	.00361	.00227	.00146	.00095
	6	.29325	.25002	.16928	.12023	.07611	.05174	.03445	.02331	.01575	.01085	.00319
	7	.65437	.54802	.42305	.32493	.23925	.16764	.13001	.09551	.06968	.05157	.03383
	8	.90591	.82474	.71763	.61004	.50435	.40312	.32968	.26313	.20740	.16499	.12633
	9	.98974	.96310	.91400	.84763	.76945	.67784	.59590	.51456	.43693	.37293	.31131
	10	1.	.99693	.98601	.96378	.93146	.87930	.82366	.76040	.69596	.62707	.56001
	11		1.	.99911	.99546	.99037	.97088	.94790	.91684	.87959	.83501	.78610
	12			1.	.99978	.99872	.99585	.99025	.98084	.96722	.94843	.92484
	13				1.	.99995	.99970	.99894	.99725	.99418	.98915	.98176
	14					1.	.99999	.99994	.99977	.99937	.99854	.99708
	15						1.	1.	.99999	.99996	.99988	.99971
	16							1.	1.	1.	1.	.99998
	17								1.	1.	1.	1.
	18									1.	1.	1.
	19										1.	1.
	20											1.

From this we conclude that at the 5% level the two groups differ significantly.

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