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Author(s): Ralph Allan Bradley and Milton E. Terry

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## RANK ANALYSIS OF INCOMPLETE BLOCK DESIGNS

## I. THE METHOD OF PAIRED COMPARISONS

BY RALPH ALLAN BRADLEY AND MILTON E. TERRY\*

*Virginia Agricultural Experiment Station of the Virginia Polytechnic Institute*

## 1. INTRODUCTION

The analysis of experiments involving paired comparisons has received considerable attention in statistical methodology. Thurstone (1927) has considered the problem on the assumptions that a linear variate is involved and that perceptible differences exist among the items presented for comparison. More recently, Mosteller (1951 *a, b*) has elaborated upon Thurstone's method and, having postulated a sensation continuum over which sensations are jointly normally distributed, has developed a  $\chi^2$  test following transformation of the observed variates.

Kendall & Babington Smith (1940) proposed a method of analysis for paired comparisons which does not depend on assumptions of a linear variate or of normality, and the procedure may be described as a combinatorial type test. They form a coefficient of agreement which essentially measures discrepancies from perfect agreement, although the model used in the test is not explicitly formulated. In subjective tests the consistency of a judge is measured in terms of circular triads. We note that tests of consistency and tests of agreement, when differences are known to exist, may also be considered to be tests of null hypotheses upon the postulation of absence of differences.

Guttman (1946) has developed a method of quantifying paired comparisons. His problem was to determine a numerical value for each of a number of items which will best represent the comparisons in some sense. The problem may be considered to be one of estimation as distinct from the problem of testing hypotheses.

When only two items are to be compared in a ranking experiment, a test of the hypothesis of no-difference between them on some characteristic may be based on the binomial distribution. The estimation of the probabilities that the items are superior in a given comparison may be accomplished, and these estimates afford a method of rating the items or a method of quantification. In the present paper a generalization of the binomial model and distribution is obtained.

A mathematical model is formulated and maximum-likelihood estimates of treatment ratings provide a simple solution to Guttman's problem of quantification. Likelihood ratio statistics are used for tests of a specified class of hypotheses. Although these tests basically agree with those of Kendall & Babington Smith, they subdivide the possible results from an experiment of a given size into more distinct subclasses, thus perhaps indicating better sensitivity.

The test procedure is flexible. In subjective testing the experimenter may assume *a priori* that the standards of judging are uniform or that they vary by judges, by time, or by both. That is, true treatment ratings may be considered to be constant throughout an

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experiment or to be functions of judges and of time. In experiments concerned with the detection of treatment differences the latter alternatives are important. Certain test characteristics may be rather intangible and difficult to describe, with the added difficulty that personal preferences may influence judges' decisions. Even in simpler cases the research worker may desire to forgo the tedious procedure of training and co-ordinating judges. In these situations tests of treatment differences may be performed and a measure of the agreement among judges obtained, although estimates of over-all treatment ratings are not usually meaningful.

Tables for the test procedures for small treatment and sample sizes are provided and asymptotic distributions are considered. The use of the tables and the method of analysis are illustrated with an example of a taste-testing experiment on pork roasts from animals fed on one of three corn rations with peanut supplementments.

## 2. MATHEMATICAL MODEL

Let us consider  $t$  treatments in an experiment involving paired comparisons. We shall first consider that these treatments have true ratings (or preferences),  $\pi_1, \dots, \pi_t$ , on a particular subjective continuum throughout an experiment. The continuum is specialized by the requirements that every  $\pi_i \geq 0$  and that  $\sum \pi_i = 1$ , the latter condition being added for convenience. Further definition follows with the assumption that, when treatment  $i$  appears with treatment  $j$  in a block, the probability that treatment  $i$  obtains top rating (or a rank of 1) is  $\pi_i/(\pi_i + \pi_j)$ . Later generalization will require the addition of a second subscript on the parameters indicative of judges or time.

Now  $r_{ijk}$  will designate the rank of the  $i$ th treatment in the  $k$ th repetition of the block in which treatment  $i$  appears with treatment  $j$ . Clearly  $r_{jik} = 3 - r_{ijk}$ . Estimates of  $\pi_1, \dots, \pi_t$  will be denoted by  $p_1, \dots, p_t$  respectively, and  $n$  will be reserved to denote the number of repetitions of the design when a repetition is defined to be a set of all pairs of treatments.

In certain cases, as noted above, repetitions of the design may be performed by different judges or at different times. We shall discuss, in a subsequent section, the analysis when true ratings  $\pi_{1u}, \dots, \pi_{tu}$  exist in the  $u$ th of  $g$  groups not necessarily identical from group to group.

## 3. THE LIKELIHOOD FUNCTION

We may now obtain the likelihood function, assuming probability independence between blocks or pairs of treatments. Consider the probability of the observed rankings in the  $k$ th repetition for the block in which treatments  $i$  and  $j$  are compared. The probability of the observed result is

$$\left( \frac{\pi_i}{\pi_i + \pi_j} \right)^{2-r_{ijk}} \left( \frac{\pi_j}{\pi_i + \pi_j} \right)^{2-r_{jik}} = \frac{\pi_i^{2-r_{ijk}} \pi_j^{2-r_{jik}}}{(\pi_i + \pi_j)^2}.$$

For if the  $i$ th treatment obtains top ranking,  $r_{ijk} = 1$  and  $r_{jik} = 2$ , and the expression above becomes  $\pi_i/(\pi_i + \pi_j)$ ; alternatively,  $r_{ijk} = 2$ ,  $r_{jik} = 1$ , and the probability is  $\pi_j/(\pi_i + \pi_j)$ . Multiplying the appropriate expressions for all comparisons within a repetition and for all  $n$  repetitions, we reach the likelihood function in the general form

$$L = \prod_i \pi_i^{2n(t-1) - \sum_{j \neq i} \sum_k r_{ijk}} \prod_{i < j} (\pi_i + \pi_j)^{-n}. \quad (1)$$

When repetitions of the design are performed by groups with distinct parameters, the likelihood function will be a product over the groups of functions of the form of (1).

## 4. LIKELIHOOD RATIO TESTS AND ESTIMATION

A general class of tests of the null hypothesis,

$$H_0: \pi_i = 1/t \quad (i = 1, \dots, t), \quad (2)$$

against alternative hypotheses

$$H_a: \pi_i = \pi(h) \quad (h = 1, \dots, m);$$

$$i = s_{h-1} + 1, \dots, s_h, \quad \text{where } s_0 = 0, \quad s_m = t \quad \text{and} \quad \sum_h (s_h - s_{h-1}) \pi(h) = 1, \quad (3)$$

are possible using likelihood ratio tests. That is, tests of the null hypothesis of identical treatment ratings may be performed when the alternative hypothesis specifies that the treatments have identical ratings within each of  $m$  groups of treatments while the groups themselves may differ. Alternative hypotheses involving only a subset of parameters do not lead to parameter-free tests. Two special cases of this general class of tests will be considered in the next section.

If  $p(h)$  is the maximum-likelihood estimate of  $\pi(h)$ , these estimates are obtained from the equations

$$\left[ \left\{ 2n(t-1)(s_h - s_{h-1}) - \sum_{i=s_{h-1}+1}^{s_h} \sum_{j \neq i} \sum_k r_{ijk} - \frac{1}{2}n(s_h - s_{h-1})(s_h - s_{h-1} - 1) \right\} / p(h) \right]$$

$$- n(s_h - s_{h-1}) \sum_{f \neq h} (s_f - s_{f-1}) / \{p(h) + p(f)\} = 0 \quad (h = 1, \dots, m), \quad (4)$$

and

$$\sum_h (s_h - s_{h-1}) p(h) = 1. \quad (5)$$

Equations (4) are obtained from the reduction of the first-order maximizing conditions on the logarithm of the likelihood function when a Lagrange multiplier is used for the restraint on the parameters (3).

The general test statistic,\* a monotone function of the likelihood ratio, is

$$B = n \sum_{h < f} (s_h - s_{h-1})(s_f - s_{f-1}) \log \{p(h) + p(f)\}$$

$$- \sum_h \left\{ 2n(t-1)(s_h - s_{h-1}) - \sum_{i=s_{h-1}+1}^{s_h} \sum_{j \neq i} \sum_k r_{ijk} - \frac{1}{2}n(s_h - s_{h-1})(s_h - s_{h-1} - 1) \right\} \log p(h). \quad (6)$$

$B$  is implicitly a function of the treatment sums of ranks.

Solution of equations (4) and (5) provides estimates of the true treatment ratings. Pairwise comparison of these estimates provides a quantitative measure of the ratings of a pair of items relative to the test attribute.

The estimates  $p_i$  of  $\pi_i$  may be used for pairwise comparisons of treatments in the sense that the ratio  $p_i/p_j$  measures the relative frequency of occurrence of rank 1 for treatment  $i$  as compared with treatment  $j$  for this particular paired comparison. If the estimates are converted to logarithms, the values  $\log p_i$  occur on a linear scale and permit over-all comparisons of the experimental treatments. Any consideration of differences among treatments should be based on the values of the  $\log p_i$ 's.

## 5. SPECIAL TESTS

Two special alternative hypotheses are of particular interest.

*Case (i).*  $H_1$ : no  $\pi_i$  is assumed equal to any  $\pi_j$  ( $i \neq j$ ). That is, in the general hypothesis (3),  $m = t$ .

\* We use logarithms to base 10 unless otherwise specified.

In this case equations (4) and (5) are simplified and become

$$\frac{a_i}{p_i} - n \sum_{j \neq i} (p_i + p_j)^{-1} = 0 \quad (i, j = 1, \dots, t), \quad (7)$$

and 
$$\sum_i p_i = 1. \quad (8)$$

We define 
$$a_i = 2n(t-1) - \sum_{j \neq i} \sum_{k=1}^n r_{ijk}. \quad (9)$$

Both equations (4) and (7) contain one degree of dependence and imply respectively equations (5) and (8).

The test statistic becomes

$$B_1 = n \sum_{i < j} \log (p_i + p_j) - \sum_i \left\{ 2n(t-1) - \sum_{j \neq i} \sum_{k=1}^n r_{ijk} \right\} \log p_i. \quad (10)$$

The preparation of tables for the exact distribution of  $B_1$  is discussed in the following section.

*Case (ii).*  $H_2: \pi_i = \pi$  ( $i = 1, \dots, s$ );  $\pi_i = \frac{1-s\pi}{(t-s)}$  ( $i = s+1, \dots, t$ ). This is a reduction of the general hypothesis to the case in which  $m = 2$ .

This special test is similar to certain single degree of freedom comparisons in the analysis of variance. It is possible to compare two groups of items so long as all experimental items are included in one or another of the groups; however, it should be noted that one may always disregard all pairs in the experiment involving one or more extraneous items and proceed with tests based on comparisons within any subgroup of items.

For the special case (ii), the maximum-likelihood equations (4) and (5) may be solved simply and the test statistic written as an explicit function of treatment sums of ranks. When  $p$  is the estimate of  $\pi$ , we have

$$p = \frac{ns(4t-s-3) - 2 \sum_{i=1}^s \sum_{j \neq i} \sum_k r_{ijk}}{ns(5st-2t^2-6s+3t) - 2(2s-t) \sum_{i=1}^s \sum_{j \neq i} \sum_k r_{ijk}}, \quad (11)$$

and the statistic, by substitution in (6), is

$$B_2 = \left\{ \sum_{i=1}^s \sum_{j \neq i} \sum_k r_{ijk} + \frac{1}{2} ns(s-1) - 2n(t-1)s \right\} \log \left\{ \frac{(t-s)p}{(t-2s)p+1} \right\} \\ + \left\{ \sum_{i=s+1}^t \sum_{j \neq i} \sum_k r_{ijk} + \frac{1}{2} n(t-s)(t-s-1) - 2n(t-1)(t-s) \right\} \log \left\{ \frac{1-sp}{(t-2s)p+1} \right\}. \quad (12)$$

A discussion of the distribution of  $B_2$  is included with that of the distribution of  $B_1$ .

## 6. TABLES FOR $B_1$ AND $B_2$

It is possible to generate all combinations of treatment sums of ranks for any given number of treatments and repetitions of the paired comparison design. The probability of each such combination may be obtained under the null hypothesis of equality of true treatment ratings.

If three items are compared in a single repetition, the possible sets of rank sums are 2, 3, 4 and 3, 3, 3. Each of the six permutations of the elements of the first set has a probability 1/8, while the probability of the second set is 2/8. The treatment sums of ranks

for two repetitions and three treatments are obtained by adding 2, 3, 4 and 3, 3, 3 in turn to corresponding elements in the sets of sums of ranks consisting of all permutations of 2, 3, 4 and to 3, 3, 3. In the sets of sums of ranks so produced, all permutations of a given set of treatment sums of ranks are taken to be equivalent. The probability of a given permutation is obtained by multiplying the basic probabilities of the combination and the permutation used to produce the given permutation. The probability of a given new combination of rank sums is obtained by adding the probabilities obtained for each permutation of the elements of the combination.

The procedure may be arranged systematically as shown in Table 1.

Table 1. *The generation of treatment sums of ranks and probabilities for three treatments and two repetitions*

Prob-abilities	Rank sums	1/8	1/8	1/8	1/8	1/8	1/8	2/8
		2, 3, 4	2, 4, 3	3, 2, 4	3, 4, 2	4, 2, 3	4, 3, 2	3, 3, 3
6/8	2, 3, 4	4, 6, 8	4, 7, 7	5, 5, 8	5, 7, 6	6, 5, 7	6, 6, 6	5, 6, 7
2/8	3, 3, 3	5, 6, 7	5, 7, 6	6, 5, 7	6, 7, 5	7, 5, 6	7, 6, 5	6, 6, 6

The combination 5, 6, 7, say, appears in its various permutations in nine places in this table. In row 1, column 4, for example, 5, 7, 6 appears and its probability is 6/64 obtained by multiplying marginal probabilities of row and column. The probability of the combination 5, 6, 7 is then the sum of the nine individual probabilities and has the value 36/64. When three repetitions with three treatments are considered, the generating rows at the top of the table are unchanged, but the columns at the left above are replaced by the possible combinations of sums of ranks obtained for two repetitions with their corresponding probabilities. This procedure is continued for larger numbers of treatments and repetitions.

When the sets of possible combinations of treatment sums of ranks are obtained with their probabilities of occurrence, for each such set we may substitute in equations (7), (8) and (9) and obtain estimates  $p_1, \dots, p_t$ . The solution of these equations is tedious; in some cases elementary methods are applicable, in others it is necessary to use repeated approximations in an iterative procedure. In the later work, many of the procedures have been programmed on I.B.M. equipment. When we substitute  $p_1, \dots, p_t$  in (10), the statistic  $B_1$  is evaluated.

Tables for the distribution of  $B_1$  for three and four items and up to ten repetitions of the design are given in Appendix A. The possible sets of treatment sums of ranks are given in the left-hand columns. Corresponding estimates,  $p_1, \dots, p_t$ , are then given with the value of  $B_1$ . The final column shows significance levels,  $P$ , in the form of cumulative probabilities. These probabilities are obtained from the individual probabilities of the possible sets, accumulated beginning with small values of  $B_1$  which are most discordant under the null hypothesis.

The distribution of the statistic  $B_2$  may be recovered from tables for  $B_1$ . When  $t$  and  $n$  are specified, it is easy to compute values of  $p$  and  $B_2$  using (11) and (12). Probabilities may be obtained by elementary considerations.

$B_2$  is no longer symmetric over the treatments, and certain permutations of treatment sums of ranks must be considered for each entry in the tables of Appendix A. However,

each such permutation is equally likely, and its probability may be obtained from the cumulative probabilities for  $B_1$ . (Sets grouped together with equal values of  $B_1$  always have equal probabilities.)

For any hypothesis for which  $B_2$  is the appropriate statistic it is possible to evaluate  $p$ ,  $B_2$  and the corresponding probability of each value of  $B_2$  as obtained from the distribution of  $B_1$ . Tables for the distribution of  $B_2$  will be prepared at a later date and are not presently available.

## 7. THE COMBINATION OF EXPERIMENTS

As noted in the introduction, it may happen that an experiment is performed in groups\* of repetitions of sizes,  $n_u$  ( $u = 1, \dots, g$ ), with  $\sum_1^g n_u = n$ . Two possible methods of performing an over-all test of significance are available and depend on the specification of the alternative hypotheses. We shall illustrate these methods with reference to the important special test (i), noting that similar procedures may be developed for all tests of the general form specified in § 4.

### (i) *Pooled analysis*

If an experimenter is willing to assume that true treatment ratings,  $\pi_1, \dots, \pi_t$ , exist as the alternative hypothesis for all groups of repetitions, no new analysis is required. Total treatment sums of ranks are obtained by addition of corresponding group treatment sums of ranks over the  $g$  groups. The experiment is treated as though one group of  $n$  repetitions of the design had been employed and the tables of Appendix A may be used.

### (ii) *Combined analysis*

In many cases the alternative hypothesis that the same true ratings exist for all groups is not realistic. If the detection of treatment differences is the main concern of the experimenter, a pooled analysis may be inappropriate and even give a non-significant result, while each group alone exhibits significant treatment differences. This is particularly likely to happen where judge preferences may prohibit the setting up of uniform ranking criteria.

Let us specify an alternative hypothesis as follows:

(a) Within the  $u$ th of  $g$  groups, true ratings  $\pi_{1u}, \dots, \pi_{tu}, \sum_{i=1}^t \pi_{iu} = 1$  exist, and these ratings may change from group to group.

(b) Group experiments are independent in probability. Then, in addition, we define  $B_1^u$  to be the likelihood ratio statistic corresponding to  $B_1$  (6) for the  $u$ th group ( $u = 1, \dots, g$ ). The statistics  $B_1^u$  are self-weighting. That is, the groups may be combined and an over-all test of significance performed depending on a statistic

$$B_1^c = \sum_{u=1}^g B_1^u. \quad (13)$$

This statistic is again a monotone function of the likelihood ratio and does not depend on values of  $n_u$  other than in the evaluation of  $B_1^u$ .

Tables for the distribution of  $B_1^c$  are discussed in the following section.

One note should be added. The decision to pool or combine group results should be made from *a priori* knowledge of group behaviour. When group data may be pooled, it is possible

\* These groups may represent judges in sensory difference experimentation, different localities, days, or non-treatment experimental techniques.

that the pooled value of  $B_1$  exhibits higher significance than the corresponding value of  $B_1^c$ . However, it is easy to show that

$$B_1 \geq B_1^c \quad (14)$$

in every situation.

Estimates of the parameters,  $p_1, \dots, p_t$ , should usually be obtained by groups when groups are combined, but over-all estimates are available when groups are pooled.

#### 8. TABLES FOR $B_1^c$

The probability of a specified value of  $B_1^c$  may be simply obtained by elementary probability.

Suppose values of  $n_u$  are equal in sets of sizes  $g_1, \dots, g_w$ ,  $\sum_1^w g_i = g$ , and that values of  $B_1^u$  within these sets are equal in subsets of sizes  $g_{i1}, \dots, g_{iw_1}$ ,  $\sum_{j=1}^{w_i} g_{ij} = g_i$  ( $i = 1, \dots, w$ ). The probability of a specified value of  $B_1^c$  is

$$P(B_1^c) = \prod_{i=1}^w g_i! \left\{ \prod_{j=1}^{w_i} g_{ij}! \right\}^{-1} \prod_{u=1}^g P(B_1^u). \quad (15)$$

Values of  $B_1^u$  and  $P(B_1^u)$  may be obtained from the table of Appendix A.  $B_1^c$  is calculated by addition as in (13), and its probability is evaluated by use of (15).

Using the results above, we have computed tables for  $B_1^c$  for certain experiments wherein there are equal numbers of repetitions in each group. Only values at approximately the 0.10 level of significance or higher have been recorded, and these are selected for easy interpolation. These tables are shown in Appendix B.

#### 9. A COEFFICIENT OF AGREEMENT

A measure of consistency of ranking from group to group is naturally provided by the difference between the pooled value of  $B_1$  and  $B_1^c$ . Small values of  $B_1 - B_1^c$  (note that  $B_1 - B_1^c \geq 0$ ) will exhibit good agreement in ranking from group to group, while large values indicate discordant rankings.

If we set up the hypotheses

$$\left. \begin{aligned} H_0: \pi_{iu} &= \pi_i \quad (u = 1, \dots, g; i = 1, \dots, t) \\ \text{and} \quad H_1: \pi_{iu} & \quad (u = 1, \dots, g; i = 1, \dots, t) \text{ unrestricted by groups,} \end{aligned} \right\} \quad (16)$$

$$\text{then} \quad -2 \log_e \lambda = 2(B_1 - B_1^c) \log_e 10, \quad (17)$$

where  $\lambda$  is the likelihood ratio statistic for comparison of  $H_0$  and  $H_1$ .  $B_1 - B_1^c$  is then a monotone function of the likelihood ratio statistic.

The distribution of  $B_1 - B_1^c$  for small samples will depend on parameters  $\pi_1, \dots, \pi_t$  under  $H_0$  and is therefore not a parameter-free test. A conditional test, which is exact, may be formed and has some value. Suppose  $B_1^c$  is fixed at the observed value. Corresponding to  $B_1^c$  we have group sums of ranks. If there is no agreement from group to group, all permutations of group sums of ranks are equally likely, and for each permutation a pooled value of  $B_1$ , and consequently the difference  $B_1 - B_1^c$ , may be obtained. Thus for fixed  $B_1^c$  the distribution of  $B_1 - B_1^c$  can be derived under an assumption of no agreement from group to group. This conditional test reverses the hypotheses (16), and small values of  $B_1 - B_1^c$  show significant agreement from group to group.

A large sample test of the hypotheses of (16) is discussed in the following section.



## 10. LARGE SAMPLE DISTRIBUTIONS

If  $\lambda$  is the likelihood ratio, it is known (Wilks, 1946, pp. 150–2, § 7.2) that  $-2 \log_e \lambda$  is distributed as  $\chi^2$  under very general conditions. This result can be employed in the special cases considered above.

*Case (i).* In the first special test (§ 5)

$$-2 \log_e \lambda_1 = nt(t-1) \log_e 2 - 2B_1 \log_e 10 \quad (18)$$

is distributed in the limit as  $\chi^2_{t-1}$ , i.e. as  $\chi^2$  with  $t-1$  degrees of freedom. (It has been noted that  $B_1$  as tabled is a linear function of logarithms to base 10.)

The authors have been unsuccessful in an attempt to evaluate the moments of  $-2 \log_e \lambda_1$  by theoretical methods. However, numerical values of the mean and variance of this statistic have been computed for small numbers of items and repetitions. These are given in Table 2.

Table 2. *Mean and variance of  $-2 \log_e \lambda_1$*

<i>n</i>	<i>t</i> = 3		<i>t</i> = 4	
	Mean	Variance	Mean	Variance
1	3.12	3.24	4.55	9.96
2	3.39	7.27	3.59	9.51
3	2.80	7.50	3.33	7.80
4	2.54	6.51	3.22	7.10
5	2.40	5.83	3.13	6.66
6	2.32	5.38	—	—
7	2.27	5.15	—	—
8	2.23	4.95	—	—
9	2.20	4.82	—	—
10	2.18	4.71	—	—
$\infty$	2.00	4.00	3.00	6.00

It may be observed that even for these numbers of items and repetitions there is definite evidence of rapid convergence to the limiting values for the means and somewhat slower convergence for the variances. For small samples, on the average  $-2 \log_e \lambda_1$  will be a little too large, and use of the large sample approximation will tend to lead to the announcement of too many significant results. The approximation appears to be fairly good for practical purposes if the number of repetitions is not too small (say  $n \geq 15$ ).

We may note that the computations are fairly difficult if the approximate test must be used. To compute  $B_1$  it is necessary to solve equations (7) and (8) and substitute in the formula (10) for  $B_1$ . The equations are most easily solved by obtaining a first approximation by comparison with available tables (multiples of  $\Sigma r_1, \dots, \Sigma r_t$  yield identical estimates  $p_1, \dots, p_t$ ) and using an iterative procedure. The iterations consist of obtaining second approximations such as

$$p_i^{(1)} = a_i \left\{ \frac{n}{p_i^{(1)} + p_i^{(0)}} + \dots + \frac{n}{p_{i-1}^{(1)} + p_i^{(0)}} + \frac{n}{p_i^{(0)} + p_{i+1}^{(0)}} + \dots + \frac{n}{p_i^{(0)} + p_t^{(0)}} \right\}^{-1},$$

where the superscript in parentheses indicates the order of iteration.

For the combined test, from the additive property of  $\chi^2$ , the limiting distribution of

$$\begin{aligned} -2 \log_e \lambda_1^c &= -2 \sum_{u=1}^g \log_e \lambda_1^u \\ &= nt(t-1) \log_e 2 - 2B_1^c \log_e 10 \end{aligned} \tag{19}$$

is that of  $\chi^2$  with  $g(t-1)$  degrees of freedom. The notation in (19) corresponds to that of § 8(b).

If we consider the test specification (16), a parameter-free test of agreement may be formed for the large sample distribution. It follows that  $2(B_1 - B_1^c) \log_e 10$  has the  $\chi^2$ -distribution with  $(g-1)(t-1)$  degrees of freedom in the limit. Large values of this statistic show discordant ranking from group to group.

The large sample test may be summarized as in Table 3.

Table 3. *Large sample analysis*  
(Note that  $\log_e 2 = 0.69315$  and  $2 \log_e 10 = 4.60518$ )

Statistic	Hypotheses	Limiting distribution
$nt(t-1) \log_e 2 - 2B_1 \log_e 10$ $2(B_1 - B_1^c) \log_e 10$	$\begin{cases} H_0: \pi_i = 1/t \\ H_1: \pi_i \\ H_0: \pi_{iu} = \pi_i \\ H_1: \pi_{iu} \end{cases}$	$\chi_{t-1}^2$ $\chi_{(g-1)(t-1)}^2$
$nt(t-1) \log_e 2 - 2B_1^c \log_e 10$	$\begin{cases} H_0: \pi_{iu} = 1/t \\ H_1: \pi_{iu} \end{cases}$	$\chi_{g(t-1)}^2$

Case (ii). In the second special test, the statistic

$$-2 \log_e \lambda_2 = 2ns(t-s) \log_e 2 - 2B_2 \log_e 10, \tag{20}$$

has in the limit the distribution of  $\chi^2$  with one degree of freedom.

# 11. THE EXPERIMENTAL PROCEDURE AND ANALYSIS ILLUSTRATED\*

In a recent taste-testing experiment, pork roasts were compared by ranking in pairs on their flavour characteristics. The roasts were obtained from three groups of hogs which had been fattened on three different rations: corn (maize), corn plus a peanut supplement, and corn plus a large peanut supplement. The object was to determine whether the addition of peanuts to the diet was recognizable in the fresh-pork roasts or not. One would like to ask expert judges to rank pairs on the basis of flavour attributable to the peanut diet; however, this characteristic proved too intangible to define, and each judge was asked to rank pairs on the basis of his own preferences. This leads *a priori* to a combined analysis (§ 8) for the experimental data.

When a new procedure is proposed, it is useful for applied work to show a systematic listing of the steps involved. We now indicate these steps with reference to the results of

\* The illustrative example is taken from preliminary experimental results of L. L. Davis, C. M. Kincaid and H. R. Thomas at the Virginia Agricultural Experiment Station.

two of the several judges used in the experiment described above. Each judge performed five repetitions of the paired design ( $t = 3, n = 5$ ).

### Procedure

*Step 1* (experimental). A competent panel of judges was selected and so instructed that they all had experience with the experimental material.

*Step 2.* For each judge and for each repetition six small containers were coded. Two samples from roasts from each of the three treatment groups of animals were placed in the containers and the three requisite pairs formed. Code numbers were recorded and the pairs presented to the judges in a random order together with score cards.

*Step 3.* For each pair a judge tasted each sample and recorded the value 1 for the sample preferred and 2 for the other sample.

*Step 4* (analysis). The experimenter collected and decoded the data for each judge and recorded the results as follows. C denotes the corn ration, Cp the corn plus peanut supplement ration, and CP the corn plus large peanut supplement ration. The treatment sums of ranks,  $\Sigma r_i$ , for C, Cp, CP are respectively 19, 13, 13 and 13, 15, 17 for the two judges.

Table 4. *Rankings for two judges in the pork experiment*

Repetition ...	1	2	3	4	5
	C Cp CP	C Cp CP	C Cp CP	C Cp CP	C Cp CP
Pair	Judge 1				
C, Cp	2 1 —	2 1 —	2 1 —	2 1 —	2 1 —
C, CP	2 — 1	1 — 2	2 — 1	2 — 1	2 — 1
Cp, CP	— 2 1	— 1 2	— 2 1	— 1 2	— 2 1
	Judge 2				
C, Cp	2 1 —	2 1 —	1 2 —	1 2 —	1 2 —
C, CP	1 — 2	1 — 2	1 — 2	1 — 2	2 — 1
Cp, CP	— 1 2	— 1 2	— 2 1	— 2 1	— 1 2

*Step 5.* Since it was agreed that the results of the two judges should be combined, we enter the table of Appendix A at  $n = 5$ . For judge 1,  $p_C = 0.05$ ,  $p_{Cp} = 0.47$ ,  $p_{CP} = 0.47$ ,  $B_1 = 2.917$ , the significance level is 0.057; for judge 2,  $p_C = 0.53$ ,  $p_{Cp} = 0.30$ ,  $p_{CP} = 0.17$ ,  $B_1 = 4.034$  and the significance level is 0.404.

*Step 6.* The combined statistic  $B_1^c$  of equation (13) was obtained and has the value  $2.917 + 4.034 = 6.951$ . From the table of Appendix B under the two equal groups,  $n = 10$ , the significance level for the combined test was found to be 0.069. It was concluded that it had not been demonstrated that ration differences detectable by these judges were present at any usual significance level.

*Step 6a.* If a decision to pool the data had been made, treatment sums of ranks added over the judges would have been 32, 28, 30, and the table of Appendix A would have been used

for  $n = 10$ . We would have found  $p_C = 0.24$ ,  $p_{CP} = 0.43$ ,  $p_{CP} = 0.32$ ,  $B_1 = 8.797$  and the significance level would have been 0.630. Since it seems extremely unlikely on the basis of this method that treatment differences are present, it is not here meaningful to compare treatments by use of their estimated ratings.

$B_1 - B_1^c = 8.7973 - 6.9516 = 1.8459$  and is indicative of poor agreement of the preferences of the two judges. In fact use of the large sample approximation (Table 3) gives  $\chi^2 = 8.50$  with 2 degrees of freedom, a result significant at the 2 % level.

## 12. DISCUSSION

The authors have not attempted to obtain the power of this rank-order test procedure. The method is clear, but any consideration of exact power would require tables for each specified set of parameters of the alternative hypotheses of substantially greater complexity than those for the null distributions. In addition, the simplifications due to symmetry over treatments in certain null cases would disappear. The merits of the test procedure are then dependent on the properties of the maximum-likelihood methods used.

Experiments using the above methods at the Virginia Polytechnic Institute and elsewhere have been satisfactorily conducted. The simplicity and appropriateness of the experimental design, together with the simplicity of the analysis, wherein one has only to add small integers and consult prepared tables, appear to be important factors in the appeal of the methods. The comprehensive tables already prepared are easy to read, and the extension of these tables is proceeding. New computing equipment is expected to speed the tabling work.

One of the questions asked in connexion with this work pertains to the possibility of extending the analysis to incomplete block designs with larger block sizes. We are proceeding with a consideration of such extensions. The method of paired comparisons becomes inefficient where it is possible to rank more than two treatments at a time and where more than a few items or treatments are considered.

Apart from the application of the theoretical considerations for the methods of this paper, it is to be observed that the probabilities of the tables of Appendix A may be useful elsewhere. Whenever ranking methods are used in incomplete blocks of size 2, tests of null hypotheses of treatment equality will depend on the probabilities tabled. The probabilities of individual sets of treatment rank sums may be recovered from the cumulative probabilities given, since all sets bracketed together have equal individual probabilities (that is, sets of rank sums with identical values of  $B_1$  also have identical probabilities). Publication of the totality of possible sets of sums of ranks in Appendix A is necessary for use with Appendix B, and further desirable in that they may form a basis for future tables for methods yet to be devised.

## 13. SUMMARY

A method of analysis of paired comparisons is provided which permits tests of hypotheses of a general class and the estimation of treatment ratings or preferences. The mathematical model developed is simple and easy to interpret and apply. Ranks are used in incomplete blocks of size 2, and such ranking will permit later generalization to larger block sizes. The method of maximum likelihood is employed and tests depend on the likelihood ratio statistics. Two special tests are featured and test the null hypothesis that true treatment ratings are equal. The alternative hypothesis (i) makes no assumptions of equality of

treatment ratings and (ii) makes the assumption that there are only two groups of treatments wherein within group treatments do not differ in ratings but the two groups themselves may have different ratings.

The procedures shown are applicable in most problems where qualitative measurements alone are reliable and are particularly useful in problems involving subjective ranking by a small panel of judges for the detection of differences. Methods of pooling and of combining the results of several judges are given. The method of combining permits an over-all test of significance without the usual assumption that members of a panel agree upon the nature of the differences to be detected. The decision to pool or to combine is made on the basis of *a priori* knowledge of judge behaviour. If results are combined, estimates of treatment ratings are usually obtained for judges individually, although average estimates for the group of judges may be obtained by reverting to the pooled analysis for this special purpose. An example from taste testing is given.

The large sample distributions of the statistics are discussed, and tables for the exact test procedures are shown in the two appendices following.

In conclusion, the authors would like to express their appreciation to Prof. Lyle L. Davis, food technologist, for advice on experimental techniques and for trial experimentation. We would also acknowledge the computational and clerical assistance of Mr A. F. Teske, Mrs T. S. Russell, Mrs F. A. Spracher, Mrs M. H. Kirkpatrick and Mrs A. L. Ruiz.

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TABLES FOR THE RANK ANALYSIS OF INCOMPLETE BLOCK DESIGNS

APPENDIX A. *The distribution of the likelihood ratio for general alternatives*

The following table gives the values of the likelihood ratio statistic,  $B_1$ , and the likelihood estimates of the true treatment ratings,  $p_1, \dots, p_t$ , together with probabilities,  $P$ , that  $B_1$  will not be exceeded if the null hypothesis is true. Since low values of  $B_1$  indicate discordant results,  $P$  gives the significance level.

$n$  is the number of repetitions of the design and  $t$  the number of treatments. The design symbols,  $t$  or  $v$ ,  $\lambda$ ,  $b$ ,  $r$ ,  $k$  are standard and as used, for example, by Fisher & Yates (1948, p. 17, Introduction to Table XVIII) and Cochran & Cox (1950, pp. 270 and 304).  $\lambda$  in this design description should not be confused with the same symbol generally used to indicate a likelihood ratio. Parentheses contain combinations with equal values of  $B_1$ .  $\Sigma r_i$  is the sum of ranks for treatment  $i$ .

In setting up the table, several conventions have been adopted to simplify the printing: (i) Where  $p_1$  is unity and the remaining probabilities are therefore all zero the result is given as 1 — — or 1 — — —. (ii) The lowest value of  $B_1$  possible for each  $n$  is zero and is printed as 0. (iii) Where there are no entries in the final column above a single entry of .0000, the corresponding values of  $P$  are less than a half unit in the fourth decimal place.

3 treatments. (Design:  $t = 3, \lambda = 1, b = 3, r = 2, k = 2$ )

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$
$n = 1$								$n = 4$							
2	3	4	1	—	—	0	.7500	8	12	16	1	—	—	0	.0015
3	3	3	.33	.33	.33	0.903	1.0000	8	13	15	1	—	—	0	.0015
								9	11	16	.75	.25	—	0.977	.0132
								8	14	14	1	—	—	1.204	.0220
$n = 2$								10	10	16	.50	.50	—	2.084	.0513
4	6	8	1	—	—	0	.0938	9	12	15	.77	.19	.04	2.468	.1684
4	7	7	1	—	—	0.602	.2812	9	13	14	.78	.13	.09	2.997	.3237
5	5	8	.50	.50	—	1.498	.8438	10	11	15	.56	.37	.06	3.158	.5347
5	6	7	.59	.28	.13	1.806	1.0000	10	12	14	.59	.28	.13	3.466	.9155
6	6	6	.33	.33	.33			10	13	13	.60	.20	.20	3.614	1.0000
$n = 3$								11	11	14	.43	.43	.14		
6	9	12	1	—	—	0	.0117	11	12	13	.45	.32	.23		
6	10	11	1	—	—	0.829	.0820	12	12	12	.33	.33	.33		
7	8	12	.67	.33	—	1.840	.2226	$n = 5$							
7	9	11	.70	.22	.07	2.077	.4336	10	15	20	1	—	—	0	.0002
7	10	10	.71	.14	.14	2.511	.8906	10	16	19	1	—	—	1.087	.0020
8	8	11	.45	.45	.09	2.709	1.0000	11	14	20	.80	.20	—	1.461	.0057
8	9	10	.50	.31	.19			10	17	18	1	—	—		
9	9	9	.33	.33	.33			12	13	20	.60	.40	—		

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$
<i>n</i> = 5 (cont.)								<i>n</i> = 7 (cont.)							
11	15	19	.81	.16	.03	2.274	.0112	14	24	25	1	—	—	2.076	.0004
11	16	18	.82	.12	.06	2.767	.0386	17	18	28	.57	.43	—		
12	14	19	.64	.32	.05			15	21	27	.86	.12	.02	2.563	.0005
11	17	17	.82	.09	.09	2.917	.0569	15	22	26	.86	.10	.03	3.213	.0016
13	13	19	.47	.47	.05			16	20	27	.73	.24	.03		
12	15	18	.66	.25	.09	3.372	.1000	15	23	25	.87	.08	.05	3.561	.0039
12	16	17	.66	.19	.14	3.645	.2464	17	19	27	.60	.36	.03		
13	14	18	.51	.38	.10			15	24	24	.87	.07	.07	3.672	.0053
13	15	17	.53	.30	.17	4.034	.4039	18	18	27	.48	.48	.04	3.942	.0076
13	16	16	.54	.23	.23	4.158	.6053	16	21	26	.74	.20	.06		
14	14	17	.41	.41	.18			16	22	25	.75	.17	.08	4.372	.0185
14	15	16	.43	.32	.25	4.399	.9313	17	20	26	.62	.31	.07		
15	15	15	.33	.33	.33	4.515	1.0000	16	23	24	.75	.14	.11	4.576	.0351
<i>n</i> = 6								18	19	26	.51	.41	.08	4.884	.0504
12	18	24	1	—	—	0	.0000	17	22	24	.65	.22	.14	5.173	.1060
12	19	23	1	—	—	1.174	.0003	18	20	25	.54	.35	.12		
13	17	24	.83	.17	—			17	23	23	.65	.18	.18	5.266	.1396
12	20	22	1	—	—	1.659	.0010	19	19	25	.44	.44	.12		
14	16	24	.67	.33	—			18	21	24	.55	.30	.16	5.544	.1992
12	21	21	1	—	—	1.806	.0014	18	22	23	.55	.25	.20	5.723	.3716
15	15	24	.50	.50	—			19	20	24	.46	.37	.17		
13	18	23	.84	.14	.02	2.431	.0024	19	21	23	.47	.32	.21	5.984	.5201
13	19	22	.84	.11	.04	3.009	.0082	19	22	22	.47	.26	.26	6.070	.6976
14	17	23	.69	.27	.04			20	20	23	.39	.39	.22		
13	20	21	.85	.09	.06	3.270	.0178	20	21	22	.40	.33	.27	6.238	.9500
15	16	23	.55	.41	.04	3.680	.0282	21	21	21	.33	.33	.33	6.322	1.0000
14	18	22	.70	.22	.07	4.040	.0708	<i>n</i> = 8							
14	19	21	.71	.18	.11			16	24	32	1	—	—	0	
15	17	22	.58	.34	.09	4.154	.0976	16	25	31	1	—	—	1.309	
14	20	20	.71	.14	.14	4.496	.1504	17	23	32	.87	.13	—		
16	16	22	.45	.45	.09	4.710	.3139	16	26	30	1	—	—	1.954	.0000
15	18	21	.59	.28	.13			18	22	32	.75	.25	—		
15	19	20	.60	.22	.18	5.022	.4680	16	27	29	1	—	—	2.298	.0001
16	17	21	.48	.38	.14	5.123	.6575	19	21	32	.62	.38	—		
16	18	20	.50	.31	.19	5.321	.9421	16	28	28	1	—	—	2.408	.0001
16	19	19	.50	.25	.25	5.418	1.0000	20	20	32	.50	.50	—	2.678	.0001
17	17	20	.40	.40	.20			17	24	31	.88	.11	.01		
17	18	19	.41	.33	.26			17	25	30	.88	.09	.03	3.390	.0003
18	18	18	.33	.33	.33			18	23	31	.76	.21	.02		
<i>n</i> = 7								17	26	29	.88	.08	.04	3.810	.0008
14	21	28	1	—	—	0		19	22	31	.65	.32	.03		
14	22	27	1	—	—	1.247	.0000	17	27	28	.88	.07	.05	4.008	.0015
15	20	28	.86	.14	—			20	21	31	.54	.43	.03		
14	23	26	1	—	—	1.819	.0002								
16	19	28	.71	.29	—										

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$p_1$	$p_2$	$p_3$	$B_1$	$P$
<i>n</i> = 8 (cont.)								<i>n</i> = 9 (cont.)							
18	24	30	.77	.19	.04	4.168	.0020	20	29	32	.80	.13	.07	5.252	.0022
18	25	29	.77	.16	.07	4.660	.0046	22	25	34	.60	.34	.06		
19	23	30	.66	.28	.06			20	30	31	.80	.11	.09	5.416	.0038
18	26	28	.78	.13	.09	4.937	.0091	23	24	34	.51	.43	.06		
20	22	30	.56	.37	.06			21	27	33	.70	.22	.07	5.524	.0048
18	27	27	.78	.11	.11			21	28	32	.71	.20	.09	5.923	.0093
21	21	30	.47	.47	.07	5.026	.0118	22	26	33	.62	.30	.08		
19	24	29	.67	.24	.08	5.222	.0158	21	29	31	.71	.17	.12	6.156	.0166
19	25	28	.68	.21	.11	5.572	.0324	23	25	33	.53	.38	.09		
20	23	29	.58	.32	.10			21	30	30	.71	.14	.14	6.231	.0208
								24	24	33	.45	.45	.09		
19	26	27	.68	.17	.14	5.741	.0560	22	27	32	.63	.26	.11	6.390	.0268
21	22	29	.49	.41	.10			22	28	31	.63	.23	.14	6.687	.0490
20	24	28	.59	.28	.13	5.994	.0758	23	26	32	.55	.33	.12		
20	25	27	.60	.24	.16	6.236	.1419	22	29	30	.64	.20	.17	6.832	.0791
21	23	28	.51	.35	.14			24	25	32	.47	.40	.12		
20	26	26	.60	.20	.20	6.316	.1808	23	27	31	.56	.29	.15	7.049	.1029
22	22	28	.43	.43	.14			23	28	30	.56	.25	.18	7.259	.1772
21	24	27	.52	.30	.18	6.552	.2447	24	26	31	.49	.35	.16		
21	25	26	.52	.26	.22	6.705	.4211	23	29	29	.56	.23	.22	7.328	.2202
22	23	27	.44	.37	.18			25	25	31	.42	.42	.16		
22	24	26	.45	.32	.23	6.931	.5631	24	27	30	.50	.31	.19	7.534	.2867
22	25	25	.45	.27	.27	7.005	.7293	24	28	29	.50	.27	.23	7.668	.4638
23	23	26	.38	.38	.23			25	26	30	.43	.37	.20	7.868	.5992
23	24	25	.39	.33	.28	7.152	.9559	25	27	29	.44	.32	.24		
24	24	24	.33	.33	.33	7.225	1.0000	25	28	28	.44	.28	.28	7.933	.7550
								26	26	29	.38	.38	.24		
<i>n</i> = 9								26	27	28	.38	.33	.29	8.063	.9606
18	27	36	1	—	—	0		27	27	27	.33	.33	.33	8.128	1.0000
18	28	35	1	—	—	1.363		<i>n</i> = 10							
19	26	36	.89	.11	—			20	30	40	1	—	—	0	
18	29	34	1	—	—	2.070		20	31	39	1	—	—	1.412	
20	25	36	.78	.22	—			21	29	40	.90	.10	—		
18	30	33	1	—	—	2.488		20	32	38	1	—	—	2.173	
21	24	36	.67	.33	—			22	28	40	.80	.20	—		
18	31	32	1	—	—	2.685		20	33	37	1	—	—	2.653	
22	23	36	.56	.44	—	2.780	.0000	23	27	40	.70	.30	—	2.861	
19	27	35	.89	.10	.01			21	30	39	.90	.09	.01	2.923	
19	28	34	.89	.09	.02	3.545	.0001	20	34	36	1	—	—		
20	26	35	.79	.19	.02	4.027	.0002	24	26	40	.60	.40	—		
19	29	33	.89	.07	.03	4.299	.0003	20	35	35	1	—	—	3.010	
21	25	35	.68	.29	.02			25	25	40	.50	.50	—		
19	30	32	.89	.06	.04	4.369	.0004	21	31	38	.90	.08	.02	3.684	
22	24	35	.58	.39	.03	4.386	.0005	22	29	39	.81	.18	.02		
20	27	34	.79	.17	.04	4.914	.0011	21	32	37	.90	.07	.03	4.220	
19	31	31	.89	.05	.05			23	28	39	.71	.27	.02		
23	23	35	.48	.48	.03										
20	28	33	.80	.15	.05										
21	26	34	.70	.26	.05										



$\Sigma r_1$ $\Sigma r_2$ $\Sigma r_3$	$p_1$ $p_2$ $p_3$	$B_1$	$P$	$\Sigma r_1$ $\Sigma r_2$ $\Sigma r_3$	$p_1$ $p_2$ $p_3$	$B_1$	$P$
<i>n</i> = 10 ( <i>cont.</i> )				<i>n</i> = 10 ( <i>cont.</i> )			
22 30 38	.81 .16 .03	4.549	.0000	24 31 35	.66 .22 .12	7.090	.0157
21 33 36	.90 .06 .03	4.554	.0001	25 29 36	.58 .31 .10	7.291	.0261
24 27 39	.62 .35 .02	4.715	.0001	24 32 34	.67 .19 .14	7.357	.0320
21 34 35	.90 .05 .04			26 28 36	.51 .38 .11		
25 26 39	.53 .44 .03			24 33 33	.67 .17 .17		
				27 27 36	.44 .44 .11		
22 31 37	.81 .14 .05	5.141	.0002	25 30 35	.59 .28 .13	7.492	.0399
23 29 38	.72 .24 .04	5.534	.0005	25 31 34	.60 .24 .16	7.752	.0674
22 32 36	.82 .12 .06	5.760	.0009	26 29 35	.52 .34 .14	7.879	.1035
24 28 38	.64 .32 .05			25 32 33	.60 .21 .18		
22 33 35	.82 .11 .08			27 28 35	.46 .40 .14		
25 27 38	.55 .39 .05			26 30 34	.53 .30 .17	8.069	.1306
				26 31 33	.54 .26 .20	8.255	.2112
23 30 37	.73 .21 .06	5.788	.0012	27 29 34	.47 .35 .17	8.316	.2571
22 34 34	.82 .09 .09	5.834	.0014	26 32 32	.54 .23 .23		
26 26 38	.47 .47 .05	6.238	.0025	28 28 34	.41 .41 .18		
23 31 36	.73 .19 .08			27 30 33	.48 .32 .21	8.499	.3250
24 29 37	.65 .28 .07			27 31 32	.48 .28 .24	8.619	.5009
				28 29 33	.42 .37 .21	8.797	.6299
23 32 35	.74 .16 .10	6.525	.0046	28 30 32	.43 .32 .24	8.856	.7762
25 28 37	.57 .35 .08	6.665	.0074	28 31 31	.43 .28 .28		
23 33 34	.74 .14 .12	6.745	.0090	29 29 32	.38 .38 .25		
26 27 37	.50 .42 .08			29 30 31	.38 .33 .29	8.973	.9644
24 30 36	.66 .25 .09			30 30 30	.33 .33 .33	9.031	1.0000

4 treatments. (Design:  $t = 4, \lambda = 1, b = 6, r = 3, k = 2$ )

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$
$n = 1$										$n = 3$ (cont.)									
3	4	5	6	1	—	—	—	0	·3750	10	14	14	16	·72	·11	·11	·05	3·837	·1030
3	5	5	5	1	—	—	—	0·903	·6250	11	13	13	17	·52	·22	·22	·03		
4	4	4	6	·33	·33	·33	—			10	14	15	15	·73	·12	·08	·08		
4	4	5	5	·38	·38	·12	·12			12	12	13	17	·36	·36	·24	·04		
										11	12	15	16	·51	·33	·10	·06	4·060	·1788
$n = 2$																			
6	8	10	12	1	—	—	—	0	·0058	11	13	14	16	·53	·24	·16	·07	4·397	·2521
6	8	11	11	1	—	—	—	0·602	·0232	12	12	14	16	·37	·37	·18	·08	4·568	·3531
6	9	9	12	1	—	—	—			11	13	15	15	·53	·24	·11	·11		
7	7	10	12	·50	·50	—	—			11	14	14	15	·54	·17	·17	·12		
7	7	11	11	·50	·50	—	—			12	13	13	16	·38	·27	·27	·09		
6	9	10	11	1	—	—	—	1·498	·0994	12	12	15	15	·38	·38	·12	·12	4·737	·5246
7	8	9	12	·59	·28	·13	—			12	13	14	15	·39	·28	·19	·14	5·046	·7759
6	10	10	10	1	—	—	—			12	14	14	14	·40	·20	·20	·20	5·197	·8879
8	8	8	12	·33	·33	·33	—			13	13	13	15	·29	·29	·29	·14		
7	8	10	11	·60	·29	·08	·04	2·359	·2245	13	13	14	14	·29	·29	·21	·21	5·346	1·0000
										$n = 4$									
7	9	9	11	·62	·17	·17	·05	2·631	·3065	12	16	20	24	1	—	—	—	0	
7	9	10	10	·62	·18	·10	·10	2·898	·5643	12	16	21	23	1	—	—	—		
8	8	9	11	·37	·37	·21	·06			12	17	19	24	1	—	—	—		
8	8	10	10	·38	·38	·12	·12	3·158	·6639	13	15	20	24	·75	·25	—	—		
8	9	9	10	·40	·23	·23	·14	3·389	·9627										
9	9	9	9	·25	·25	·25	·25	3·612	1·0000										
$n = 3$																			
9	12	15	18	1	—	—	—	0	·0001	12	16	22	22	1	—	—	—	1·204	
9	12	16	17	1	—	—	—	0·829	·0010	12	18	18	24	1	—	—	—		
9	13	14	18	1	—	—	—			14	14	20	24	·50	·50	—	—		
10	11	15	18	·67	·33	—	—	13	15	21	23	·75	·25	—	—				
10	11	16	17	·67	·33	—	—	1·659	·0018	12	17	20	23	1	—	—	—	1·954	
										13	16	19	24	·77	·19	·04	—		
10	12	14	18	·70	·22	·07	—	1·840	·0040	13	15	22	22	·75	·25	—	—		
9	13	15	17	1	—	—	—			14	14	21	23	·50	·50	—	—		
9	14	14	17	1	—	—	—	2·077	·0072	14	14	22	22	·50	·50	—	—	2·408	·0000
10	13	13	18	·71	·14	·14	—			12	17	21	22	1	—	—	—		
9	13	16	16	1	—	—	—	13	17	18	24	·78	·13	·09	—				
11	11	14	18	·45	·45	·09	—	14	15	19	24	·56	·37	·06	—				
										12	18	19	23	1	—	—	—	2·468	·0004
9	14	15	16	1	—	—	—	2·511	·0144	12	18	20	22	1	—	—	—		
11	12	13	18	·50	·31	·19	—			14	16	18	24	·59	·28	·13	—		
9	15	15	15	1	—	—	—	2·709	·0160	12	18	21	21	1	—	—	—		
12	12	12	18	·33	·33	·33	—			12	19	19	22	1	—	—	—		
10	12	15	17	·71	·23	·05	·02	2·836	·0204	14	17	17	24	·60	·20	·20	—	3·158	·0012
										15	15	18	24	·43	·43	·14	—		
10	12	16	16	·71	·23	·03	·03	3·069	·0270	13	16	20	23	·78	·18	·04	·01		
11	11	15	17	·46	·46	·06	·02			15	16	17	24	·45	·32	·23	—		
10	13	14	17	·72	·16	·10	·02	3·248	·0361	12	19	20	21	1	—	—	—	3·466	·0021
11	11	16	16	·46	·46	·04	·04	3·301	·0386	14	15	20	23	·56	·38	·05	·01		
10	13	15	16	·72	·16	·07	·05	3·659	·0766	13	16	21	22	·78	·18	·03	·02		
11	12	14	17	·50	·32	·14	·03												

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$
$n = 4$ (cont.)										$n = 5$									
12	20	20	20	1	—	—	—	3.612	·0029	15	20	25	30	1	—	—	—	0	
16	16	16	24	·33	·33	·33	—	3.698	·0033	15	20	26	29	1	—	—	—	1.087	
13	17	19	23	·78	·14	·07	·01	3.854	·0035	16	19	25	30	·80	·20	—	—		
13	18	18	23	·78	·10	·10	·01	3.944	·0041	15	21	24	30	1	—	—	—		
14	15	21	22	·56	·38	·04	·02			15	20	27	28	1	—	—	—	1.461	
										17	18	25	30	·60	·40	—	—		
										15	22	23	30	1	—	—	—		
13	17	20	22	·78	·14	·05	·02	4.211	·0059	16	19	26	29	·80	·20	—	—	1.474	
14	16	19	23	·60	·28	·10	·02			15	21	25	29	1	—	—	—	2.274	
15	15	19	23	·43	·43	·11	·02	4.368	·0071	16	20	24	30	·81	·16	·03	—		
13	17	21	21	·78	·14	·04	·04			16	19	27	28	·80	·20	—	—	2.548	
13	18	19	22	·78	·11	·08	·03	4.502	·0105	17	18	26	29	·60	·40	—	—		
14	17	18	23	·61	·22	·16	·02												
14	16	20	22	·60	·29	·08	·04	4.718	·0129	15	21	26	28	1	—	—	—		
13	18	20	21	·78	·11	·06	·04	4.794	·0187	15	22	24	29	1	—	—	—	2.767	
15	16	18	23	·46	·33	·18	·03			16	21	23	30	·82	·12	·06	—		
14	16	21	21	·60	·29	·06	·06	4.872	·0219	17	19	24	30	·64	·31	·05	—		
15	15	20	22	·44	·44	·09	·04												
13	19	19	21	·78	·08	·08	·05	4.928	·0257	15	21	27	27	1	—	—	—	2.917	
15	17	17	23	·47	·25	·25	·03			15	23	23	29	1	—	—	—		
15	15	21	21	·44	·44	·06	·06	5.026	·0268	16	22	22	30	·82	·09	·09	—		
13	19	20	20	·79	·09	·06	·06	5.063	·0318	18	18	24	30	·47	·47	·05	—		
16	16	17	23	·35	·35	·26	·03			17	18	27	28	·60	·40	—	—	2.923	
										15	22	25	28	1	—	—	—	3.373	
14	17	19	22	·61	·22	·12	·04	5.131	·0372	17	20	23	30	·66	·25	·09	—	3.458	
14	18	18	22	·62	·17	·17	·05	5.262	·0407	16	20	25	29	·81	·16	·02	·00		
14	17	20	21	·61	·23	·09	·07	5.414	·0595	15	22	26	27	1	—	—	—	3.645	
15	16	19	22	·47	·34	·14	·05			15	23	24	28	1	—	—	—		
15	17	18	22	·48	·26	·20	·06	5.668	·0905	17	21	22	30	·67	·19	·14	—		
14	18	19	21	·62	·18	·13	·07			18	19	23	30	·52	·38	·11	—		
15	16	20	21	·47	·34	·11	·08	5.694	·1067	16	20	26	28	·81	·16	·02	·01	3.948	·0000
14	18	20	20	·62	·18	·10	·10	5.797	·1267	17	19	25	29	·64	·32	·04	·01		
16	16	18	22	·37	·37	·21	·06			15	23	25	27	1	—	—	—	4.035	·0001
16	17	17	22	·37	·28	·28	·06	5.920	·1523	18	20	22	30	·53	·30	·17	—	4.053	·0001
14	19	19	20	·62	·14	·14	·10			16	21	24	29	·81	·13	·05	·01	4.098	·0002
15	17	19	21	·49	·27	·16	·09	6.064	·1860	16	20	27	27	·81	·16	·01	·01		
15	18	18	21	·49	·21	·21	·09	6.183	·2074	18	18	25	29	·47	·47	·04	·01		
16	16	19	21	·37	·37	·16	·09	6.190	·2506	15	23	26	26	1	—	—	—	4.158	·0002
15	17	20	20	·49	·27	·12	·12	6.316	·2645	15	24	24	27	1	—	—	—		
16	16	20	20	·37	·38	·12	·12			18	21	21	30	·54	·23	·23	—		
										19	19	22	30	·41	·41	·18	—		
16	17	18	21	·39	·29	·22	·10	6.426	·4033	16	22	23	29	·82	·10	·07	·01	4.321	·0002
15	18	19	20	·50	·21	·16	·12			15	24	25	26	1	—	—	—	4.399	·0003
15	19	19	19	·50	·17	·17	·17	6.543	·4325	19	20	21	30	·43	·32	·25	—	4.437	·0003
17	17	17	21	·30	·30	·30	·10	6.665	·5444	17	19	26	28	·64	·32	·03	·01		
16	17	19	20	·39	·30	·18	·13			15	25	25	25	1	—	—	—	4.516	·0003
										20	20	20	30	·33	·33	·33	—		
16	18	18	20	·40	·23	·23	·14	6.778	·6147	17	19	27	27	·64	·31	·02	·02	4.586	·0004
16	18	19	19	·40	·24	·18	·18	6.892	·7915	18	18	26	28	·47	·47	·03	·02		
17	17	18	20	·31	·31	·24	·14	7.005	·8470	16	21	25	28	·82	·13	·04	·02	4.649	·0005
17	17	19	19	·31	·31	·19	·19	7.115	·9858	17	20	24	29	·66	·25	·08	·01		
17	18	18	19	·32	·25	·25	·19	7.225	1.0000	18	18	27	27	·47	·47	·02	·02	4.735	·0005
18	18	18	18	·25	·25	·25	·25												

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$
$n = 5$ (cont.)										$n = 5$ (cont.)									
16	21	26	27	.82	.13	.03	.02	4.917	.0006	19	20	25	26	.45	.35	.11	.09	7.304	.0559
18	19	24	29	.52	.38	.09	.01			18	22	24	26	.56	.21	.14	.09	7.385	.0729
16	22	24	28	.82	.10	.06	.02	5.024	.0008	19	21	23	27	.46	.29	.18	.07	7.482	.0833
17	21	23	29	.67	.20	.12	.01			18	23	23	26	.57	.17	.17	.09		
16	23	23	28	.82	.08	.08	.02	5.144	.0009	19	22	22	27	.46	.23	.23	.07	7.486	.0937
17	22	22	29	.67	.16	.16	.02			18	22	25	25	.57	.21	.11	.11		
17	20	25	28	.66	.26	.06	.02	5.239	.0010	20	20	23	27	.37	.37	.19	.07	7.679	.1249
16	22	25	27	.82	.11	.05	.03	5.401	.0013	18	23	24	25	.57	.18	.14	.11	7.694	.1409
18	20	23	29	.54	.31	.14	.02			20	21	22	27	.38	.30	.24	.08		
17	20	26	27	.66	.26	.05	.04	5.505	.0017	19	21	24	26	.46	.29	.15	.09	7.775	.1472
18	19	25	28	.52	.38	.07	.03			18	24	24	24	.57	.14	.14	.14		
16	22	26	26	.82	.11	.04	.04	5.521	.0019	21	21	21	27	.31	.31	.31	.08	7.795	.1673
19	19	23	29	.42	.42	.14	.02			19	21	25	25	.47	.29	.12	.12		
16	23	24	27	.82	.08	.06	.03	5.629	.0024	20	20	24	26	.37	.37	.16	.10	7.895	.1728
18	21	22	29	.55	.24	.19	.02			20	20	25	25	.37	.37	.12	.12		
17	21	24	28	.67	.21	.09	.03	5.714	.0027	19	22	23	26	.47	.24	.19	.10	7.884	.1964
18	19	26	27	.52	.38	.06	.04	5.770	.0031	19	22	24	25	.47	.24	.16	.13	8.077	.2666
16	23	25	26	.82	.09	.05	.04			20	21	23	26	.39	.31	.20	.10		
19	20	22	29	.44	.34	.20	.02	5.858	.0039	19	23	23	25	.48	.20	.20	.13	8.169	.3090
17	22	23	28	.68	.17	.13	.03	5.938	.0044	20	22	22	26	.39	.25	.25	.11		
16	24	24	26	.82	.07	.07	.04	5.967	.0049	19	23	24	24	.48	.20	.16	.16	8.263	.3605
19	21	21	29	.44	.27	.27	.02			21	21	22	26	.32	.32	.26	.11		
16	24	25	25	.82	.07	.05	.05	6.075	.0055	20	21	24	25	.39	.31	.17	.13	8.269	.4125
20	20	21	29	.35	.35	.27	.02			20	22	23	25	.39	.26	.21	.14		
17	21	25	27	.67	.21	.08	.04	6.083	.0068	20	22	24	24	.40	.26	.17	.17	8.449	.4883
18	20	24	28	.54	.31	.11	.04			21	21	23	25	.32	.32	.21	.14		
17	21	26	26	.67	.21	.06	.06	6.201	.0075	20	23	23	24	.40	.21	.21	.17	8.632	.6904
19	19	24	28	.42	.42	.12	.04			21	22	22	25	.33	.27	.27	.14		
17	22	24	27	.68	.17	.10	.05	6.408	.0099	21	21	24	24	.32	.32	.17	.17	8.634	.7181
18	21	23	28	.55	.25	.16	.04			21	22	23	24	.33	.27	.22	.18		
18	20	25	27	.54	.32	.09	.05	6.479	.0112	22	22	22	24	.27	.27	.27	.18	8.900	.9423
17	23	23	27	.68	.14	.14	.05			21	23	23	23	.33	.22	.22	.22		
18	22	22	28	.56	.20	.20	.04	6.512	.0127	22	22	23	23	.27	.27	.22	.22	8.988	1.0000
18	20	26	26	.54	.32	.07	.07			19	19	25	27	.42	.42	.10	.06		
19	19	25	27	.42	.42	.10	.06	6.566	.0143	17	22	25	26	.68	.17	.08	.07	6.629	.0180
17	22	25	26	.68	.17	.08	.07			19	20	23	28	.44	.34	.17	.04		
19	20	23	28	.44	.34	.17	.04	6.682	.0185	$n = 6$									
19	19	26	26	.42	.42	.08	.08			17	23	24	26	.68	.14	.11	.07	6.835	.0242
17	23	24	26	.68	.14	.11	.07	18	24	30	36	1	—	—	—				
19	21	22	28	.45	.28	.22	.05	6.869	.0271	18	24	31	35	1	—	—	—	1.174	
18	21	24	27	.55	.26	.13	.06			18	25	29	36	1	—	—	—		
17	23	25	25	.68	.14	.09	.09	6.939	.0306	19	23	30	36	.83	.17	—	—	1.659	
20	20	22	28	.36	.36	.23	.05			18	24	32	34	1	—	—	—		
17	24	24	25	.68	.11	.11	.09	7.040	.0349	18	26	28	36	1	—	—	—	1.806	
20	21	21	28	.37	.29	.29	.05			20	22	30	36	.67	.33	—	—		
18	22	23	27	.56	.21	.17	.06	7.071	.0394	18	24	33	33	1	—	—	—	1.806	
18	21	25	26	.56	.26	.10	.08			18	27	27	36	1	—	—	—		
19	20	24	27	.45	.35	.14	.06	7.087	.0487	21	21	30	36	.50	.50	—	—		

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$
<i>n = 6 (cont.)</i>										<i>n = 6 (cont.)</i>									
19	23	31	35	.83	.17	—	—	2.348		18	28	31	31	1	—	—	—		
18	25	30	35	1	—	—	—			18	29	29	32	1	—	—	—	5.123	
19	24	29	36	.84	.14	.02	—	2.431		22	25	25	36	.50	.25	.25	—		
19	23	32	34	.83	.17	—	—			23	23	26	36	.40	.40	.20	—		
20	22	31	35	.67	.33	—	—	2.833		18	29	30	31	1	—	—	—	5.321	
										23	24	25	36	.41	.33	.26	—		
19	23	33	33	.83	.17	—	—												
21	21	31	35	.50	.50	—	—	2.980		21	22	32	33	.55	.41	.02	.02	5.355	
18	25	31	34	1	—	—	—			19	25	31	33	.84	.12	.02	.01	5.368	
18	26	29	35	1	—	—	—			21	23	29	35	.58	.34	.07	.01		
19	25	28	36	.84	.11	.04	—	3.009		18	30	30	30	1	—	—	—	5.419	.0000
20	23	29	36	.69	.27	.04	—			24	24	24	36	.33	.33	.33	—		
18	25	32	33	1	—	—	—			19	26	29	34	.85	.10	.05	.01	5.456	.0001
18	27	28	35	1	—	—	—			20	25	28	35	.71	.19	.09	.01		
19	26	27	36	.85	.09	.06	—	3.270		19	25	32	32	.84	.12	.02	.02	5.481	.0001
21	22	29	36	.55	.41	.04	—			22	22	29	35	.46	.46	.08	.01		
20	22	32	34	.67	.33	—	—	3.317											
20	22	33	33	.67	.33	—	—			19	27	28	34	.85	.08	.06	.01	5.667	.0001
21	21	32	34	.50	.50	—	—	3.465		20	26	27	35	.72	.15	.12	.01		
21	21	33	33	.50	.50	—	—			20	24	30	34	.70	.23	.05	.02	5.672	.0001
18	26	30	34	1	—	—	—	3.612		19	26	30	33	.85	.10	.04	.02	5.903	.0001
20	24	28	36	.70	.22	.07	—	3.680		21	24	28	35	.59	.28	.11	.01		
19	24	30	35	.84	.14	.02	—	3.685		20	24	31	33	.71	.23	.04	.02	6.026	.0001
18	26	31	33	1	—	—	—			21	23	30	34	.58	.34	.06	.02		
18	27	29	34	1	—	—	—			19	26	31	32	.85	.10	.03	.02	6.114	.0001
20	25	27	36	.71	.18	.10	—	4.040		22	23	28	35	.48	.38	.12	.01		
21	23	28	36	.57	.34	.09	—			20	24	32	32	.71	.23	.03	.03	6.138	.0001
										22	22	30	34	.46	.46	.06	.02		
18	26	32	32	1	—	—	—			20	25	29	34	.71	.19	.08	.02	6.200	.0002
18	28	28	34	1	—	—	—			19	27	29	33	.85	.08	.05	.02	6.204	.0002
20	26	26	36	.71	.14	.14	—	4.154		21	25	27	35	.60	.23	.15	.01		
22	22	28	36	.45	.45	.09	—			19	28	28	33	.85	.07	.07	.02	6.301	.0002
										21	26	26	35	.61	.19	.19	.01		
19	24	31	34	.84	.14	.01	.01												
20	23	30	35	.69	.27	.03	.01	4.262		21	23	31	33	.58	.34	.05	.03	6.378	.0002
19	25	29	35	.84	.11	.04	.01			21	23	32	32	.58	.34	.04	.04	6.490	.0002
18	27	30	33	1	—	—	—	4.348		22	22	31	33	.46	.46	.05	.03	6.497	.0003
21	24	27	36	.59	.28	.13	—	4.496		20	26	28	34	.72	.16	.10	.02	6.505	.0003
										19	27	30	32	.85	.08	.04	.03		
19	24	32	33	.84	.14	.01	.01			22	24	27	35	.50	.32	.16	.02		
21	22	30	35	.55	.41	.04	.01	4.521											
19	26	28	35	.85	.09	.05	.01												
18	27	31	32	1	—	—	—	4.703											
18	28	29	33	1	—	—	—			20	27	27	34	.72	.13	.13	.02	6.593	.0003
21	25	26	36	.60	.22	.18	—	4.710		22	22	32	32	.46	.46	.04	.04	6.602	.0003
22	23	27	36	.48	.38	.14	—			19	27	31	31	.85	.08	.03	.03	6.603	.0004
										23	23	27	35	.41	.41	.17	.02		
19	27	27	35	.85	.07	.07	.01	4.713		20	25	30	33	.71	.19	.06	.03	6.640	.0004
20	23	31	34	.69	.27	.02	.01	4.837		21	24	29	34	.60	.29	.09	.02		
19	25	30	34	.84	.12	.03	.01												
20	24	29	35	.70	.23	.06	.01	5.012		19	28	29	32	.85	.07	.05	.03	6.694	.0005
										22	25	26	35	.51	.26	.21	.02		
18	28	30	32	1	—	—	—			20	25	31	32	.71	.19	.05	.04	6.848	.0006
22	24	26	36	.50	.31	.19	—	5.023		22	23	29	34	.49	.39	.10	.03		
20	23	32	33	.69	.27	.02	.01			19	28	30	31	.85	.07	.05	.04	6.883	.0007
21	22	31	34	.55	.41	.03	.01	5.096		23	24	26	35	.42	.34	.22	.02		

$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$	$\Sigma r_1$	$\Sigma r_2$	$\Sigma r_3$	$\Sigma r_4$	$p_1$	$p_2$	$p_3$	$p_4$	$B_1$	$P$
$n = 6$ (cont.)										$n = 6$ (cont.)									
19	29	29	31	.85	.06	.06	.04	6.974	.0008	22	25	30	31	.52	.28	.11	.09	8.726	.0294
23	25	25	35	.42	.28	.28	.02			23	24	29	32	.43	.36	.14	.07		
20	26	29	33	.72	.16	.08	.03	7.022	.0009	22	26	28	32	.53	.24	.16	.07	8.795	.0321
21	25	28	34	.61	.24	.13	.03			21	28	29	30	.62	.15	.12	.10		
19	29	30	30	.85	.06	.05	.05	7.066	.0010	24	25	26	33	.37	.31	.26	.06	8.859	.0383
24	24	25	35	.35	.35	.28	.02			22	27	27	32	.53	.20	.20	.07		
21	24	30	33	.60	.29	.08	.04	7.077	.0011	23	24	30	31	.44	.36	.11	.09	8.875	.0399
20	27	28	33	.72	.13	.11	.04			21	29	29	29	.62	.12	.12	.12		
21	26	27	34	.61	.20	.16	.03	7.206	.0013	25	25	25	33	.31	.31	.31	.06	8.903	.0432
21	24	31	32	.60	.29	.06	.05			22	26	29	31	.53	.24	.14	.09	8.941	.0444
22	23	30	33	.49	.39	.08	.04	7.283	.0015	23	25	28	32	.45	.30	.17	.08		
20	26	30	32	.72	.16	.07	.05			22	26	30	30	.53	.24	.11	.11	9.052	.0536
22	24	28	34	.50	.32	.14	.03	7.318	.0018	24	24	28	32	.37	.37	.18	.08		
20	26	31	31	.72	.16	.06	.06			22	27	28	31	.53	.20	.17	.10	9.136	.0590
23	23	28	34	.41	.41	.14	.03	7.413	.0020	23	26	27	32	.45	.26	.21	.08		
22	23	31	32	.49	.39	.07	.05			23	25	29	31	.45	.30	.15	.10	9.212	.0718
21	25	29	33	.61	.24	.11	.04	7.489	.0021	22	27	29	30	.54	.20	.14	.12		
20	27	29	32	.72	.14	.09	.05			24	25	27	32	.38	.32	.22	.08	9.307	.0796
22	25	27	34	.51	.27	.18	.03	7.540	.0023	23	25	30	30	.45	.31	.12	.12		
20	28	28	32	.72	.11	.11	.05			24	24	29	31	.37	.37	.15	.10	9.375	.0976
22	26	26	34	.52	.22	.22	.03	7.587	.0028	22	28	28	30	.54	.17	.17	.12		
20	27	30	31	.72	.14	.08	.06			24	26	26	32	.38	.26	.26	.08	9.390	.1069
23	24	27	34	.43	.35	.19	.04	7.675	.0031	24	24	30	30	.38	.38	.12	.12		
21	26	28	33	.61	.20	.14	.05			22	28	29	29	.54	.17	.14	.14	9.454	.1175
21	25	30	32	.61	.25	.09	.06	7.770	.0037	25	25	26	32	.32	.32	.27	.09		
22	24	29	33	.51	.33	.12	.05			23	26	28	31	.46	.26	.18	.10	9.474	.1202
21	27	27	33	.62	.17	.17	.05	7.806	.0041	23	27	27	31	.46	.22	.22	.10		
21	25	31	31	.61	.25	.07	.07			23	26	29	30	.46	.26	.15	.13	9.533	.1328
23	23	29	33	.41	.41	.12	.05	7.831	.0048	24	25	28	31	.38	.32	.19	.11		
20	28	29	31	.73	.12	.10	.06			23	27	28	30	.46	.22	.19	.13	9.543	.1455
23	25	26	34	.43	.29	.24	.04	7.892	.0050	24	26	27	31	.39	.27	.23	.11		
20	28	30	30	.73	.12	.08	.08			24	25	29	30	.39	.32	.16	.13	9.620	.1530
24	24	26	34	.36	.36	.24	.04	7.926	.0055	23	27	29	29	.46	.22	.16	.16		
20	29	29	30	.73	.10	.10	.08			25	25	27	31	.33	.33	.23	.11	9.704	.1888
24	25	25	34	.36	.30	.30	.04	7.944	.0064	23	28	28	29	.46	.19	.19	.16		
22	24	30	32	.51	.33	.10	.06			25	26	26	31	.33	.28	.28	.11	9.858	.2382
21	26	29	32	.62	.21	.12	.06	8.032	.0070	24	26	28	30	.39	.28	.19	.14		
22	25	28	33	.52	.28	.15	.05			24	25	29	30	.39	.32	.16	.13	9.864	.2632
22	24	31	31	.51	.33	.08	.08	8.117	.0076	23	27	29	29	.46	.22	.16	.16		
23	23	30	32	.42	.42	.10	.07			25	25	27	31	.33	.33	.23	.11	9.936	.2923
23	23	31	31	.42	.42	.08	.08	8.121	.0083	23	28	28	29	.46	.19	.19	.16		
21	27	28	32	.62	.17	.14	.06			25	26	26	31	.33	.28	.28	.11	10.012	.3264
22	26	27	33	.52	.23	.19	.05	8.179	.0098	24	26	28	30	.39	.28	.19	.14		
21	26	30	31	.62	.21	.10	.08			24	27	27	30	.40	.23	.23	.14	10.093	.3669
23	24	28	33	.43	.35	.16	.05	8.215	.0106	24	26	29	29	.39	.28	.16	.16		
22	25	29	32	.52	.28	.13	.07			25	25	28	30	.33	.33	.20	.14	10.168	.3906
21	27	29	31	.62	.18	.12	.08	8.308	.0108	25	25	29	29	.33	.33	.17	.17		
23	25	27	33	.44	.30	.20	.06			24	27	28	29	.40	.24	.20	.17	10.170	.4382
21	28	28	31	.62	.15	.15	.08	8.348	.0130	25	26	27	30	.34	.28	.24	.14		
23	26	26	33	.44	.25	.25	.06			25	26	28	28	.40	.20	.20	.20	10.247	.4521
21	27	30	30	.62	.18	.10	.10	8.359	.0152	26	26	26	30	.29	.29	.28	.14		
24	24	27	33	.37	.37	.21	.06			25	26	28	29	.34	.28	.20	.17	10.320	.5826
								8.548	.0168	25	27	27	29	.34	.24	.24	.17		
21	27	29	31	.62	.18	.12	.08			25	27	28	28	.34	.24	.21	.21	10.394	.6081
23	25	27	33	.44	.30	.20	.06	8.610	.0204	26	26	27	29	.29	.29	.24	.17		
21	28	28	31	.62	.15	.15	.08			26	26	28	28	.29	.29	.21	.21	10.471	.6978
23	26	26	33	.44	.25	.25	.06	8.692	.0226	26	26	28	28	.29	.29	.21	.21		
21	27	30	30	.62	.18	.10	.10			26	27	27	28	.29	.25	.25	.21	10.544	.7502
24	24	27	33	.37	.37	.21	.06	8.695	.0248	27	27	27	27	.25	.25	.25	.25		

APPENDIX B. *The distribution of the combined likelihood ratio for general alternatives*

This table gives selected values of the combined likelihood ratio statistics,  $B_1^c$ , together with cumulative probabilities (levels of significance) associated with each tabular value. Only groups of equal size are considered. Thus if  $n$  is the total number of repetitions of the design and three groups are considered, each group contains  $n/3$  repetitions.

$B_1^c$  is computed by adding values of  $B_1$  for each group as obtained from Appendix A. Only values significant at approximately the 0.10 level of significance or higher are recorded and these are selected for easy interpolation.

3 treatments. (Design:  $t = 3, \lambda = 1, b = 3, r = 2, k = 2$ )

$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$	$B_1^c$	$P$
2 equal groups								4 equal groups							
$n = 4$		$n = 6$		$n = 8$		$n = 10$		$n = 8$		$n = 12$		$n = 16$		$n = 20$	
0	·009	0·8293	·002	2·4683	·001	4·3987	·001	1·2042	·003	4·3281	·001	7·9978	·001	11·7538	·001
0·6021	·044	1·6586	·007	3·4452	·006	5·2447	·005	1·8063	·007	5·1807	·005	8·9950	·005	12·7753	·005
1·2042	·079	1·8402	·010	3·9738	·013	5·6469	·010	2·1005	·019	5·5759	·010	9·4390	·010	13·2106	·010
1·4984	·185	2·5112	·026	4·1686	·019	6·2895	·020	2·4084	·023	6·0498	·020	9·9076	·020	13·6708	·020
		2·7093	·048	4·3620	·025	6·4123	·030	2·7026	·045	6·3897	·030	10·0686	·026	13·8394	·025
		2·9064	·078	4·4424	·034	6·6731	·041	2·9968	·062	6·6266	·039	10·1624	·030	13·9669	·030
		3·3405	·142	4·5526	·041	6·8013	·052	3·0104	·068	6·6810	·048	10·3965	·040	14·1835	·040
				4·6696	·050	6·9250	·063	3·3047	·092	6·8791	·061	10·5843	·050	14·3529	·050
				4·9366	·065	6·9514	·069	3·5989	·159	7·0209	·069	10·7074	·060	14·4811	·060
				5·0812	·074	7·0179	·082			7·0995	·080	10·8684	·070	14·6057	·069
										7·2578	·105	10·9854	·080	14·7232	·079
				5·2422	·086	7·0751	·089					11·0658	·092	14·8393	·089
				5·4652	·123	7·1656	·107					11·1320	·101	14·9368	·100
3 equal groups								5 equal groups							
$n = 6$		$n = 9$		$n = 12$		$n = 15$		$n = 10$		$n = 15$		$n = 20$		$n = 25$	
0	·001	2·5112	·001	5·3727	·001	8·0688	·001	1·8063	·001	6·0498	·001	10·7582	·001	15·4283	·001
1·2042	·016	2·7093	·002	6·2191	·005	9·0642	·005	2·4084	·004	7·0762	·005	11·8177	·005	16·4902	·005
1·4984	·030	3·3405	·005	6·6031	·010	9·4794	·010	2·7026	·009	7·5103	·010	12·2791	·010	16·9568	·010
1·8063	·041	3·7357	·011	7·0209	·021	9·8945	·020	3·3047	·022	8·0715	·019	12·8047	·020	17·4901	·020
2·1005	·101	4·1698	·022	7·1379	·026	10·0456	·025	3·5989	·038	8·2687	·026	12·9851	·025	17·6727	·025
		4·5097	·032	7·3265	·030	10·1738	·031	3·6125	·040	8·3240	·030	13·0873	·030	17·8042	·030
		4·5883	·040	7·5199	·039	10·4352	·039	3·9068	·052	8·5221	·040	13·3387	·040	18·0249	·040
		4·7466	·052	7·6341	·049	10·5704	·052	4·2010	·083	8·7425	·049	13·5254	·049	18·2179	·050
		4·9835	·063	7·8146	·059	10·6882	·060	4·2146	·085	8·9174	·060	13·6443	·060	18·3626	·060
		5·0224	·071	7·9079	·068	10·8049	·066	4·4952	·101	9·0592	·068	13·7889	·070	18·4900	·069
		5·2205	·101	8·0181	·083	10·9031	·080			9·1543	·080	13·9161	·080	18·6137	·080
				8·0781	·088	10·9594	·090			9·2961	·089	14·0263	·089	18·7191	·090
				8·1351	·100	10·9858	·097			9·3349	·101	14·1000	·100	18·7831	·100