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A BAYESIAN APPROACH TO SOME MISSING VALUE PROBLEMS

IN ANOVA AND CONTINGENCY TABLES

by

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A Bayesian Approach to some Missing Value Problems in ANOVA and Contingency Tables*

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1. Introduction

Non-Bayesian procedures for dealing with missing values in ANOVA and contingency tables are well-known (see e.g. [3] and [6]). In this paper we derive the appropriate Bayesian procedures for a randomized block design and for an $r \times c$ contingency table. The posterior distributions for the missing observation are also given. This paper shows that the classical non-Bayesian procedures do have a simple and natural Bayesian interpretation.

2. Missing values in a randomized block design.

Suppose that the observations in a b-block $\times$ t-treatment randomized block design are incomplete because y_{11} is missing. Our model for the available observations is

$$y_{ij} = \mu + \tau_j + \beta_i + \epsilon_{ij} \, , \quad (i, j) \neq (1, 1); \; i=1,\dots,b \; ; \; j=1,\dots,t. \tag{2.1}$$

We assume that $\sum_{i=1}^{b} \beta_i = 0$, $\sum_{j=1}^{t} \tau_j = 0$, and the ϵ_{ij}'s are independent and normally distributed with mean zero and variance σ^2. (μ is the over-all mean effect, τ_j $(j=1,\dots,t)$ is the j^{th} treatment effect, and $\beta_i (i=1,\dots,b)$ is the i^{th} block effect).

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We now make the usual "non-informative" assumption that the joint prior distribution of $(\mu, \sigma, \tau_j\text{'s}, \beta_i\text{'s})$ is proportional to $1/\sigma$. From the resulting posterior distribution, μ, σ and the β_i's may be integrated out to obtain the distribution of most interest--the posterior distribution of the τ_j's. The lack of balance caused by the missing observation y_{11} makes this an awkward calculation. If however we introduce y_{11} as a random variable, this balance is restored. Since $y_{11} = \mu + \tau_1 + \beta_1 + \epsilon_1$, the density of y_{11} given $\mu + \tau_1 + \beta_1$ is normal with mean $\mu + \tau_1 + \beta_1$ and variance σ^2. The joint posterior density of $(y_{11}, \mu, \sigma, \tau_j\text{'s}, \beta_i\text{'s})$ is therefore proportional to the product of the conditional normal density of y_{11} and the likelihood of the available observations and σ^{-1}. Hence

$$\text{Post}\,(\mu,\sigma,\tau_j\text{'s},\beta_i\text{'s},y_{11}) \propto \frac{1}{\sigma^2}\exp\left\{\frac{-1}{2\sigma^2}(y_{11}-\mu-\tau_1-\beta_1)^2\right\}\times \begin{array}{l}\text{Likelihood function}\\ \text{for the available}\\ \text{observations}\end{array}$$

$$\propto \frac{1}{\sigma^{tb+1}}\exp\left\{\frac{-1}{2\sigma^2}\left[\sum_{i=1}^{b}\sum_{j=1}^{t}(y_{ij}-\mu-\tau_j-\beta_i)^2\right]\right\}. \tag{2.2}$$

The exponent can be written as

$$\sum_{i=1}^{b}\sum_{j=1}^{t}(y_{ij}-\mu-\tau_j-\beta_i)^2 = tb(\bar{y}-\mu)+b\sum_{j=1}^{t}(\bar{y}_j-\bar{y}-\tau_j)^2 + t\sum_{i=1}^{b}(\bar{y}_i-\bar{y}-\beta_i)^2 + S^2, \tag{2.3}$$

where

$$y_{i.} = \sum_{j=1}^{t} \frac{y_{ij}}{t}, \quad \bar{y}_{.j} = \sum_{i=1}^{b} \frac{y_{ij}}{b}, \quad \bar{y} = \sum_{i=1}^{b} \sum_{j=1}^{t} \frac{y_{ij}}{tb}, \text{ and}$$

$$s^2 = \sum_{i=1}^{b} \sum_{j=1}^{t} (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y})^2$$

Substituting (2.3) into (2.2) we have that

$$\text{Post}\,(\sigma, \tau_j\text{'s}, y_{11}) \propto \frac{1}{\sigma^{tb-b+1}} \exp\left\{\frac{-1}{2\sigma^2}\left[s^2 + b\sum_{j=1}^{t} (\bar{y}_{.j} - \bar{y} - \tau_j)^2\right]\right\} \tag{2.4}$$

$$\times \int \frac{d\mu}{\sigma} \exp\left\{\frac{-tb}{2\sigma^2}(\bar{y} - \mu)^2\right\} \int\limits_{\substack{(b-1)\text{-dimensional} \\ \text{space with } \sum_{i=1}^{b} \beta_i = 0}} \frac{d\beta_1 \cdots d\beta_b}{\sigma^{b-1}} \exp\left\{\frac{-t}{2\sigma^2}\sum_{i=1}^{b} (\bar{y}_{i.} - \bar{y} - \beta_i)^2\right\}$$

$$\propto \frac{1}{\sigma^{tb-b+1}} \exp\left\{\frac{-1}{2\sigma^2}\left[s^2 + b\sum_{j=1}^{t} (\bar{y}_{.j} - \bar{y} - \tau_j)^2\right]\right\}.$$

Denote the missing observation, y_{11}, by x.

Let $\bar{y}' = \bar{y} - \frac{x}{tb}$, $\bar{y}'_{1.} = \bar{y}_{1.} - \frac{x}{t}$, $\bar{y}'_{.1} = \bar{y}_{.1} - \frac{x}{b}$.

It is easily verified that

$$b\sum_{j=1}^{t} (\bar{y}_{.j} - \bar{y} - \tau_j)^2 = \frac{x^2(t-1)}{tb} - 2x(\bar{y}' - \bar{y}'_{.1} + \tau_1)$$

$$+ b\sum_{j=2}^{t} (\bar{y}_{.j} - \bar{y}' - \tau_j)^2 + b(y'_{.1} - y' - \tau_1)^2 \quad , \tag{2.5}$$

and

$$S^2 = \sum_{i=1}^{b} \sum_{j=1}^{t}{}' (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y}')^2 + \frac{x^2(t-1)(b-1)}{tb}$$

$$+ 2x(\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1}) + (\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2 \quad , \tag{2.6}$$

where "/" means $\bar{y}_{1.}$ and $\bar{y}_{.1}$ are to be replaced by $\bar{y}'_{1.}$ and $\bar{y}'_{.1}$ respectively and the summation does not incluse $(i,j) = (1,1)$, i.e.,

$$\sum_{i=1}^{b} \sum_{j=1}^{t}{}' (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} - \bar{y}')^2 = \sum_{i=2}^{b} \sum_{j=2}^{t} (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y}')^2$$

$$+ \sum_{j=2}^{t} (y_{1j} - \bar{y}'_{1.} - \bar{y}_{.j} + \bar{y}')^2 + \sum_{i=2}^{b} (y_{i1} - \bar{y}_{i.} - \bar{y}'_{.1} + \bar{y}')^2 .$$

From (2.5) and (2.6) we have that the coefficients of the x^2 and $2x$ terms from $s^2 + b \sum_{j=1}^{t} (\bar{y}_{.j} - \bar{y} - \tau_j)^2$ are $\left(\frac{t-1}{t}\right)$ and $-(\bar{y}'_{1.} + \tau_1)^2$ respectively.

Since

$$\left(\frac{t-1}{t}\right) x^2 - 2x(\bar{y}'_{1.} + \tau_1) = \left(\frac{t-1}{t}\right)\left[x - \frac{(\bar{y}'_{1.}+\tau_1)t}{t-1}\right]^2 - \frac{(\bar{y}'_{1.}+\tau_1)^2 t}{t-1}$$

we have that

$$\text{Post }(\sigma, \tau_j\text{'s}) \propto \frac{1}{\sigma^{tb-b}} \exp\left\{\frac{-1}{2\sigma^2}\left[\sum_{i,j}{}' (\bar{y}_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y}')^2 + (\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2 \right.\right.$$

$$\left.\left. + b\sum_{j=2}^{t} (\bar{y}_{.j} - \bar{y}' - \tau_j)^2 + b(\bar{y}'_{.1} - \bar{y}' - \tau_1)^2 - \frac{(\bar{y}'_{1.}+\tau_1)^2 t}{t-1}\right]\right\}. \tag{2.7}$$

If is easily shown that

$$(\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2 + b(\bar{y}'_{.1} - \bar{y}' - \tau_1)^2 - \frac{(\bar{y}'_{1.}+\tau_1)^2 t}{t-1} =$$

$$= \left(\frac{bt-b-t}{t-1}\right)\left[\tau_1 - \frac{\{b(t-1)(\bar{y}'_{.1} - \bar{y}') + t\bar{y}'_{1.}\}}{bt-b-t}\right]^2 - \frac{(b+t)}{bt-b-t}(\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2$$

Hence

$$\text{Post } (\tau_j\text{'s} \mid \text{available data}) \propto \frac{1}{[c^2+(\tau-a)'M(\tau-a)]^{\frac{tb-b-1}{2}}}, \quad \sum_{j=1}^{t} \tau_j = 0, \tag{2.8}$$

where

$$a = \left(\frac{b(t-1)(\bar{y}'_{.1}-\bar{y}')+t\,\bar{y}'_{1.}}{bt-b-t},\ \bar{y}_{.2}-\bar{y}',\ldots,\bar{y}_{.t}-\bar{y}'\right)'$$

$$\tau = (\tau_1,\ldots,\tau_t),$$

$$\underset{t\times t}{M} = \begin{pmatrix} \frac{bt-b-t}{t-1} & & & \\ & b & & 0 \\ & & \ddots & \\ & 0 & & b \end{pmatrix},$$

and

$$c^2 = \sum_{i,j}{}'(y_{ij}-\bar{y}_{i.}-\bar{y}_{.j}+\bar{y}')^2 - \frac{(b+t)}{bt-b-t}(\bar{y}'-\bar{y}_{1.}-\bar{y}'_{.1})^2$$

The posterior density, (2.8), is constant where $(\tau-a)'M(\tau-a)$ is constant. The surfaces $(\tau-a)'M(\tau-a) = c$ are ellipsoids in the (t-1)-dimensional spare with $\sum_{j=1}^{t}\tau_j = 0$. The density decreases as the distance from the center of the ellipsoids increases. Hence a confidence region is an ellipsoid. The same argument as used in proving theorem 6.4.1 in [5] shows that if

$$\phi = \frac{(\tau-a)'M(t-a)/(t-1)}{c^2/(t-1)(b-1)-1},$$

then

$$\text{Post}\ (\phi \mid \text{available observations}) \propto \frac{\phi^{\frac{t-3}{2}}}{[(t-1)+[(t-1)(b-1)-1]\phi]^{\frac{tb-b-1}{2}}} \tag{2.9}$$

and hence

$$\frac{(\tau-a)'M(\tau-a)/(t-1)}{c^2/(t-1)(b-1)-1} \sim F_{t-1,\ (t-1)(b-1)-1}. \tag{2.10}$$

An α-level test of the null hypothesis that there are no treatment effects is therefore to declare the results significant if

$$\frac{a'Ma/(t-1)}{c^2/(t-1)(b-1)-1} > F^{(1-\alpha)}_{t-1,\ (t-1)(b-1)-1}$$

If no observations are missing, then it can be verified that the posterior distribution of $\phi_1 = \dfrac{(t-a_1)'M_1(\tau-a_1)(t-1)}{s^2/(t-1)(b-1)}$ is $F_{t-1,(t-1)(b-1)}$

where $a_1 = (\bar{y}_{.1} - \bar{y}, \bar{y}_{.2} - \bar{y}, \ldots, \bar{y}_{.t} - \bar{y})$

and $\underset{t\times t}{M_1} = \begin{pmatrix} b & & 0 \\ & b & \\ 0 & & b \end{pmatrix}$.

This is the same as the sampling result. The effect of the missing observation is to decrease the error degrees of freedom by unity. In the analysis a_1, M_1 and s^2 should be replaced by a, M and c^2 respectively.

We have from (2.4) that

$$\text{Post }(x,\sigma) \propto \frac{1}{\sigma^{tb-b-t+2}} \exp\left\{\frac{-S^2}{2\sigma^2}\right\} \int_{\substack{(t-1)\text{-dimensional}\\ \text{spare with } \sum \tau_j = 0}} \frac{d\tau_1 \ldots d\tau_t}{\sigma^{t-1}} \exp\left\{\frac{-1}{2\sigma^2}\left[b \sum_{j=1}^{t} (\bar{y}_{.j} - \bar{y} - \tau_j)^2\right]\right\} \tag{2.11}$$

$$\propto \frac{1}{\sigma^{tb-b-t+2}} \exp\left\{\frac{-S^2}{2\sigma^2}\right\}$$

Hence, using the expression for S^2 given by (2.6),

$$\text{Post }(x,\sigma) \propto \frac{1}{\sigma^{tb-b-t-2}} \exp\left\{\frac{-1}{2\sigma^2}\left[\sum_{i,j}{}' (y_{ij} - \bar{y}_{i.} - \bar{y}_{.j} + \bar{y}')^2 \right.\right. \tag{2.12}$$

$$+ x^2 \frac{(t-1)(b-1)}{tb} + 2x(\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})$$

$$\left.\left. + (\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2\right]\right\}$$

$$\propto \frac{1}{\sigma^{tb-b-t+2}} \exp\left\{\frac{-1}{2\sigma^2}\left[\sum_{i,j}{}' (y_{ij} - \bar{y}_{.j} - \bar{y}_{i.} + \bar{y}')^2 - \frac{(b+t-1)}{(t-1)(b-1)} (\bar{y}' - \bar{y}_{1.} - \bar{y}'_{.1})^2\right.\right.$$

$$\left.\left. + \frac{(t-1)(b-1)}{tb}\left[x - \frac{(\bar{y}'_{1.} + \bar{y}'_{.1} - \bar{y}')tb}{(t-1)(b-1)}\right]^2\right]\right\}$$

upon completing the square with respect to x. Therefore the posterior distribution for the missing observation x is given by

$$\text{Post }(x) \propto \frac{1}{\left[D^2 + \frac{(t-1)(b-1)}{tb} \left(x - \frac{(\bar{y}'_{1.} + \bar{y}'_{.1} - \bar{y}')tb}{(t-1)(b-1)} \right)^2 \right]^{\frac{tb+b-t+1}{2}}} \tag{2.13}$$

where $D^2 = \sum_{i,j}' (y_{ij} - \bar{y}_{.j} - \bar{y}_{i.} + \bar{y}')^2 - \frac{(b+t-1)}{(t-1)(b-1)} (\bar{y}' - \bar{y}'_{1.} - \bar{y}'_{.1})^2$.

Notice that

$$\frac{(\bar{y}'_{1.} + \bar{y}'_{.1} - \bar{y}')tb}{(t-1)(b-1)} = \frac{bB + t\tau - b}{(t-1)(b-1)} = \text{yates estimator for the missing observation } x, \tag{2.14}$$

where $G = t\,b\,\bar{y}' =$ Grand total of the available observations,

$B = t\,\bar{y}'_{1.} =$ total of the remaining units in the block where the missing unit appears,

$\tau = b\,\bar{y}'_{.1} =$ total of the yields of this treatment in the other blocks

From (2.13) we have that

$$\text{Post }(x) \propto \frac{1}{\left[1 + \frac{(t-1)(b-1)}{tb} \left(\frac{x - \mu(x)}{D} \right)^2 \right]^{\frac{(t-1)(b-1)}{2}}} \tag{2.15}$$

where $\mu(x)$ is the Yates estimator for x and is given by (2.14).

If we let

$$\tau = \sqrt{\frac{(tb-b-t)(t-1)(b-1)}{tb}} \left(\frac{x - \mu(x)}{D} \right) ,$$

then

$$\text{Post}(v) \propto \frac{1}{\left[1 + \frac{v^2}{tb-b-t}\right]^{\frac{(t-1)(b-1)}{2}}} \quad \text{,i.e.} \tag{2.16}$$

v is distributed as a student-t random variable with $(tb-b-t) = (t-1)(b-1)-1$ degrees of freedom. It is interesting to note that if x is replaced by $\mu(x)$ in (2.6), then S^2 is identical to D^2. Inferences about the missing observation x should be made by referring to (2.16)

3. Missing values in contingency tables.

Let n_{ij} be the cell frequency in the $(ij)^{th}$ cell in an $r \times c$ contingency table. Let p_{ij} be the probability that an observation lies in the $(ij)^{th}$ cell. If no cell frequencies are missing, then under the null hypothesis of no association between rows and columns

$$p_{ij} = p_i\, q_j \;, \; i = 1,\ldots,r_j \; j=1,\ldots, c, \tag{3.1}$$

where the p_i's (q_j's) are the probabilities of an observation falling into the i^{th} row (j^{th} column), $\sum_{i=1}^{r} p_i = \sum_{j=1}^{c} q_j = 1.$

If n_{11} is missing, then under the null hypothesis the joint distribution of the available n_{ij}'s is given by an $(rc-1)$ - nomial distribution with cell probabilities

$$p'_{ij} = \frac{p_i q_j}{1-p_1 q_1} \;, \; i=1,\ldots,r;\; j=1,\ldots, c;\; (i,j) \neq (1,1) \tag{3.2}$$

Let N be the total of available frequencies.

The likelihood function for the available frequencies is

$$L = \prod_{(i,j)\neq(1,1)}^{(r,c)} \left(\frac{p_i q_j}{1-p_1 q_1}\right)^{n_{ij}} . \tag{3.3}$$

Let the prior distribution for the missing frequency n_{11}, $p(n_{11})$ say, be given by the negative binomial distribution

$$p(n_{11}) = \binom{N+n_{11}-1}{n_{11}} (p_1\, q_1)^{n_{11}} (1-p_1 q_1)^N, \; n_{11} = 0,1,2,\ldots \tag{3.4}$$

The choice of (3.4) for the prior distribution of n_{11} can be motivated by noting that if n_{11} were not missing, then the marginal probability of observing n_{11} in the first cell would equal $\binom{N+n_{11}}{n_{11}}(p_1 q_1)^{n_{11}}(1-p_1 q_1)^N$.

We replace $\binom{N+n_{11}}{n_{11}}$ by $\binom{N+n_{11}-1}{n_{11}}$ so that $\sum_{n_{11}=0}^{\infty} p(n_{11}) = 1$.

If the prior distribution of $(p_1,\ldots,p_r,q_1,\ldots,q_c)$ is proportional to

$\prod_{(i,j)=(1,1)}^{(r,c)} (p_i q_j)^{m_{ij}}$, then the posterior distribution of the p_i's, q_j's

and n_{11} is proportional to

$$\binom{N+n_{11}-1}{n_{11}} (p_1q_1)^{n_{11}} (1-p_1q_1)^{N} \prod_{(i,j)\neq(1,1)}^{(r,c)} \left(\frac{p_i q_j}{1-p_1q_1}\right)^{n_{ij}} \prod_{(i,j)=(1,1)}^{(r,c)} (p_iq_j)^{m_{ij}} . \tag{3.5}$$

In the derivation below we take all m_{ij} equal to zero. Non-zero values can usually be introduced at the end. From (3.5) we than have that the joint posterior distribution of the p_i's and q_j's is given by

$$\text{Post } (p_i\text{'s}, q_j\text{'s}) \propto \sum_{n_{11}=0}^{\infty} \binom{N+n_{11}-1}{n_{11}} (p_1q_1)^{n_{11}} (1-p_1q_1)^{N} \prod_{(i,j)\neq(1,1)}^{(r,c)} \left(\frac{p_iq_j}{1-p_1q_1}\right)^{n_{ij}}$$

$$\propto \prod_{(i,j)\neq(1,1)}^{(r,c)} \left(\frac{p_iq_j}{1-p_1q_1}\right)^{n_{ij}} \tag{3.6}$$

Jeffreys (see [4]) showed that the joint posterior density (3.6) can, as $N \to \infty$, be approximated by the normal density with exponent $-\frac{1}{2}\chi^2$, where

$$\chi^2 = \sum_{(i,j)\neq(1,1)}^{(r,c)} \frac{\left(n_{ij}-Np'_{ij}\right)^2}{Np'_{ij}} . \tag{3.7}$$

χ^2 is an approximation to the likelihood ratio statistic

$$C = -2 \sum_{(i,j)\neq(1,1)}^{(r,c)} n_{ij} \quad \log \left(\frac{N\,p'_{ij}}{n_{ij}}\right) \tag{3.8}$$

The exact posterior distribution of C is obtainable by using the methods of Watson [7].

The quantity χ^2 has the $\chi^2_{(r\ c)-1}$ distribution as $N \to \infty$. Hence, using theorem 7.5.1 in [5],

$$\tilde{\chi}^2 = \sum_{(i,j)\neq(1,1)}^{(r,c)} \frac{\left(n_{ij}-N\,\hat{p}'_{ij}\right)^2}{N\,\hat{p}'_{ij}} \tag{3.9}$$

has the $\chi^2_{(rc-2)-(r+c-2)=(r-1)(c-1)-1}$ distribution as $N \to \infty$. The $\hat{p}'_{ij}$'s are the maximum likelihood estimates for the p_{ij}'s assuming that the null hypothesis of no association between rows and columns is true. Watson [6] showed that the M.L. estimates of the p_i's, q_j's and n_{11} are given by

$$\left\{\begin{array}{l} \hat{p}_1 = \dfrac{R_1+\hat{n}_{11}}{N+\hat{n}_{11}} \;,\quad \hat{p}_i = \dfrac{R_i}{N+\hat{n}_{11}} \;,\quad (i = 2, \ldots, r) \\[2ex] \hat{q}_1 = \dfrac{C_1+\hat{n}_{11}}{N+\hat{n}_{11}} \;,\quad \hat{q}_j = \dfrac{C_j}{N+\hat{n}_{11}} \;,\quad (j = 2,\ldots,c) \\[2ex] \hat{n}_{11} = \dfrac{R_1 C_1}{N-R_1-C_1} \quad = \dfrac{N\,\hat{p}_1\hat{q}_1}{1-\hat{p}_1\hat{q}_1} \end{array}\right. \tag{3.10}$$

where R_i $(i=1,\ldots,r)$ and $C_j(j=1,\ldots,c)$ are the existing row and column totals. From (3.10) we find that the $\hat{p}'_{ij}$'s are given by

$$\hat{p}'_{1j} = \frac{R_1 C_j}{N(N-C_1)} \quad , \quad (j=2,\ldots,c)$$

$$\hat{p}'_{i1} = \frac{C_1 R_i}{N(N-R_1)} \quad , \quad (i=2,\ldots,r) \tag{3.11}$$

$$\hat{p}'_{ij} = \frac{R_i C_j (N-R_1-C_1)}{N(N-R_1)(N-C_1)} \quad , \quad (i=2,\ldots,r\,;j=2,\ldots,c)$$

The test given by (3.9) is, operationally, the same as the sampling result.

The joint distribution of $(p_1,\ldots,p_r;q_1,\ldots,q_c;n_{11})$ can be rewritten as

$$\text{Post } (p_i\text{'s},q_j\text{'s},n_{11}) \propto \binom{N+n_{11}-1}{n_{11}} p_1^{\,R_1+n_{11}} q_1^{\,C_1+n_{11}} \prod_{i=2}^{r} p_i^{\,R_i} \prod_{j=2}^{c} q_j^{\,C_j} \tag{3.12}$$

From the normalizing constant of the Dirichlet distribution we know that

$$\int_{S_1} p_1^{R_1+n_{11}} \prod_{i=2}^{r} p_i^{R_i} \, d\,p_1 \ldots d\,p_r = \prod_{i=2}^{r} \frac{R_i!(n_{11}+R_1)!}{(N+n_{11}+r-1)!} \quad ;$$

where $S_1 = \left\{ \text{all } p_i \text{ in } (0,1), \sum_{i=1}^{r} p_i = 1 \right\}$

and

$$\int_{S_2} q_1^{C_1+n_{11}} \prod_{j=2}^{c} q_j^{C_j} dq_1 \ldots dq_c = \prod_{j=2}^{c} \frac{C_j!(n_{11}+C_1)!}{(N+n_{11}+C-1)!} \quad ;$$

where $S_2 = \left\{ \text{all } q_j \text{ in } (0,1), \sum_{i=1}^{c} q_j = 1 \right\}$.

Therefore

$$\text{Post } (n_{11}) \propto \frac{(n_{11}+R_1)! \ (n_{11}+C_1)! \binom{N+n_{11}-1}{n_{11}}}{(N+n_{11}+r-1)! \ (N+n_{11}+c-1) \ !} \quad , \quad n_{11} = 0,1,\ldots \qquad (3.13)$$

We use Barnes'(see [2]) asymptotic series for $\log \Gamma(x + h)$,

$$\log \Gamma(x+h) = \log \sqrt{2\pi} + (x+h-\tfrac{1}{2}) \log x - x - \sum_{p=1}^{m} \frac{(-1)^p B_{p+1}(h)}{p\,(p+1)\,x^p} + R_{m+1}(x), \qquad (3.14)$$

where the B_p (h)'s are the Bernouille polynomial and $R_{m+1}(x) = O(x^{-(m+1)})$, to obtain the large sample distribution for the missing frequency n_{11}. We find that log Post (n_{11}) is proportional to

$$(n_{11}+R_1+\tfrac{1}{2})\log(\hat{n}_{11}+R_1)+(n_{11}+C_1+\tfrac{1}{2})\log(\hat{n}_{11}+C_1)-(N+n_{11}+r+c-\tfrac{1}{2})\log(N+\hat{n}_{11})$$

$$-\log\Gamma(n_{11}+1)+(N-C_1-R_1-\hat{n}_{11})+\sum_{p=1}^{m}\left\{\frac{(-1)^p}{p(p+1)(N+\hat{n}_{11})^p}\right. \tag{3.15}$$

$$\left.[B_{p+1}(n_{11}-\hat{n}_{11}+r)+B_{p+1}(n_{11}-\hat{n}_{11}+c)-B_{p+1}(n_{11}-\hat{n}_{11}+c)-B_{p+1}(n_{11}-\hat{n}_{11})]\right\}$$

$$-\sum_{p=1}^{m}\frac{(-1)^p}{p(p+1)}\; B_{p+1}(n_{11}-\hat{n}_{11}+1)\left[\frac{1}{(\hat{n}_{11}+R_1)^p}+\frac{1}{(\hat{n}_{11}+C_1)^p}\right]$$

$$+\;O\left\{\max\left((\hat{n}_{11}+R_1)^{-(m+1)},\ (\hat{n}_{11}+C_1)^{-(m+1)}\right)\right\}.$$

Using the identity (see e.g. [1])

$$B_n(x+h)=\sum_{k=0}^{n}\binom{n}{k}B_k(x)\,h^{n-k} \tag{3.16}$$

$$\log \text{Post}(n_{11}) \propto (n_{11}+R_1+\tfrac{1}{2}) \log(\hat{n}_{11}+R_1)+(n_{11}+C_1+\tfrac{1}{2})\log(\hat{n}_{11}+C_1)$$

$$-(N+n_{11}+r+c-\tfrac{1}{2})\log (N+\hat{n}_{11}) - \log \Gamma(n_{11}+1) + (N-C_1-R_1-\hat{n}_{11})$$

$$+\sum_{p=1}^{m}\sum_{k=0}^{p+1} \frac{(-1)^p \binom{p+1}{k}}{p\ (p+1)} B_k(n_{11}-\hat{n}_{11})\times$$

$$\times \left\{a_k\left(\frac{r^{p+1-k}+c^{p+1-k}}{(N+\hat{n}_{11})^p}\right)\frac{-1}{(\hat{n}_{11}+R_1)^p} - \frac{-1}{(\hat{n}_{11}+C_1)^p}\right\} \qquad (3.17)$$

$$+ O\left\{\max\left((\hat{n}_{11}+R_1)^{-(m+1)},\ (\hat{n}_{11}+C_1)^{-(m+1)}\right)\right\},$$

where

$$a_k = \begin{cases} 1, & k = 0, 1, \ldots, p \\ \tfrac{1}{2}, & k = p + 1. \end{cases}$$

Hence

$$\text{Post}\ (n_{11}) \propto \frac{(\hat{n}_{11}+R_1)^{n_{11}}\ (\hat{n}_{11}+C_1)^{n_{11}}\ (N+\hat{n}_{11})^{-n_{11}}}{n_{11}\ !} + \text{remainder which goes to zero as the observed frequencies} \to \infty\ . \qquad (3.18)$$

Using the relationships given by (3.10) we thus have that the large sample posterior distribution of n_{11} is the Poisson distribution with mean $\hat{n}_{11} = \dfrac{N\,\hat{p}_1\hat{q}_1}{1-\hat{p}_1\hat{q}_1}$, i.e.,

$$\text{Post}\,(n_{11}) = \frac{\exp\left\{-\dfrac{N\,\hat{p}_1\hat{q}_1}{1-\hat{p}_1\hat{q}_1}\right\}\left(\dfrac{N\,\hat{p}_1\hat{q}_1}{1-\hat{p}_1\hat{q}_1}\right)^{n_{11}}}{n_{11}\,!}\ , \quad n_{11} = 0,\ 1, 2, \ldots\ .$$

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Non-Bayesian procedures for dealing with missing values in ANOVA and contingency tables are well-known In this paper we derive the appropriate Bayesian procedures for a randomized block design and for and r × c contingency table. The posterior distributions for the missing observation are given. This paper shows that the classical non-Bayesian procedures do have a simple and natural Bayesian interpretation.

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