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A Gibbs sampling algorithm that estimates the Q-matrix for the DINA model

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HIGHLIGHTS

- A saturated Multinomial model is used to overcome correlated attributes.
- Closed form posteriors for sampling guess and slip parameters are found.
- A relabeling algorithm that accounts for label switching is presented.

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ABSTRACT

Cognitive diagnostic assessment has drawn more attention in recent years, which attempts to evaluate whether an examinee has mastered those cognitive skills or attributes being measured in an assessment. To achieve this objective, a variety of cognitive diagnosis models have been developed. The core element of these models is the Q-matrix, which is a binary matrix that establishes item-to-attribute mapping in an exam. Traditionally, the Q-matrix is fixed and designed by domain experts. However, there are concerns that some domain experts might neglect certain attributes, and that different experts could have different opinions. It is therefore of practical importance to develop an automated method for estimating the attribute-to-item mapping, and the purpose of this study is to develop a Markov Chain Monte Carlo (MCMC) algorithm to estimate the Q-matrix in a Bayesian framework.

1. Introduction

Cognitive diagnostic assessment (CDA) is a framework that aims to evaluate whether an examinee has mastered or possessed a particular cognitive skill called an *attribute* (Leighton & Gierl, 2007). The last 20 years have seen the development of a few cognitive diagnosis models (CDMs), such as the deterministic input, noisy "and" gate (DINA) model (Junker & Sijtsma, 2001), the noisy input, deterministic "and" gate (NIDA) model (Maris, 1999), and the reparameterized unified model (RUM) (DiBello, Stout, & Roussos, 1995; Hartz, 2002). The core element of these models is the Q-matrix (Tatsuoka, 1983), which is a binary matrix that establishes item-to-attribute mapping in an exam (see Table 1).

The DINA model is a popular CDM that has been widely used. The DINA model, in which an examinee is viewed as either having or not having a particular attribute, is parsimonious and easy to interpret. Whether examinee i possesses attribute k is typically denoted as α_{ik}, a dichotomous latent response variable with values of 0 or 1 indicating absence or presence of a skill, respectively. The DINA model is conjunctive. That is, in order to correctly answer item j, examinee i must possess all the required attributes. Whether examinee i ($i = 1, \ldots, I$) is able to correctly answer item j ($j = 1, \ldots, J$) is defined by another latent response variable η_{ij},

$$\eta_{ij} = \prod_{k=1}^{K} \alpha_{ik}^{q_{jk}}. \tag{1}$$

The latent response variable η_{ij} is related to observed item performance X_{ij} according to the guess parameter,

$$g_j = P(X_{ij} = 1 | \eta_{ij} = 0),$$

and the slip parameter,

$$s_j = P(X_{ij} = 0 | \eta_{ij} = 1).$$

In other words, g_j represents the probability of $X_{ij} = 1$ when at least one required attribute is lacking, and s_j denotes the probability of $X_{ij} = 0$ when all required attributes are present. $1 - s_j$ indicates the probability of a correct response for an examinee classified as having all required skills. The item response function (IRF) for item j is

$$P(X_{ij} = 1 | \boldsymbol{\alpha}_i) = (1 - s_j)^{\eta_{ij}} g_j^{1-\eta_{ij}}, \tag{2}$$

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Table 1
Q-matrix.

Item	Attributes	
	Addition	Subtraction
$2+3$	1	0
$4-2$	0	1
$2+3-1$	1	1

and, when local independence and independence among examinees are assumed, the joint likelihood function for all responses is expressed as

$$P(X_{ij}=x_{ij}|\boldsymbol{\alpha}_i)=\prod_{i=1}^{I}\prod_{j=1}^{J}\left((1-s_j)^{x_{ij}}s_j^{1-x_{ij}}\right)^{\eta_{ij}}\left(g_j^{x_{ij}}(1-g_j)^{1-x_{ij}}\right)^{1-\eta_{ij}}.$$

It should be noted that the monotonicity constraint, $1-s_j > g_j$, should be placed in the estimation in order to enhance the interpretability of the DINA model. Junker and Sijtsma (2001) observe that the monotonicity does not always hold for the DINA model if no constraint is imposed.

To illustrate, we use the Q-matrix (Table 1) for the DINA model to assess whether an examinee has acquired addition (attribute 1) and subtraction (attribute 2). The examinee has to possess attribute 1 in order to correctly answer the first item. Let $g_1 = g_3 = 0.1$ and $s_1 = s_3 = 0.2$. Suppose that $(1, 0)$ be the attribute status of the examinee. Accordingly $\eta_{11} = 1$, and the probability of the examinee correctly answering the first item is $1-s_1 = 0.8$. In answering item 3, as the examine has not acquired the subtraction attribute, consequently $\eta_{13} = 0$. Therefore the probability of the examinee correctly answering item 3 is $g_3 = 0.1$.

Traditionally, the Q-matrix is fixed and designed by domain experts. This could raise some issues. While some of the exams are written with the purpose of being CDAs, their Q-matrices are not specified during exam development and therefore have to be assigned after the fact. Even when the Q-matrix is specified during the stage of exam development, there are concerns that domain experts might neglect some attributes or have different opinions. For instance, DeCarlo (2011) remarks that virtually every researcher who has considered the fraction subtraction data (Tatsuoka, 1990) has suggested different modifications of the Q-matrix (e.g., Henson, Templin, & Willse, 2009; Tatsuoka, 1990, 2002; de la Torre, 2008, 2009; de la Torre & Douglas, 2004). Therefore, it is of practical importance to develop an automated method for estimating the Q-matrix. Despite the need of an automated Q-matrix searching method, related research is still limited. The objective of this research is to develop an MCMC algorithm for estimating the Q-matrix in a Bayesian framework. Explicitly, we assume that all of the Q-matrix entries are unknown and attempt to extract the entire Q-matrix from data.

Estimating the whole Q-matrix is not an easy task, in that the number of possible Q-matrices grows quickly as the number of Q-matrix elements increases. For example, the following simulation estimates a 15 by 4 Q-matrix, which gives $2^{60}/4!$ possible Q-matrices when column permutation is considered. Following the suggestions by DeCarlo (2012) and Templin and Henson (2006) that Bayesian method is simple and useful in estimating the Q-matrix under confirmatory conditions where some Q-matrix entries are known, this study expands the Bayesian concept and develops a Gibbs Sampler to estimate the Q-matrix in an exploratory manner where the whole Q-matrix is unknown.

A few studies that address the issue of estimating the Q-matrix have emerged (e.g., Barnes, 2003; Chen, Culpepper, Chen, & Douglas, 2018; Chen, Liu, Xu, & Ying, 2015; Chiu, 2013; DeCarlo, 2012; Desmarais, 2012; Henson & Templin, 2007; Liu, Xu, & Ying, 2012; Templin & Henson, 2006; de la Torre, 2008; Winters, 2006; Xu & Desmarais, 2016). In particular, Templin and Henson (2006) first advance a Bayesian procedure to verify some uncertain Q-matrix entries for the DINA model. In their procedure, uncertain Q-matrix entries in terms of subjective probabilities are specified first, and posterior probabilities of Q-matrix entries are the likelihood of an attribute required for a successful response to an item. Subsequently, DeCarlo (2012) applies the same Bayesian procedure to different Q-matrix conditions. However, unlike Templin and Henson (2006) and DeCarlo (2012) indicates that the recovery rate is not always 100% and the recovery is poor in some conditions where there is complete uncertainty as to whether an attribute should be included or not. Nevertheless, DeCarlo (2012) concludes that the Bayesian approach is in general helpful to determine which attributes should be included or excluded for each item. Extending Templin and Henson (2006) in an exploratory manner, Chung (2014) advances a Gibbs Sampler for estimating the whole Q-matrix, which is in fact a preceding version of this paper. Chen et al. (2018) later also use a Bayesian procedure that incorporates the identifiability conditions (Chen et al., 2015) to estimate the Q-matrix.

2. Proposed Gibbs sampling algorithm

The setting for the estimation is comprised of item responses from I examinees to J items that measure K attributes. In order to estimate the J by K Q-matrix, the following steps are performed sequentially at iteration t, $t = 1, \ldots, T$. It should be noted that three basic assumptions are required in estimating the Q-matrix (see Tatsuoka, 1983, 1990). First, no two columns are identical in the Q-matrix. Second, an item measures at lease one attribute, and finally each attribute is measured by at least one item. The following algorithm is implemented in R R Development Core Team (2017). The R code can be downloaded from https://github.com/mengtachung/JMP.

Step 1: Binary Decimal Conversion

With K attributes, there are a total of 2^K *possible* attribute patterns for examinee i. Let $2^K = M$, and let the matrix, $\boldsymbol{x}_{M\times K} = (x_{mk})_{M\times K}$, be the binary matrix of *possible* attribute patterns. Each of the M rows in $\boldsymbol{x}$ is a binary number that represents a possible attribute pattern, which is converted to a decimal number by $(b_n b_{n-1}\cdots b_0)_2 = b_n(2)^n + b_{n-1}(2)^{n-1} + \cdots + b_0(2)^0$, where $(b_n b_{n-1}\cdots b_0)_2$ denotes a binary number.

After the conversion, these M possible attribute patterns become a Multinomial distribution. To estimate correlated attributes, a saturated Multinomial model is used that assumes no restrictions on the probabilities of the attribute patterns (see Maris, 1999). Assuming a Dirichlet prior $\boldsymbol{\theta}$, the hierarchical model for estimating attributes is

$$\boldsymbol{x}|\boldsymbol{\theta} \sim Multinomial(M, \boldsymbol{\theta}),$$
$$\boldsymbol{\theta} \sim Dirichlet(a_1, a_2, \ldots, a_M).$$

Step2: Updating Probability of Attribute Pattern

Let $\boldsymbol{y}$ and $\boldsymbol{q}$ be the data and the Q-matrix. Because the conjugate prior for a Multinomial distribution is a Dirichlet distribution, the posterior $p(\boldsymbol{\theta}|\boldsymbol{x}) \propto p(\boldsymbol{x}|\boldsymbol{\theta})p(\boldsymbol{\theta})$ is also a Dirichlet distribution. Therefore, use $Dirichlet(1, 1, \ldots, 1)$ as the prior, and the conditional posterior is distributed as $Dirichlet(1+y_1, 1+y_2, \ldots, 1+y_M)$, where y_ℓ $(\ell = 1, \ldots, M)$ is the number of examinees possessing the ℓ^{th} attribute pattern. As no function in R can be used to sample from the Dirichlet distribution, Gamma distributions are used to construct the Dirichlet distribution. Suppose that $w_1, \ldots, w_M$ are distributed as $Gamma(a_1, 1), \ldots, Gamma(a_M, 1)$, and let $\tau = w_1 + \cdots + w_M$. Then $(w_1/\tau, w_2/\tau, \ldots, w_M/\tau)$ is distributed as $Dirichlet(a_1, a_2, \ldots, a_M)$.

For each of the M possible attribute patterns, we calculate the total number of examinees $(y_1, y_2, \ldots, y_M)$ falling into an attribute pattern, and then sample from $Gamma(1 + y_1, 1) = w'_1, Gamma(1 + y_2, 1) = w'_2, \ldots, Gamma(1 + y_M, 1) = w'_M$. Let $\tau' = w'_1 + w'_2 + \cdots + w'_M$, and we can get the posterior distribution $p(\boldsymbol{\theta}|\boldsymbol{x}) \propto p(\boldsymbol{x}|\boldsymbol{\theta})p(\boldsymbol{\theta}) = (w'_1/\tau', w'_2/\tau', \ldots, w'_M/\tau')$ (see Devroye, 1986). This posterior $p(\boldsymbol{\theta}|\boldsymbol{x})$ is used as the prior $p(\boldsymbol{\theta})$ in the upper stage of the hierarchical model. With the updated prior and the likelihood of each possible attribute pattern, we obtain the full conditional posterior, $p(\boldsymbol{\theta}|\boldsymbol{y}) \propto p(\boldsymbol{y}|\boldsymbol{\theta})p(\boldsymbol{\theta}) = p(\boldsymbol{y}|\boldsymbol{\theta})(w'_1/\tau', w'_2/\tau', \ldots, w'_M/\tau')$.

Step 3: Updating Attribute

The full conditional posterior distribution is sampled using the discrete version of inverse transform sampling. Let the posterior $(p_1, p_2, \ldots, p_M)$ be the PMF of the M possible attribute patterns. The CDF is computed by adding up the probabilities for the M points of the distribution. To sample from this discrete distribution, we partition $(0, 1)$ into M subintervals $(0, p_1), (p_1, p_1 + p_2), \ldots, (\sum_{m=0}^{M} p_{m-1}, \sum_{m=0}^{M} p_m)$, and then generate a value u from $Uniform(0, 1)$.

Updating the attribute state of examinee i is achieved by checking which subinterval the value u falls into. This subinterval number (a decimal number) is then converted to its corresponding binary number (see step 1), which represents the attribute state of examinee i. After steps 1 to 3 are carried out, attribute states for all examinees, denoted as $\boldsymbol{\alpha}$, are obtained for iteration t. It is noteworthy that the first 3 steps can also be used to estimate $\boldsymbol{\alpha}$ in the NIDA model and the RUM (see Chung & Johnson, 2017).

Step 4: Updating Guess and Slip Parameters

In general, posterior distributions are not available in closed forms and therefore are usually approximated by MCMC sampling. The DINA model has distinctive features, and we derive closed forms of the full conditional posteriors for guess and slip parameters as follows.

With the estimated attribute states from step 3, this step updates g_j and s_j. $Beta(1, 1)$, which is equal to $Uniform(0, 1)$, is chosen as the prior for both g_j and s_j. Because the conjugate prior for a Binomial distribution is a Beta distribution, the full conditional posteriors of the guess and slip parameters are also Beta distributions. In the DINA model, for examinee i answering item j, *guess* occurs when $\eta_{ij} = 0$ but $y_{ij} = 1$, and *slip* happens when $\eta_{ij} = 1$ but $y_{ij} = 0$. Consequently, in estimating g_j, the total number of *successes* is $\sum_{i=1}^{I}(1-\eta_{ij})y_{ij}$, and the total number of *failures* is $\sum_{i=1}^{I}(1-\eta_{ij})(1-y_{ij})$. As $g_j \sim Beta(1, 1)$ and $s_j \sim Beta(1, 1)$, the full conditional posterior distribution for g_j is

$$g_j|s_j, \boldsymbol{\alpha}, \boldsymbol{y}, \boldsymbol{q} \sim Beta\left(1+\sum_{i=1}^{I}(1-\eta_{ij})y_{ij},\ 1+\sum_{i=1}^{I}(1-\eta_{ij})(1-y_{ij})\right). \quad (3)$$

In estimating s_j, the total number of *successes* is $\sum_{i=1}^{I}\eta_{ij}(1-y_{ij})$, and the total number of *failures* is $\sum_{i=1}^{I}\eta_{ij}y_{ij}$. Therefore, the full conditional posterior distribution for s_j is

$$s_j|g_j, \boldsymbol{\alpha}, \boldsymbol{y}, \boldsymbol{q} \sim Beta\left(1+\sum_{i=1}^{I}\eta_{ij}(1-y_{ij}),\ 1+\sum_{i=1}^{I}\eta_{ij}y_{ij}\right). \quad (4)$$

The monotonicity constraint indicates that the probability of answering an item correctly is supposed to be higher for an examinee who possesses all the required attributes than for one who lacks at least one attribute, that is, $1 - s_j > g_j$. To achieve monotonicity, we use inverse transform sampling to sample from a truncated Beta distribution. The g_j and s_j parameters are sampled from $Uniform(0, 1 - s_j)$ and $Uniform(0, 1 - g_j)$, and then inverted to Beta distributions.

Of note is that along the way to estimate the Q-matrix, steps 1 to 4 can be employed to estimate $\boldsymbol{\alpha}$, $\boldsymbol{g}$ and $\boldsymbol{s}$ when the Q-matrix is known.

Step 5: Updating the Q-matrix

Let $\boldsymbol{q}$ be the estimated Q-matrix from iteration $t - 1$. With the updated $\boldsymbol{\alpha}$, $\boldsymbol{g}$ and $\boldsymbol{s}$ from previous steps, step 5 updates the Q-matrix. Similar to step 1, this step uses a saturated Multinomial model to cope with correlated attributes. With K attributes, there are 2^K possible Q-matrix patterns for item j. Because an item has to measure at least one attribute, the pattern with all 0's has to be excluded, thus leaving only $2^K - 1$ possible patterns. Let $2^K - 1 = H$, and let $\boldsymbol{\epsilon}_{H\times K} = (\varepsilon_{hk})_{H\times K}$ be the matrix of *possible* Q-matrix patterns for item j. Accordingly, $\boldsymbol{\epsilon}$ has H rows, and each row of $\boldsymbol{\epsilon}$ represents a possible Q-matrix pattern. Convert each of the H possible Q-matrix patterns to a decimal number (see step 1), and these patterns are distributed as a Multinomial distribution. In updating the Q-matrix for item j, the model is

$$\boldsymbol{\epsilon}|\boldsymbol{\phi} \sim Multinomial(H, \boldsymbol{\phi}),$$
$$\boldsymbol{\phi} \sim p(\boldsymbol{\phi}).$$

Unlike step 2 that adopts a Dirichlet prior to estimate $\boldsymbol{\alpha}$, step 5 uses the following approach in order to observe the underlying probability of each Q-matrix entry. Denote an entry in the Q-matrix as q_{jk}. Let $p(q_{jk} = 1) = \phi_{jk}$ and $p(q_{jk} = 0) = 1-\phi_{jk}$. Because the conjugate prior for a Bernoulli distribution is a Beta distribution, $Beta(1, 1)$ is chosen as the prior, $\phi_{jk} \sim Beta(1, 1)$. Therefore, the conditional posterior for ϕ_{jk} is distributed as $Beta(1 + q_{jk}, 2 - q_{jk})$. It is anticipated that the posterior mean is 2/3 for $q_{jk} = 1$ and 1/3 for $q_{jk} = 0$.

Let $\boldsymbol{\phi}_{H\times K} = (\boldsymbol{\phi}_1, \ldots, \boldsymbol{\phi}_H)$, where each element in the vector is a row in $\boldsymbol{\phi}$. That is, $\boldsymbol{\phi}_1 = (\phi_{11}, \phi_{12}, \ldots, \phi_{1K})$ and $\boldsymbol{\phi}_H = (\phi_{H1}, \phi_{H2}, \ldots, \phi_{HK})$. Therefore, the prior for sampling from possible Q-matrix patterns of item j is distributed as

$$p(\boldsymbol{\phi}) \sim \left(\prod_{k=1}^{K}\phi_{1k}^{\varepsilon_{1k}}(1-\phi_{1k})^{1-\varepsilon_{1k}}, \prod_{k=1}^{K}\phi_{2k}^{\varepsilon_{2k}} \times (1-\phi_{2k})^{1-\varepsilon_{2k}}, \ldots, \prod_{k=1}^{K}\phi_{Hk}^{\varepsilon_{Hk}}(1-\phi_{Hk})^{1-\varepsilon_{Hk}}\right).$$

Each element in $p(\boldsymbol{\phi})$ is the probability of a possible Q-matrix pattern for item j. The full conditional posterior distribution is $p(\boldsymbol{\phi}|\boldsymbol{y}) \propto p(\boldsymbol{y}|\boldsymbol{\phi})p(\boldsymbol{\phi})$. With the likelihood for item j from each of the H possible patterns and the prior $p(\boldsymbol{\phi})$, the Q-matrix for item j can be sampled from the full conditional posterior. This sampled decimal number is then converted to a binary number (see step 1), which is the Q-matrix estimate for item j.

After the procedure is applied to every item, the whole Q-matrix for iteration t is derived. As the number of iterations is T, there is a total of T estimated Q-matrices, which are stored in a 3-dimensional array $\mathcal{A}_{J\times K\times T}$.

Step 6: Relabeling Q-matrix Estimates

One potential issue in Bayesian Q-matrix estimation is label switching, which arises when columns of the Q-matrix of the Bayesian model are switched multiple times on different iterations during one run of an MCMC sampling. Since the label sampled is assigned at each step of the sampling, the assignment of the particular label is unique only up to the permutation group (Jasra, Holmes, & Stephens, 2005). Label switching can be perceived as *column* switching in the Q-matrix estimation. For example, the following two Q-matrices are equivalent even though the first column and the third column are switched,

$$\begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{bmatrix} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 1 & 0 & 1 \end{bmatrix}.$$

This raises concerns in the estimation. If label switching happens during a run of MCMC, posterior summaries will be biased and have inflated variance, although the result may match after columns are relabeled. As a consequence, simply calculating the mean of these T estimated Q-matrices from T iterations without relabeling might yield a misleading final Q-matrix estimate.

Erosheva and Curtis (2017) propose a relabeling algorithm to account for label switching in Bayesian confirmatory factor analysis. The essential concept of their procedure is to relabel the factors after the fact. We adopt the same concept and relabel each of the T estimated Q-matrices stored in $\mathcal{A}_{J\times K\times T}$ from step 5. The logic of our procedure is as the following. Let $\mathcal{C}_{J\times K}$ be the average of the T estimated Q-matrices stored in $\mathcal{A}_{J\times K\times T}$, and use $\mathcal{C}_{J\times K}$ as the first arbitrary reference. The Euclidean distance is calculated from each permutation of a Q-matrix estimate to $\mathcal{C}$. The permutation with the shortest Euclidean distance is the relabeled Q-matrix $\mathcal{A}_r^{(t)}$,

$$\mathcal{A}_r^{(t)} = \min_{\mathcal{A}^{(1)},\ldots,\mathcal{A}^{(K!)}} \left[d(\mathcal{A}^{(k)} - \mathcal{C}) \right],\ t = 1, \ldots, T. \tag{5}$$

After each of the T estimated Q-matrices in $\mathcal{A}_r^{(t)}$ is relabeled and stored as $\mathcal{A}'$, the average of these T relabeled Q-matrices in $\mathcal{A}'$ is the new arbitrary reference $\mathcal{C}'$. Using Eq. (5), $\mathcal{A}'$ is relabeled again with $\mathcal{C}'$ as the arbitrary reference. This subroutine is run recursively until $\mathcal{A}'$ converges. The final Q-matrix estimate is then derived by calculating the average of the T estimated Q-matrices stored in $\mathcal{A}'$.

2.1. Summary of the algorithm

The algorithm is summarized as follows. With the binary decimal conversion, possible attribute patterns are transformed to a saturated Multinomial distribution (step 1). Along with the likelihood of an attribute pattern, a Dirichlet distribution is used as the prior to sample from the posterior. The Dirichlet distribution is constructed using Gamma distributions (step 2), and attributes of examinees are updated using inverse transform sampling (step 3). Sequentially, guess and slip parameters are generated by Gibbs sampling using expressions (3) and (4) (step 4). The Q-matrix is generated using a saturated Multinomial model (step 5). The final Q-matrix is obtained after the relabeling algorithm in accomplished (step 6).

3. Simulation study

3.1. Procedure for simulating data

Generating Correlated Attributes. Simulated data sets were generated using the following procedure. The first step is to generate correlated attributes. Let $\boldsymbol{\vartheta}$ be the N by K underlying probability matrix of $\boldsymbol{\alpha}$, and let column k of $\boldsymbol{\vartheta}$ be a vector $\boldsymbol{\vartheta}_k$, $k = 1, \ldots, K$. That is, $\boldsymbol{\vartheta} = (\boldsymbol{\vartheta}_1, \ldots, \boldsymbol{\vartheta}_K)$. A copula is used to generate intercorrelated $\boldsymbol{\vartheta}$ (see Ross, 2006). The correlation coefficient for each pair of columns in $\boldsymbol{\vartheta}$ takes a constant value ρ, and the correlation matrix $\boldsymbol{\Sigma}$ is expressed as

$$\boldsymbol{\Sigma} = \begin{bmatrix} 1 & & \rho \\ & \ddots & \\ \rho & & 1 \end{bmatrix},$$

where the off-diagonal entries are ρ. Each entry in $\boldsymbol{\Sigma}$ corresponds to the correlation coefficient between two columns in $\boldsymbol{\vartheta}$. Symmetric with all the eigenvalues positive, $\boldsymbol{\Sigma}$ is a real symmetric positive-definite matrix that can be decomposed as $\boldsymbol{\Sigma} = \boldsymbol{\nu}^{\mathrm{T}}\boldsymbol{\nu}$ using Choleski decomposition, where $\boldsymbol{\nu}$ is an upper triangular matrix.

After $\boldsymbol{\nu}$ is derived, create an $I \times K$ matrix $\boldsymbol{\tau}$, in which each entry is generated from $N(0, 1)$. $\boldsymbol{\tau}$ is then transformed to $\boldsymbol{\gamma}$ by using $\boldsymbol{\gamma} = \boldsymbol{\tau}\boldsymbol{\nu}$, so that $\boldsymbol{\gamma}$ and $\boldsymbol{\Sigma}$ will have the same correlation structure. Set $\Phi(\boldsymbol{\gamma}) = \boldsymbol{\vartheta}$, where $\Phi(\cdot)$ is the CDF of the standard normal distribution. To generate $\boldsymbol{\alpha}$, researchers have been using one of the following two ways. Chen et al. (2015) generate $\boldsymbol{\alpha}$ by

$$\alpha_{ik} = \begin{cases} 1 & \text{if } \vartheta_{ik} \geq 0 \\ 0 & \text{otherwise,} \end{cases} \tag{6}$$

and Chiu, Douglas, and Li (2009) and Liu et al. (2012) use the following criteria,

$$\alpha_{ik} = \begin{cases} 1 & \text{if } \vartheta_{ik} \geq \Phi^{-1}(\frac{k}{K+1}) \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Generating Item Responses. For the DINA model, $\boldsymbol{\eta}$ is determined by Eq. (1). After setting the guess and slip parameters for each item, we can calculate the probability of an examinee correctly answering an item by Eq. (2). An $N \times J$ probability matrix $\boldsymbol{y}$ is thus formed, wherein each of the elements represents the probability of an examinee correctly answering an item. Inverse transform sampling for two categories, 0 and 1, is used to generate the data. Create another $N \times J$ probability matrix $\boldsymbol{c}$, with each element generated from $Uniform(0, 1)$. These two $N \times J$ matrices are then compared. If the corresponding value in $\boldsymbol{y}$ is greater than that in $\boldsymbol{c}$, then set y_{nj} to 1; if otherwise, set y_{nj} to 0. The final altered $\boldsymbol{y}$ is the simulated data. Simply put,

$$y_{nj} = \begin{cases} 1 & \text{if } y_{nj} \geq c_{nj} \\ 0 & \text{otherwise.} \end{cases}$$

3.2. Measure of accuracy

For M simulated data sets, let $\hat{\boldsymbol{q}}^{(m)} = (\hat{q}_{jk}^{(m)})_{J\times K}$ $(m = 1, \ldots, M)$ be the estimated Q-matrix from mth data set, and let $\boldsymbol{q} = (q_{jk})_{J\times K}$ represent the true $\boldsymbol{q}$. To measure how well the algorithm recovers the true $\boldsymbol{q}$, the recovery rate Δ_q, confined between 0 and 1, is defined as

$$\Delta_q = \frac{1}{M} \sum_{m=1}^{M} \left(1 - \frac{\left| \hat{\boldsymbol{q}}^{(m)} - \boldsymbol{q} \right|}{JK} \right),\ m = 1, 2, \ldots, M, \tag{8}$$

where $|\cdot|$ is the absolute value.

3.3. Settings for simulation

Congdon (2005) indicates that using single long runs may be adequate only for straightforward problems, and Gelman and Shirley (2011) suggest simulating three or more parallel chains in general. As estimating the Q-matrix is a complicated process, we simulated 3 chains with different random initial values.

Geyer (1991) points out that the accuracy of calculated quantities depends on the adequacy of the burn-in period, which however can never be validated for certain. Gelman and Shirley (2011) recommend discarding the first half of simulated sequences as burn-in periods and mix all the simulations from the second halves of the chains together to summarize the target distribution so that the issue of autocorrelation is reduced. We followed the advice advocated by Gelman and Shirley (2011). Corresponding R codes were run 50,000 iterations after 50,000 burn-in periods for each of the 3 chains.

For each of the following simulations, examinees in groups of 500, 1000 and 2000 were simulated with the correlation between each pair of attributes set to 0.1, 0.3 and 0.5. A hundred data sets were simulated for each combination of sample size and correlation. The following simulations were performed on 20 different Mac Pro computers, each of which equipped an 8-core Intel Xeon E5 processor and 32 GB memory.

3.4. Simulation I

The first simulation serves to see how the algorithm performs in a simple condition. The Q-matrix for simulation I is exhibited on the left side of Table 1. This artificial Q-matrix (Q-matrix I) is obtained from Rupp and Templin (2008). Fifteen items measuring 4 attributes comprise a Q-matrix manifesting a clear pattern, which is constructed in such a way that each attribute appears alone from items 1 to 4, in a pair from items 5 to 10 , in triplicate from items 11 to 14 and in quadruplet on item 15.

This Q-matrix is balanced, as each attribute is measured by 12 items. This Q-matrix is complete, containing at least one item devoted solely to each attribute (see Chiu et al., 2009). On average, each item measures 2.133 attributes. In generating the data for simulation I, $\boldsymbol{\alpha}$ was determined using Eq. (6), which suggested the same difficulty level for each attribute. Guess and slip parameters were set to 0.2 for all items in generating data.

3.5. Simulation II

In reality, different attributes could have different levels of difficulty. The purpose of simulation II is to see whether using more complicated cutoff criteria in generating $\boldsymbol{\alpha}$ affects the recovery of the Q-matrix. The second simulation also used Q-matrix I. The difference between simulation I and simulation II was that $\boldsymbol{\alpha}$ was generated using Eq. (7) instead of Eq. (6). Assuming each attribute has a different difficulty level, Eq. (7) is more complicated than equation (6) that regards each attribute as having the same difficulty level. Specifically, Eq. (7) implies that attribute 5 is the most difficult while attribute 1 is the easiest. Guess and slip parameters were also set to 0.2 for all items as in simulation I.

3.6. Simulation III

In addition to using the more complicated equation (7) to generate $\boldsymbol{\alpha}$, simulation III uses a more intricate Q-matrix. On the right side of Table 1 is the contrived Q-matrix (Q-matrix II) for the third simulation. This 15 by 5 Q-matrix is modified from the Q-matrix offered by de la Torre (2009). We excluded the first half of the original Q-matrix and retained the remaining 15 items (items 16 to 30) to make it imbalanced and incomplete. Q-matrix II was imbalanced in that each attribute appeared a different number of times in each item (6, 8, 8, 9, 9 times). Q-matrix II was incomplete, because it did not include items that measure each attribute alone. Each item measures at least 2 attributes. On average, each item measured 2.67 attributes. Like simulations I and II, simulation III set guess and slip parameters to 0.2 for all items.

3.7. Results

The recovery rate of each concoction before and after relabeling is exhibited in Table 2. Note that if the improvement of recovery rate was less than 0.001, we did not list the recovery rate before the relabeling algorithm was applied.

The recovery rate for each combination in simulation I was above 0.990, suggesting that this Gibbs sampling algorithm should be effective when the difficulty of each attribute is the same and the Q-matrix is complete. No label switching was found in simulation I even when the sample size was as small as 500 and the correlation was as high as 0.5.

Compared with simulation I, simulation II had a lower recovery rate ranging from 0.831 to 0.994. In general, when the sample size increases, the recovery rate also increases; when the correlation increases, the recovery rate decreases. Unlike simulation I, simulation II saw label switching under some conditions. The biggest improvement in recovery rate was 1.4%, which was the result from a sample size of 500 with correlation 0.5.

For simulation III that used an incomplete and imbalanced Q-matrix, results are shown on the right side of Table 2. It can be seen that the recovery rate in simulation III, ranging from 0.822 to 0.843, was the worst among the three simulations. Results show that the recovery rate increases with sample size and decreases with attribute correlation. Label switching was observed. Even though the trend was not very obvious, label switching seemed to prone to occur when the sample size was decreased and the correlation was increased. When the sample size was 500 with correlation between each pair of attributes equal to 0.5, the recovery rate increased the by 6.2% after the relabeling algorithm, the highest increase of all the combinations.

Table 2
Q-matrices for simulations.

Q-matrix I					Q-matrix II					
Item	Attribute				Item	Attribute				
	1	2	3	4		1	2	3	4	5
1	1	0	0	0	1	0	1	0	1	0
2	0	1	0	0	2	0	1	0	0	1
3	0	0	1	0	3	0	0	1	1	0
4	0	0	0	1	4	0	0	1	0	1
5	1	1	0	0	5	0	0	0	1	1
6	1	0	1	0	6	1	1	1	0	0
7	1	0	0	1	7	1	1	0	1	0
8	0	1	1	0	8	1	1	0	0	1
9	0	1	0	1	9	1	0	1	1	0
10	0	0	1	1	10	1	0	1	0	1
11	1	1	1	0	11	1	0	0	1	1
12	1	1	0	1	12	0	1	1	1	0
13	1	0	1	1	13	0	1	1	0	1
14	0	1	1	1	14	0	1	0	1	1
15	1	1	1	1	15	0	0	1	1	1

4. Empirical study

4.1. The ECPE data

A standardized English as a foreign language examination, the Examination for the Certificate of Proficiency in English (ECPE) is recognized in several countries as official proof of advanced proficiency in English (ECPE, 2015). Obtained from the CDM R package, the data consists of responses of 2922 examinees to 28 multiple choice items that measure 3 attributes (morphosyntactic, cohensive, lexical) in the grammar section of the ECPE. The data has been analyzed by Feng, Habing, and Huebner (2013), Templin and Hoffman (2013) and Templin and Bradshaw (2014). It consists of the responses of 2922 examinees to 28 multiple-choice questions in the grammar section of the ECPE. We tentatively tried to extract the Q-matrix from the ECPE data. In analyzing the data, the current MCMC algorithm was run 50,000 iterations, in which the first 50,000 were discarded as burn-in periods.

4.2. Initial values

In estimating the Q-matrix for the ECPE data, we referred to the Q-matrix (Table 3) obtained from Templin and Bradshaw (2014) that assumes 28 items measuring 3 attributes as the initial value to reflect our prior knowledge. According to Templin and Bradshaw (2014), these 3 attributes represent: (1) morphosyntactic rules, (2) cohensive rules, (3) lexical rules. For other parameters, initial values were randomly assigned as in the simulation studies.

Table 3
Recovery rate.

Sample size	Simulation I			Simulation II			Simulation III		
	Correlation			Correlation			Correlation		
	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
500	0.997	0.996	0.994	(0.915) 0.921	(0.867) 0.876	(0.817) 0.831	(0.751) 0.800	(0.730) 0.783	(0.696) 0.758
1000	1.000	0.998	0.996	0.963	(0.928) 0.932	(0.883) 0.888	(0.838) 0.846	(0.816) 0.825	(0.769) 0.781
2000	1.000	1.000	0.998	0.994	0.968	(0.927) 0.929	(0.860) 0.861	(0.839) 0.841	(0.810) 0.813

Note: Numbers in parenthesis is the recovery rate before relabeling.

4.3. Results

The estimated Q-matrix is given on the right side of Table 3. If the Q-matrix suggested by Templin and Bradshaw (2014) is assumed to be the true Q-matrix, 52 out of the 84 entries were correct in the estimation when the cutoff was set to 0.5. The recovery rate of the estimated Q-matrix was about 62%. For attributes 1 to 3, the number of incorrect estimates were respectively 5, 11 and 16. Among the 32 incorrect estimates, 12 entries had estimated values of less than 0.5 whereas the correct values would have been 1's; 20 entries had estimated values above 0.5 whereas the correct entries would have been 0's. The Akaike information criterion (AIC) is 85 812.92 for the initial Q-matrix and 85 693.58 for the estimated Q-matrix, suggesting that the estimated Q-matrix fits the data better than the initial Q-matrix (see Table 4).

Table 4
Estimated Q-matrix for the ECPE data.

Item	Initial[1]			Estimated		
	1	2	3	1	2	3
1	1	1	0	(1) 0.988	(1) 0.622	(1) 0.999
2	0	1	0	(1) 0.584	(1) 0.976	(0) 0.000
3	1	0	1	(1) 1.000	(1) 0.804	(1) 1.000
4	0	0	1	(0) 0.000	(1) 1.000	(0) 0.000
5	0	0	1	(0) 0.000	(1) 1.000	(0) 0.000
6	0	0	1	(0) 0.000	(1) 1.000	(0) 0.000
7	1	0	1	(1) 1.000	(0) 0.033	(0) 0.000
8	0	1	0	(0) 0.001	(1) 1.000	(0) 0.006
9	0	0	1	(0) 0.000	(0) 0.002	(1) 1.000
10	1	0	0	(1) 1.000	(0) 0.206	(1) 1.000
11	1	0	1	(0) 0.000	(0) 0.000	(1) 1.000
12	1	0	1	(1) 1.000	(0) 0.321	(1) 1.000
13	1	0	0	(1) 1.000	(0) 0.001	(0) 0.000
14	1	0	0	(1) 1.000	(1) 0.991	(1) 0.999
15	0	0	1	(0) 0.000	(1) 1.000	(0) 0.000
16	1	0	1	(1) 1.000	(1) 0.673	(0) 0.000
17	0	1	1	(0) 0.055	(1) 0.959	(0) 0.001
18	0	0	1	(0) 0.000	(1) 1.000	(0) 0.000
19	0	0	1	(0) 0.000	(0) 0.000	(1) 1.000
20	1	0	1	(1) 1.000	(0) 0.000	(1) 1.000
21	1	0	1	(0) 0.000	(1) 1.000	(1) 1.000
22	0	0	1	(1) 1.000	(0) 0.003	(0) 0.000
23	0	1	0	(0) 0.000	(1) 1.000	(0) 0.000
24	0	1	0	(0) 0.000	(1) 0.999	(1) 1.000
25	1	0	0	(1) 1.000	(1) 0.920	(1) 0.989
26	0	0	1	(1) 1.000	(1) 0.694	(0) 0.002
27	1	0	0	(1) 1.000	(0) 0.082	(1) 1.000
28	0	0	1	(0) 0.000	(0) 0.000	(1) 1.000

Note: Initial[1] is the Q-matrix obtained from Templin and Bradshaw (2014); Numbers in parenthesis are the estimates rounded to the nearest whole number.

5. Discussion

We advance a Gibbs sampling algorithm for estimating the Q-matrix in a Bayesian framework. This automated Q-matrix searching procedure is based on the DINA model. A prominent discovery is that closed-form posterior distributions for generating guess and slip parameters are found. This not only conveys a delicate statistical characteristic of the DINA model but also facilitates the speed of the algorithm.

In estimating attributes and the Q-matrix, 2-stage hierarchical Multinomial models are used. Saturated Multinomial models appear to be useful in coping with correlated attributes, and the relabeling procedure to account for label switching seems to improve the recovery rate. Our findings from the simulation studies indicate that sample size, degree of correlation, difficulty of attributes and structure of Q-matrix all influence the recovery rate. In addition, label switching indeed occurs in the estimation; however it is not as severe as we at first supposed.

Among other studies on estimating the Q-matrix, Chen et al. (2018) also offer a promising and statistically sound method that imposes the identifiability constraints, as opposed to the present study that freely estimates the Q-matrix. Chen et al. (2015) suggest that the Q-matrix for the DINA model is identifiable when the model satisfies the monotonicity constraint ($1 - s_j > g_j$) and when the true Q-matrix is complete. The Gibbs sampler indeed demands the monotonicity constraint in the step 4 but not the completeness constraint, in which each attribute has to be measured by at least one item that dedicates to that attribute only. An example of an incomplete Q-matrix is the Q-matrix II in Table 2. While we acknowledge the necessity of enforcing the completeness constraint in some conditions, the average recovery rate in simulation I is over 0.99 without imposing the completeness constraint. That is, if the actual Q-matrix is complete, this Gibbs sampler does just as good. In addition, the completeness assumption might be dubious because not every exam is developed with cognitive diagnosis in mind. As a result, the estimated Q-matrix might be far off from the actual Q-matrix. That being said, the completeness constraint can be useful when the Q-matrix is developed manually during exam development.

Simulation studies using different sample sizes and correlations are designed to examine how the proposed algorithm performs in different Q-matrices. To cope with correlated attributes, Chen et al. (2018) adopt the Multinomial concept proposed in this study, in which the Dirichlet distribution is the conjugate prior for the Multinomial distribution. In estimating guess and slip parameters, this research finds a closed-form for sampling from the posterior distribution of each parameter, whereas Chen et al. (2018) apply the method developed by Chen et al. (2015).

Results from simulation I of the current research is used to compared with those from Chen et al. (2018), in that the setting of simulation I ($K = 4, \rho = 0.3, N = 500, 1000, 2000$) is most similar to that of their simulations ($K = 4, \rho = 0.25, N = 500, 1000, 2000$). Recovery rates (or entry-wise average) in Chen et al. (2018) with the identifiable constraints are 99.58% for $N = 500$, 98.57% for $N = 1000$ and 95.64% for $N = 2000$. Recovery rates of simulation I of this study are 0.996 for $N = 500$, 0.998 for $N = 1000$ and 1 for $N = 2000$. For estimating incomplete Q-matrix, no simulation is conducted in Chen et al. (2018). One finding worthy addressing is that our results imply that the recovery rate increases when the sample size is increased, whereas the results in Chen et al. (2018) suggest that an increased sample size would result in a worse recovery rate (entry-wise average). In addition, our results show that the recovery rate decreases when the correlation (ρ) is increased; however we are not able to identify how correlations among attributes affect recovery rates from Chen et al. (2018).

Some limitations of this research and recommendations for future work are as follows. First, this research was not entirely exploratory as we assumed that the number of attributes was known. Calculating log-likelihood might be able to reveal how the estimated Q-matrix with any given number of attributes fits the data. Moreover, while the number of attributes increases, the sample space will grow exponentially. The time spent on sampling is expected to be longer. Second, the correlation for each pair of attributes is fixed for each of the simulations. More complicated correlation structures are needed to examine how they affect the Q-matrix recovery. Applying Choleski decomposition, along with Dirichlet priors, to estimating the Q-matrix might be a possible way to better understand the correlation structure among attributes, and this could also make the algorithm more efficient.

Third, this research is based on the DINA model. However because of the conjunctive nature of the model that divides examinees only into either the mastery or non-mastery category, further research might apply the estimation procedure to more general models, such as the G-DINA model, which can identify the probability of different attribute patterns. In addition, we recognize the impracticality to set the guess and slip parameters to 0.2 for all items, as an item with more required attributes is supposed to be more difficult. Thus the probability of correctly answering a question by guessing should be lower. It is suggested that future research use a mix of values ranging from 0.1 to 0.3.

As for the measure of accuracy, researchers might argue that in calculating the recovery rate Δ_q, $\hat{\boldsymbol{q}}$ should be rounded to the nearest whole before subtracting the actual Q-matrix. That is, instead of using Eq. (8), the recovery rate should be defined as

$$\Delta_q = \frac{1}{M}\sum_{m=1}^{M}\left(1 - \frac{\left|\left[\hat{\boldsymbol{q}}^{(m)}\right] - \boldsymbol{q}\right|}{JK}\right),\ m = 1, 2, \ldots, M, \tag{9}$$

where the $[\cdot]$ returns the value rounded to the nearest whole. This concern matters only when Q-matrix estimates are mostly close to 0.5. As a matter of fact, when tested, using Eq. (9) increased the recovery rate in each of the simulation studies.

Another issue concerns the software. Estimating the Q-matrix is computationally intensive. Although the customized R program ran well, it took more than 12 h for a run of MCMC in the simulation. Therefore it would be worth the effort to convert the code to another lower-level programming language, such as C or Java, to facilitate efficiency.

Among the many issues, how to interpret the estimated Q-matrix might be the most challenging. Although our Q-matrix estimate for the ECPE data is somewhat close to the initial Q-matrix in Table 3, we are not sure whether these 3 attributes derived from the data correspond to those 3 attributes appeared in Henson and Templin (2007). Based on the AIC, the preferred Q-matrix is the one estimated Q-matrix. Nevertheless, we certainly do not claim our Q-matrix estimate is the correct answer. This estimated Q-matrix should be treated circumspectly. Discussion of the meaning of each entry is beyond the scope of this paper, and the interpretation and implication are left to domain experts.

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