Psychometrika

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BUILDING AN IDENTIFIABLE LATENT CLASS MODEL WITH COVARIATE EFFECTS ON UNDERLYING AND MEASURED VARIABLES

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In recent years, latent class models have proven useful for analyzing relationships between measured multiple indicators and covariates of interest. Such models summarize shared features of the multiple indicators as an underlying categorical variable, and the indicators' substantive associations with predictors are built directly and indirectly in unique model parameters. In this paper, we provide a detailed study on the theory and application of building models that allow mediated relationships between primary predictors and latent class membership, but that also allow direct effects of secondary covariates on the indicators themselves. Theory for model identification is developed. We detail an Expectation-Maximization algorithm for parameter estimation, standard error calculation, and convergent properties. Comparison of the proposed model with models underlying existing latent class modeling software is provided. A detailed analysis of how visual impairments affect older persons' functioning requiring distance vision is used for illustration.

Key words: EM algorithm, finite mixture model, identifiability, multiple discrete indicators, visual functioning.

1. Introduction

In many studies, the conceptually or clinically most meaningful outcome is inaccessible due to cost, time, and difficulty of measurement. A set of multiple indicators is then measured in place of this outcome. For example, psychiatric disorders are often assessed by applying standardized criteria to patients' report of symptoms (Eaton, Dryman, Sorenson, & McCutcheon, 1989). Biomarkers are used very often as substitutes for observing new cases of cancer in testing treatments for cancer prevention, where event rates are low and a long time may be needed to obtain cancer cases (Piantadosi, 1997). Functional disability is commonly quantified as self-reported categorical responses to a series of questions about difficulty performing tasks of routine living (e.g., Katz et al., 1963), because no obvious single measure of disability exists. Statistical methods for analyzing these measured indicators should have the capability to model the relationship between indicators and conceptual outcomes, and to describe the underlying mechanism of the condition under investigation. The present paper investigates an increasingly widespread strategy for analyzing data collected in situations where investigators use multiple discrete indicators to measure the conceptually defined outcome.

Particularly in psychosocial research, latent variable models are recognized as an effective tool for analyzing measured indicators. There are two primary latent variable approaches for situations where multiple categorical indicators are used: latent trait models and latent class models.

This work was supported by National Institute on Aging (NIA) Program Project P01-AG-10184-03 and National Institutes of Mental Health grant R01-MH-56639-01A1. Dr. Bandeen-Roche is a Brookdale National Fellow. The authors wish to thank Drs. Gary Rubin and Sheila West for kindly making the Salisbury Eye Evaluation data available. We also thank the Editor, the Associate Editor, and three referees for their valuable comments.

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0033-3123/2004-1/2002-0971-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 33–54
MARCH 2004

THE REPEATED INSERTION MODEL FOR RANKINGS: MISSING LINK BETWEEN TWO SUBSET CHOICE MODELS

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Several probabilistic models for subset choice have been proposed in the literature, for example, to explain approval voting data. We show that Marley et al.'s latent scale model is subsumed by Falmagne and Regenwetter's size-independent model, in the sense that every choice probability distribution generated by the former can also be explained by the latter. Our proof relies on the construction of a probabilistic ranking model which we label the "repeated insertion model." This model is a special case of Marden's orthogonal contrast model class and, in turn, includes the classical Mallows ϕ-model as a special case. We explore its basic properties as well as its relationship to Fligner and Verducci's multistage ranking model.

Key words: Approval voting, probabilistic choice models, probabilistic ranking models, subset choice.

Introduction

In order to be of general interest, a model of judgment and decision making needs to be generalizable beyond the specific empirical paradigm for which it was originally designed. Thus, a major open challenge in probabilistic modeling of preference and choice behavior is to formulate models that are applicable to (or can easily be reformulated for) a broad range of empirical paradigms. In this vein, the present paper investigates the interrelationship among a specific set of models for ranking and/or choice data.

There is a substantial past and evolving literature on probabilistic models specifically for ranking data (Critchlow, Fligner & Verducci, 1991, 1993; Marden, 1992, 1995). Every probabilistic ranking model in turn naturally induces a series of choice models: In a binary choice task, the respondent is asked to choose one of two choice alternatives. Given a latent or overt preference ranking of all choice alternatives, the respondent can simply choose the higher ranked among the two choice alternatives. In a multiple choice task, the respondent is asked to choose one object out of k many objects. Again, given a preference ranking over the choice alternatives, the respondent can simply choose the highest ranked among the k available options. In a subset choice task, the respondent is asked to choose a subset of any size from a given available set of

The authors are grateful to the National Science Foundation for grants SES98-18756 to Regenwetter and Pekeč, and SBR97-30076 to Regenwetter. This collaborative research was carried out in the context of the conference Random Utility 2000 held at Duke University and sponsored by NSF, the Fuqua School of Business and the Center for International Business Education and Research. We thank the editor and four referees for helpful suggestions and we are grateful to Prof. J. I. Marden for providing useful information on contrast models. We thank Moon-Ho Ho for programming and running the data analyses.

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0033-3123/2004-1/2002-0967-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 55–64
MARCH 2004

A WIDELY APPLICABLE EXTENSION OF THE RANDOM EFFECTS TWO-WAY LAYOUT: ITS DEFINITION AND STATISTICAL ANALYSIS BASED ON GROUP INVARIANCE

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A type of data layout that may be considered as an extension of the two-way random effects analysis of variance is characterized and modeled based on group invariance. The data layout seems to be suitable for several scenarios in psychometrics, including the one in which multiple measurements are taken on each of a set of variables, and the measurements can be divided into exchangeable subsets. The algebraic structure of the model is studied, which leads to results that are applicable to such problems as estimating correlation matrix corrected for attenuation and testing symmetry hypotheses.

Key words: disattenuation, group invariance, measurement error, reliability.

Introduction

In most statistical models, the observed data are considered as following a probability distribution which is invariant (unchanged) under the action of some group. Such group invariance has long been studied from various perspectives at various levels of generality. A comprehensive theory of group invariance in multivariate normal models exists (e.g., Andersson, 1975; Andersson & Madsen, 1998), as is reviewed in part in Perlman (1987), who used the phrase group symmetry instead of group invariance. It has been demonstrated that analysis of variance and multivariate analysis of variance type models and procedures can be derived from covariance patterns induced by group invariance in structured data layouts (Dawid, 1986, 1988; Li, 2001, 2002a,b; Li & Loken, 2002). Dawid (1988) described a general scheme, which is then illustrated by a classic data structure exemplifying factorial layouts. Li (2002b), embracing the framework of Andersson and Madsen (1998), studied a data structure that seems not to have previously appeared in the statistical literature. For a different but related approach to structured data layouts, see Tjur (1984). Similar to Dawid (1988) and Li (2002b), the current paper also derives statistical analysis for a structured data layout based on its defining group invariance, but at a less technical level. The data structure considered in this paper is in between those in Dawid (1988) and Li (2002b) in terms of its familiarity: Although well-known in some of its simplified forms, it is less often treated in its full generality.

The data structure that we will deal with can be viewed as an immediate extension of the random effects two-way analysis of variance defined by two factors, to be called I and II, by restricting the requirements of invariance implied by the model. Specifically, the set of levels of one factor, say factor II, is partitioned into p subsets, and the distribution of the data vector is only required to be invariant under the permutations of levels within those subsets, but not across them; whereas any permutation on the levels of factor I still leaves the distribution of the entire data vector unchanged. For convenience, we introduce some terms to describe the group invariance in this extended model. The above partition will be called “segmentation,” the

The author would like to thank NIH for support through grants M01 RR00044 and P01 DE13539, and NSF and ASA Survey Section for a travel grant which allowed him to present this paper as an invited young researcher at the Conference in Celebration of Wayne A. Fuller’s 70th birthday. Requests for reprints should be sent to Heng Li, FDA/CDRH (HFZ-550), 1350 Piccard Dr., Rockville MD 20850.

0033-3123/2004-1/2001-0897-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 65–79
MARCH 2004

A MULTIVARIATE REDUCED-RANK GROWTH CURVE MODEL WITH UNBALANCED DATA

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HEC MONTREAL

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A multivariate reduced-rank growth curve model is proposed that extends the univariate reduced-rank growth curve model to the multivariate case, in which several response variables are measured over multiple time points. The proposed model allows us to investigate the relationships among a number of response variables in a more parsimonious way than the traditional growth curve model. In addition, the method is more flexible than the traditional growth curve model. For example, response variables do not have to be measured at the same time points, nor the same number of time points. It is also possible to apply various kinds of basis function matrices with different ranks across response variables. It is not necessary to specify an entire set of basis functions in advance. Examples are given for illustration.

Key words: Multivariate growth curve models, reduced-rank restriction, longitudinal data.

1. Introduction

In a variety of areas, observations are taken over multiple time points on a particular characteristic, often called a response variable, to investigate temporal patterns of change on the characteristic. For instance, students may be asked to take a standardized test repeatedly over several months. Satisfaction of customers toward a particular brand may be tracked down every quarter. Effects of a certain drug on animals, blood sugar concentrations may be measured over time.

Data of this type are usually analyzed by the growth curve model, initiated by Potthoff and Roy (1964), and extensively studied by numerous authors, including Khatri (1966), Grizzle and Allen (1969), and Rao (1965). (Refer to von Rosen (1991) for a nice review on the growth curve model.) The basic idea of the growth curve model is to introduce some known functions, so-called basis functions (e.g., polynomial functions), so as to capture patterns of change for time-dependent measurements. The traditional growth curve model was designed for the situations where individuals are measured on a single response variable. Reinsel (1982) extended the univariate growth curve model to the multivariate case, where several response variables are measured over multiple time points. The multivariate growth curve model enables us to examine relationships between different response variables (also see Carter & Hubert, 1984; Lundbye-Christensen, 1996; Nummi & Möttönen, 2000). Another recent extension is to impose reduced-rank restrictions on the univariate growth curve model, motivated by the fact that the mathematical structure of the growth curve model is akin to that of the reduced-rank

The work reported in this paper was supported by Grant A6394 from the Natural Sciences and Engineering Research Council of Canada to the second author. We thank Jennifer Stephan for her helpful comments on an earlier version of this paper. We also thank Patrick Curran and Terry Duncan for kindly letting us use the NLSY and substance use data, respectively. The substance use data were provided by Grant DA09548 from the National Institute on Drug Abuse.
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0033-3123/2004-1/2001-0910-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 81–99
MARCH 2004

GENERALIZED STRUCTURED COMPONENT ANALYSIS

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HEC MONTREAL

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We propose an alternative method to partial least squares for path analysis with components, called generalized structured component analysis. The proposed method replaces factors by exact linear combinations of observed variables. It employs a well-defined least squares criterion to estimate model parameters. As a result, the proposed method avoids the principal limitation of partial least squares (i.e., the lack of a global optimization procedure) while fully retaining all the advantages of partial least squares (e.g., less restricted distributional assumptions and no improper solutions). The method is also versatile enough to capture complex relationships among variables, including higher-order components and multi-group comparisons. A straightforward estimation algorithm is developed to minimize the criterion.

Key words: Path analysis with components, partial least squares, alternating least squares.

1. Introduction

Partial least squares (Wold, 1966, 1973, 1982) is employed for path analysis with components or weighted composites of observed variables. Partial least squares (PLS) estimates model parameters by the so-called fixed point (FP) algorithm (Lyttkens, 1968, 1973; Wold, 1965, 1981). In the FP algorithm, a set of model parameters is divided into subsets, and each subset is "partially" estimated by ordinary least squares (OLS) with other subsets fixed. This OLS estimation is cycled through repeatedly until convergence is reached.

PLS avoids improper solutions (e.g., factor correlation estimates greater than ± 1, negative variance estimates, and so on) since it replaces factors by linear composites of observed variables as in component analysis (Meredith & Millsap, 1985; Schönemann & Steiger, 1976). PLS provides unique component score estimates of cases, which may be used for additional analyses or for selection or segmentation of the cases. Furthermore, since its parameter estimation is based on (partial) OLS, PLS does not rely on stringent distributional assumptions, such as the multivariate normality of observed variables, which is often violated in nonexperimental data (Micceri, 1989). Nonetheless, PLS does not solve a global optimization problem for parameter estimation, indicating that there exists no single criterion consistently minimized or maximized to determine model parameter estimates (Jöreskog & Wold, 1982; Fornell & Bookstein, 1982). Due to the lack of a global optimization criterion, it is difficult to evaluate the PLS procedures (McDonald, 1996). Also, it is not guaranteed that the obtained PLS solutions are optimal in a well-defined sense (Coolen & de Leeuw, 1987). More seriously, PLS provides no mechanism to evaluate the overall goodness of fit of the model. Given no overall goodness of fit measures, it

The work reported in this paper was supported by Grant A6394 from the Natural Sciences and Engineering Research Council of Canada to the second author. We wish to thank Richard Bagozzi for permitting us to use his organizational identification data and Wynne Chin for providing PLS-Graph 3.0. Requests for reprints should be addressed to: Heungsun Hwang, HEC Montreal, Department of Marketing, 3000 Chemin de la Cote Ste-Catherine, Montreal, Quebec, H3T 2A7, CANADA. Email: heungsun.hwang@hec.ca.

0033-3123/2004-1/2002-0985-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 101–122
MARCH 2004

AN EM ALGORITHM FOR FITTING TWO-LEVEL STRUCTURAL EQUATION MODELS

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Maximum likelihood is an important approach to analysis of two-level structural equation models. Different algorithms for this purpose have been available in the literature. In this paper, we present a new formulation of two-level structural equation models and develop an EM algorithm for fitting this formulation. This new formulation covers a variety of two-level structural equation models. As a result, the proposed EM algorithm is widely applicable in practice. A practical example illustrates the performance of the EM algorithm and the maximum likelihood statistic.

Key words: Chi-square statistic, mean and covariance structures, EM algorithm, maximum likelihood, multivariate normal distribution, two-level structural equation models

1. Introduction

Methods for fitting two-level structural equation models (SEM for simplicity) have been proposed by a number of authors. These methods were derived based on certain formulations of two-level SEM. Although existing formulations of two-level SEM may not be completely equivalent to one another, there is a close relation or an overlap among them. Goldstein and McDonald (1988) proposed a general model for analysis of multilevel data. Their model includes as its special case latent variable models. McDonald and Goldstein (1989) proposed a formulation of general two-level models for linear structural relations, which is a special case of the model treated by Goldstein and McDonald (1988). Muthén (1989) and Muthén and Satorra (1989) used a slightly different framework from that used by McDonald and Goldstein (1989) to formulate a two-level SEM but obtained the same ML (maximum likelihood) function. Lee (1990) defined a formulation of two-level SEM and gave a general treatment for ML analysis and GLS (Generalized Least Squared) analysis. Lee's (1990) model is different from those treated in McDonald and Goldstein (1989) and Muthén and Satorra (1989) in the sense that no observable group-level (or level-2) variables are involved. McDonald (1993) proposed a missing data framework of two-level SEM and provided an ML analysis method. Raudenbush (1995) implemented a balanced data routine to show how ML analysis on two-level SEM with unbalanced designs can be done by available software. Du Toit and du Toit (2002) gave comprehensive details on a Fisher scoring algorithm for McDonald's (1993) formulation of two-level SEM.

A careful study of the models cited in the above references shows that there is a common characteristic to these formulations of two-level SEM. That is, an observed two-level data set consists of two parts: (1) a set of group-level (level-2) observations, say, $\{\mathbf{z}_g, g = 1, \ldots, G\}$, which are measures from variables characterizing level-2 units (e.g., schools); and (2) a set of

We are thankful to the reviewers for their constructive comments that have led to significant improvement on the first version of this paper. Special thanks are due to the reviewer who suggested a comparison with the LISREL program in the saturated means model, and provided its setup and output. This work was supported by National Institute on Drug Abuse grants DA01070, DA00017, and a UNH 2002 Summer Faculty Fellowship.

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0033-3123/2004-1/1999-0786-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 123–146
MARCH 2004

MEASURING THE ABILITY OF TRANSITIVE REASONING, USING PRODUCT AND STRATEGY INFORMATION

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Cognitive theories disagree about the processes and the number of abilities involved in transitive reasoning. This led to controversies about the influence of task characteristics on individuals' performance and the development of transitive reasoning. In this study, a computer test was constructed containing 16 transitive reasoning tasks having different characteristics with respect to presentation form, task format, and task content. Both product and strategy information were analyzed to measure the performance of 6- to 13-year-old children. Three methods (MSP, DETECT, and Improved DIMTEST) were used to determine the number of abilities involved and to test the assumptions imposed on the data by item response models. Nonparametric IRT models were used to construct a scale for transitive reasoning. Multiple regression was used to determine the influence of task characteristics on the difficulty level of the tasks. It was concluded that: (1) the qualitatively distinct abilities predicted by Piaget's theory could not be distinguished by means of different dimensions in the data structure; (2) transitive reasoning could be described by one ability, and some task characteristics influenced the difficulty of a task; and (3) strategy information provided a stronger scale than product information.

Key words: cognitive ability, cognitive strategies, dimensionality of test data, IRT models, transitive reasoning, transitive reasoning scale.

1. Introduction

1.1. *Definition of Transitive Reasoning*

Suppose an experimenter shows a child two sticks, A and B, which differ in length, Y, such that $Y_A > Y_B$. Next, stick B is compared with another stick C, which differs in length such that $Y_B > Y_C$. In this example the length relations $Y_A > Y_B$ and $Y_B > Y_C$ are the premises. When the child is asked, without being given the opportunity to visually compare this pair of sticks, which is longer, stick A or stick C, (s)he may or may not be able to give the correct answer. When a child is able to infer the unknown relation ($Y_A > Y_C$) using the information of the premises ($Y_A > Y_B$ and $Y_B > Y_C$), (s)he is capable of *transitive reasoning*.

1.2. *Theories of Transitive Reasoning*

Three general theories on transitive reasoning can be distinguished. They are the developmental theory of Piaget, information processing theory, and fuzzy trace theory. These theories propose different definitions of the transitive reasoning ability and different operationalizations into transitive reasoning tasks. Consequently, the theories lead to contradictory conclusions about children's transitive reasoning ability.

1.2.1. *Developmental Theory of Piaget*

According to Piaget's theory (Piaget, Inhelder, & Szeminska, 1948), children acquire the cognitive operations to understand rules of logic at the *concrete operational stage*, at about six or

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0033-3123/2004-1/2003-1056-A $00.75/0

PSYCHOMETRIKA—VOL. 69, NO. 1, 147–157
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NOTES AND COMMENTS

RELIABILITY AS A FUNCTION OF THE NUMBER OF ITEM OPTIONS DERIVED FROM THE "KNOWLEDGE OR RANDOM GUESSING" MODEL

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For (0, 1) scored multiple-choice tests, a formula giving test reliability as a function of the number of item options is derived, assuming the "knowledge or random guessing model," the parallelism of the new and old tests (apart from the guessing probability), and the assumptions of classical test theory. It is shown that the formula is a more general case of an equation by Lord, and reduces to Lord's equation if the items are effectively parallel. Further, the formula is shown to be closely related to another formula derived from Lord's randomly parallel tests model.

Key words: guessing (tests), test reliability, distractors, test length, error of measurement

1. Introduction

For dichotomously scored multiple choice tests, researchers have long attempted to relate test reliability to the number of options per item. In theory, an increase in the number of options should reduce the probability of guessing correct answers, which should increase test reliability. In early theoretical work, Lord (1944) derived a formula relating test reliability to the number of options from a consideration of the phi coefficient between items. He assumed the "knowledge or random guessing model," equal item difficulties and equal item intercorrelations. Later, Horst (1954) used Carroll's (1945) work to relate test reliability to the number of options for a test where the only error considered was that from guessing, giving "immediate retest reliability." Mattson (1965), using Lord's (1957, 1959) randomly parallel tests model, constructed a table showing reliability as a function of option numbers, but his table is based on an unobservable quantity, the mean proportion of answers known in the hypothetical population of items. Basing his approach on empirical data, Ebel (1969) took the interval between the maximum possible score and the expected chance score and, assuming the mean was at the midpoint and the standard deviation was one sixth of the width, employed KR21 to relate test reliability to option numbers. Later theoretical work (Grier, 1975; Lord, 1977) considered the option number that maximised test reliability, assuming that for fixed testing time, the product of item and option numbers would be constant, an assumption Lord acknowledged was likely to be false for many or most item types.

This paper extends this work in deriving a formula relating test reliability to the number of options, and showing the relationships between this formula and the work of Lord (1944) and Mattson (1965). To place this development in context, suppose test developers wish to increase test reliability, while retaining the same number of items, and desire an approximate reliability estimate were the number of options to be increased from three to four. One approach would involve writing an additional distractor to each item of an existing test and trialling it on a large sample similar to the examinee population. Alternatively, an approximate reliability estimate could be obtained from theory. In developing this theory, it is not necessary to assume that the individual test items be parallel (as Lord, 1944, assumed). What is required is that, when guessing

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Psychometrika, the official journal of the Psychometric Society, is devoted to the development of psychology as a quantitative rational science. Issued four times a year, on March 15, June 15, September 15, and December 15.

MARCH 2004, VOLUME 69, NUMBER 1

(ISSN 0033-3123) is published by the Psychometric Society, 3040 Cornwallis Road, Research Triangle Institute, P.O. Box 12194, Research Triangle Park, NC 27709-2194 U.S.A. and at additional mailing offices.

Subscription Price: The regular subscription rate is $125.00 per volume. All annual subscriptions start with the March issue and cover the calendar year. All bills and orders are payable in advance. Checks should be made payable to the *Psychometric Society*. All checks, notices of change of address, and business communications (including notification of the nonreceipt of journals) should be sent to the Business Office of the Psychometric Society. Membership in the Psychometric Society includes a subscription to *Psychometrika*. Regular members pay annual dues of $60.00, except that family members pay annual dues of $75.00. The annual dues for a student in a recognized college or university is $25.00. Credit card payments may be made on-line at http://www.psychometricsociety.org.

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