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References

Bauer et al.: Conceptualizing and testing random indirect effects and moderated mediation in multilevel models: New procedures and recommendations

Bauer-Preacher-Gil-2006

Daniel J. Bauer, Kristopher J. Preacher, and Karen M. Gil. "Conceptualizing and testing random indirect effects and moderated mediation in multilevel models: New procedures and recommendations". In: *Psychological Methods* 11.2 (2006), pp. 142–163. DOI: 10.1037/1082-989x.11.2.142.

G. W. Cheung et al.: Testing mediation and suppression effects of latent variables

Cheung-Lau-2007

Gordon W. Cheung and Rebecca S. Lau. "Testing mediation and suppression effects of latent variables". In: *Organizational Research Methods* 11.2 (July 2007), pp. 296–325. DOI: 10.1177/1094428107300343.

Abstract: Because of the importance of mediation studies, researchers have been continuously searching for the best statistical test for mediation effect. The approaches that have been most commonly employed include those that use zero-order and partial correlation, hierarchical regression models, and structural equation modeling (SEM). This study extends MacKinnon and colleagues (MacKinnon, Lockwood, Hoffmann, West, & Sheets, 2002; MacKinnon, Lockwood, & Williams, 2004, MacKinnon, Warsi, & Dwyer, 1995) works by conducting a simulation that examines the distribution of mediation and suppression effects of latent variables with SEM, and the properties of confidence intervals developed from eight different methods. Results show that SEM provides unbiased estimates of mediation and suppression effects, and that the bias-corrected bootstrap con-

fidence intervals perform best in testing for mediation and suppression effects. Steps to implement the recommended procedures with Amos are presented.

M. W.-L. Cheung: Comparison of approaches to constructing confidence intervals for mediating effects using structural equation models **Cheung-2007**

Mike W.-L. Cheung. "Comparison of approaches to constructing confidence intervals for mediating effects using structural equation models". In: *Structural Equation Modeling: A Multidisciplinary Journal* 14.2 (May 2007), pp. 227–246. DOI: 10.1080/10705510709336745.

Abstract: Mediators are variables that explain the association between an independent variable and a dependent variable. Structural equation modeling (SEM) is widely used to test models with mediating effects. This article illustrates how to construct confidence intervals (CIs) of the mediating effects for a variety of models in SEM. Specifically, mediating models with 1 mediator, 2 intermediate mediators, 2 specific mediators, and 1 mediator in 2 independent groups are illustrated. By using phantom variables (Rindskopf, 1984), a Wald CI, percentile bootstrap CI, bias-corrected bootstrap CI, and a likelihood-based CI on the mediating effect are easily constructed with some existing SEM packages, such as LISREL, Mplus, and Mx. Monte Carlo simulation studies are used to compare the coverage probabilities of these CIs. The results show that the coverage probabilities of these CIs are comparable when the mediating effect is large or when the sample size is large. However, when the mediating effect and the sample size are both small, the bootstrap CI and likelihood-based CI are preferred over the Wald CI. Extensions of this SEM approach for future research are discussed.

M. W.-L. Cheung: Comparison of methods for constructing confidence intervals of standardized indirect effects **Cheung-2009a**

Mike W.-L. Cheung. "Comparison of methods for constructing confidence intervals of standardized indirect effects". In: *Behavior Research Methods* 41.2 (May 2009), pp. 425–438. DOI: 10.3758/brm.41.2.425.

Abstract: Mediation models are often used as a means to explain the psychological mechanisms between an independent and a dependent variable in the behavioral and social sciences. A major limitation of the unstandardized indirect effect calculated from raw scores is that it cannot be interpreted as an effect-size measure. In contrast, the standardized indirect effect calculated from standardized scores can be a good candidate as a measure of effect size because it is scale invariant. In the present article, 11 methods for constructing the confidence intervals (CIs) of the standardized indirect effects were evaluated via a computer simulation. These included six Wald CIs, three bootstrap CIs, one likelihood-based CI, and the PRODCLIN CI. The results consistently showed that the percentile bootstrap, the bias-corrected bootstrap, and the likelihood-based approaches had the best coverage probability. Mplus, LISREL, and Mx syntax were included to facilitate the use of these preferred methods in applied settings. Future issues on the use of the standardized indirect effects are discussed.

M. W.-L. Cheung: Constructing approximate confidence intervals for parameters with structural equation models **Cheung-2009b**

Mike W.-L. Cheung. "Constructing approximate confidence intervals for parameters with structural equation models". In: *Structural Equation Modeling: A Multidisciplinary Journal* 16.2 (Apr. 2009), pp. 267–294. DOI: 10.1080/10705510902751291.

Abstract: Confidence intervals (CIs) for parameters are usually constructed based on the estimated standard errors. These are known as Wald CIs. This article argues that likelihood-based CIs (CIs based on likelihood ratio statistics) are often preferred to Wald CIs. It shows how the likelihood-based CIs and the Wald CIs for many statistics and psychometric indexes can be constructed with the use of phantom variables (Rindskopf, 1984) in some of the current structural equation modeling (SEM) packages. The procedures to form CIs for the differences in correlation coefficients, squared multiple correlations, indirect effects, coefficient alphas, and reliability estimates are illustrated. A simulation study on the Pearson correlation is used to demonstrate the advantages of the likelihood-

based CI over the Wald CI. Issues arising from this SEM approach and extensions of this approach are discussed.

Cribari-Neto et al.: Inference under heteroskedasticity and leveraged data

CribariNeto-Souza-Vasconcellos-2007

Francisco Cribari-Neto, Tatiene C. Souza, and Klaus L. P. Vasconcellos. "Inference under heteroskedasticity and leveraged data". In: *Communications in Statistics - Theory and Methods* 36.10 (Aug. 2007), pp. 1877–1888. DOI: 10.1080/03610920601126589.

Abstract: We evaluate the finite-sample behavior of different heteros-ke-das-ticity-consistent covariance matrix estimators, under both constant and unequal error variances. We consider the estimator proposed by Halbert White (HC0), and also its variants known as HC2, HC3, and HC4; the latter was recently proposed by Cribari-Neto (2004). We propose a new covariance matrix estimator: HC5. It is the first consistent estimator to explicitly take into account the effect that the maximal leverage has on the associated inference. Our numerical results show that quasi-t inference based on HC5 is typically more reliable than inference based on other covariance matrix estimators.

Fritz et al.: Required sample size to detect the mediated effect **Fritz-MacKinnon-2007**

Matthew S. Fritz and David P. MacKinnon. "Required sample size to detect the mediated effect". In: *Psychological Science* 18.3 (Mar. 2007), pp. 233–239. DOI: 10.1111/j.1467-9280.2007.01882.x.

Abstract: Mediation models are widely used, and there are many tests of the mediated effect. One of the most common questions that researchers have when planning mediation studies is, "How many subjects do I need to achieve adequate power when testing for mediation?" This article presents the necessary sample sizes for six of the most common and the most recommended tests of mediation for various combinations of parameters, to provide a guide for researchers when designing studies or applying for grants.

Graham et al.: How many imputations are really needed? Some practical clarifications of multiple imputation theory **Graham-Olchowski-Gilreath-2007**

John W. Graham, Allison E. Olchowski, and Tamika D. Gilreath. "How many imputations are really needed? Some practical clarifications of multiple imputation theory". In: *Prevention Science* 8.3 (June 2007), pp. 206–213. DOI: 10.1007/s11121-007-0070-9.

Abstract: Multiple imputation (MI) and full information maximum likelihood (FIML) are the two most common approaches to missing data analysis. In theory, MI and FIML are equivalent when identical models are tested using the same variables, and when m, the number of imputations performed with MI, approaches infinity. However, it is important to know how many imputations are necessary before MI and FIML are sufficiently equivalent in ways that are important to prevention scientists. MI theory suggests that small values of m, even on the order of three to five imputations, yield excellent results. Previous guidelines for sufficient m are based on relative efficiency, which involves the fraction of missing information (γ) for the parameter being estimated, and m. In the present study, we used a Monte Carlo simulation to test MI models across several scenarios in which γ and m were varied. Standard errors and p-values for the regression coefficient of interest varied as a function of m, but not at the same rate as relative efficiency. Most importantly, statistical power for small effect sizes diminished as m became smaller, and the rate of this power falloff was much greater than predicted by changes in relative efficiency. Based our findings, we recommend that researchers using MI should perform many more imputations than previously considered sufficient. These recommendations are based on γ, and take into consideration one's tolerance for a preventable power falloff (compared to FIML) due to using too few imputations.

Hayes: Beyond Baron and Kenny: Statistical mediation analysis in the new millennium **Hayes-2009**

Andrew F. Hayes. "Beyond Baron and Kenny: Statistical mediation analysis in the new millennium". In: *Communication Monographs* 76.4 (Dec. 2009), pp. 408–420. DOI: 10.1080/03637750903310360.

Abstract: Understanding communication processes is the goal of most communication researchers. Rarely are we satisfied merely ascertaining whether messages have an effect on some outcome of focus in a specific context. Instead, we seek to understand how such effects come to be. What kinds of causal sequences does exposure to a message initiate? What are the causal pathways through which a message exerts its effect? And what role does communication play in the transmission of the effects of other variables over time and space? Numerous communication models attempt to describe the mechanism through which messages or other communication-related variables transmit their effects or intervene between two other variables in a causal model. The communication literature is replete with tests of such models. Over the years, methods used to test such process models have grown in sophistication. An example includes the rise of structural equation modeling (SEM), which allows investigators to examine how well a process model that links some focal variable X to some outcome Y through one or more intervening pathways fits the observed data. Yet frequently, the analytical choices communication researchers make when testing intervening variables models are out of step with advances made in the statistical methods literature. My goal here is to update the field on some of these new advances. While at it, I challenge some conventional wisdom and nudge the field toward a more modern way of thinking about the analysis of intervening variable effects.

MacKinnon et al.: Distribution of the product confidence limits for the indirect effect: Program PRODCLIN **MacKinnon-Fritz-Williams-etal-2007**

David P. MacKinnon, Matthew S. Fritz, et al. "Distribution of the product confidence limits for the indirect effect: Program PRODCLIN". In: *Behavior Research Methods* 39.3 (Aug. 2007), pp. 384–389. DOI: 10.3758/bf03193007.

Abstract: This article describes a program, PRODCLIN (distribution of the PRODuct Confidence Limits for INdirect effects), written for SAS, SPSS, and R, that computes confidence limits for the product of two normal random variables. The program is important because it can be used to obtain more accurate confidence limits for the indirect effect, as demonstrated in several recent articles (MacKinnon, Lockwood, & Williams, 2004; Pituch, Whittaker, & Stapleton, 2005). Tests of

the significance of and confidence limits for indirect effects based on the distribution of the product method have more accurate Type I error rates and more power than other, more commonly used tests. Values for the two paths involved in the indirect effect and their standard errors are entered in the PRODCLIN program, and distribution of the product confidence limits are computed. Several examples are used to illustrate the PRODCLIN program. The PRODCLIN programs in rich text format may be downloaded from www.psychonomic.org/archive.

MacKinnon et al.: A comparison of methods to test mediation and other intervening variable effects **MacKinnon-Lockwood-Hoffman-etal-2002**

David P. MacKinnon, Chondra M. Lockwood, Jeanne M. Hoffman, et al. "A comparison of methods to test mediation and other intervening variable effects". In: *Psychological Methods* 7.1 (2002), pp. 83–104. DOI: 10.1037/1082-989x.7.1.83.

Abstract: A Monte Carlo study compared 14 methods to test the statistical significance of the intervening variable effect. An intervening variable (mediator) transmits the effect of an independent variable to a dependent variable. The commonly used R. M. Baron and D. A. Kenny (1986) approach has low statistical power. Two methods based on the distribution of the product and 2 difference-in-coefficients methods have the most accurate Type I error rates and greatest statistical power except in 1 important case in which Type I error rates are too high. The best balance of Type I error and statistical power across all cases is the test of the joint significance of the two effects comprising the intervening variable effect.

MacKinnon et al.: Confidence limits for the indirect effect: Distribution of the product and resampling methods **MacKinnon-Lockwood-Williams-2004**

David P. MacKinnon, Chondra M. Lockwood, and Jason Williams. "Confidence limits for the indirect effect: Distribution of the product and resampling methods". In: *Multivariate Behavioral Research* 39.1 (Jan. 2004), pp. 99–128. DOI: 10.1207/s15327906mbr3901_4.

Abstract: The most commonly used method to test an indirect effect is to divide the estimate of the indirect effect by its standard error and compare the resulting z statistic with a critical value from the standard normal distribution. Confidence limits for the indirect effect are also typically based on critical values from the standard normal distribution. This article uses a simulation study to demonstrate that confidence limits are imbalanced because the distribution of the indirect effect is normal only in special cases. Two alternatives for improving the performance of confidence limits for the indirect effect are evaluated: (a) a method based on the distribution of the product of two normal random variables, and (b) resampling methods. In Study 1, confidence limits based on the distribution of the product are more accurate than methods based on an assumed normal distribution but confidence limits are still imbalanced. Study 2 demonstrates that more accurate confidence limits are obtained using resampling methods, with the bias-corrected bootstrap the best method overall.

Peugh et al.: Missing data in educational research: A review of reporting practices and suggestions for improvement **Peugh-Enders-2004**

James L. Peugh and Craig K. Enders. "Missing data in educational research: A review of reporting practices and suggestions for improvement". In: *Review of Educational Research* 74.4 (Dec. 2004), pp. 525–556. DOI: 10.3102/00346543074004525.

Abstract: Missing data analyses have received considerable recent attention in the methodological literature, and two "modern" methods, multiple imputation and maximum likelihood estimation, are recommended. The goals of this article are to (a) provide an overview of missing-data theory, maximum likelihood estimation, and multiple imputation; (b) conduct a methodological review of missing-data reporting practices in 23 applied research journals; and (c) provide a demonstration of multiple imputation and maximum likelihood estimation using the Longitudinal Study of American Youth data. The results indicated that explicit discussions of missing data increased substantially between 1999 and 2003, but the use of maximum likelihood estimation or multiple imputation was rare; the studies relied almost exclusively on listwise and pairwise deletion.

Preacher et al.: SPSS and SAS procedures for estimating indirect effects in simple mediation models **Preacher-Hayes-2004**

Kristopher J. Preacher and Andrew F. Hayes. "SPSS and SAS procedures for estimating indirect effects in simple mediation models". In: *Behavior Research Methods, Instruments, & Computers* 36.4 (Nov. 2004), pp. 717–731. DOI: 10.3758/bf03206553.

Abstract: Researchers often conduct mediation analysis in order to indirectly assess the effect of a proposed cause on some outcome through a proposed mediator. The utility of mediation analysis stems from its ability to go beyond the merely descriptive to a more functional understanding of the relationships among variables. A necessary component of mediation is a statistically and practically significant indirect effect. Although mediation hypotheses are frequently explored in psychological research, formal significance tests of indirect effects are rarely conducted. After a brief overview of mediation, we argue the importance of directly testing the significance of indirect effects and provide SPSS and SAS macros that facilitate estimation of the indirect effect with a normal theory approach and a bootstrap approach to obtaining confidence intervals, as well as the traditional approach advocated by Baron and Kenny (1986). We hope that this discussion and the macros will enhance the frequency of formal mediation tests in the psychology literature. Electronic copies of these macros may be downloaded from the Psychonomic Society's Web archive at www.psychonomic.org/archive/.

Preacher et al.: Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models **Preacher-Hayes-2008**

Kristopher J. Preacher and Andrew F. Hayes. "Asymptotic and resampling strategies for assessing and comparing indirect effects in multiple mediator models". In: *Behavior Research Methods* 40.3 (Aug. 2008), pp. 879–891. DOI: 10.3758/brm.40.3.879.

Abstract: Hypotheses involving mediation are common in the behavioral sciences. Mediation exists when a predictor affects a dependent variable indirectly through at least one intervening variable,

or mediator. Methods to assess mediation involving multiple simultaneous mediators have received little attention in the methodological literature despite a clear need. We provide an overview of simple and multiple mediation and explore three approaches that can be used to investigate indirect processes, as well as methods for contrasting two or more mediators within a single model. We present an illustrative example, assessing and contrasting potential mediators of the relationship between the helpfulness of socialization agents and job satisfaction. We also provide SAS and SPSS macros, as well as Mplus and LISREL syntax, to facilitate the use of these methods in applications.

Raghunathan et al.: A multivariate technique for multiply imputing missing values using a sequence of regression models **Raghunathan-Lepkowski-Hoewyk-etal-2001**

Trivellore E. Raghunathan et al. "A multivariate technique for multiply imputing missing values using a sequence of regression models". In: *Survey Methodology* 27.1 (2001), pp. 85–95.

Abstract: This article describes and evaluates a procedure for imputing missing values for a relatively complex data structure when the data are missing at random. The imputations are obtained by fitting a sequence of regression models and drawing values from the corresponding predictive distributions. The types of regression models used are linear, logistic, Poisson, generalized logit or a mixture of these depending on the type of variable being imputed. Two additional common features in the imputation process are incorporated: restriction to a relevant subpopulation for some variables and logical bounds or constraints for the imputed values. The restrictions involve subsetting the sample individuals that satisfy certain criteria while fitting the regression models. The bounds involve drawing values from a truncated predictive distribution. The development of this method was partly motivated by the analysis of two data sets which are used as illustrations. The sequential regression procedure is applied to perform multiple imputation analysis for the two applied problems. The sampling properties of inferences from multiply imputed data sets created using the sequential regression method are evaluated through simulated data sets.

Schafer et al.: Missing data: Our view of the state of the art **Schafer-Graham-2002**

Joseph L. Schafer and John W. Graham. "Missing data: Our view of the state of the art". In: *Psychological Methods* 7.2 (2002), pp. 147–177. DOI: 10.1037/1082-989x.7.2.147.

Abstract: Statistical procedures for missing data have vastly improved, yet misconception and unsound practice still abound. The authors frame the missing-data problem, review methods, offer advice, and raise issues that remain unresolved. They clear up common misunderstandings regarding the missing at random (MAR) concept. They summarize the evidence against older procedures and, with few exceptions, discourage their use. They present, in both technical and practical language, 2 general approaches that come highly recommended: maximum likelihood (ML) and Bayesian multiple imputation (MI). Newer developments are discussed, including some for dealing with missing data that are not MAR. Although not yet in the mainstream, these procedures may eventually extend the ML and MI methods that currently represent the state of the art.

Serlin: Testing for robustness in Monte Carlo studies **Serlin-2000**

Ronald C. Serlin. "Testing for robustness in Monte Carlo studies". In: *Psychological Methods* 5.2 (2000), pp. 230–240. DOI: 10.1037/1082-989x.5.2.230.

Abstract: Monte Carlo studies provide the information needed to help researchers select appropriate analytical procedures under design conditions in which the underlying assumptions of the procedures are not met. In Monte Carlo studies, the 2 errors that one could commit involve (a) concluding that a statistical procedure is robust when it is not or (b) concluding that it is not robust when it is. In previous attempts to apply standard statistical design principles to Monte Carlo studies, the less severe of these errors has been wrongly designated the Type I error. In this article, a method is presented for controlling the appropriate Type I error rate; the determination of the number of iterations required in a Monte Carlo study to achieve desired power is described; and a confidence

interval for a test's true Type I error rate is derived. A robustness criterion is also proposed that is a compromise between W. G. Cochran's (1952) and J. V. Bradley's (1978) criteria.

Shrout et al.: Mediation in experimental and nonexperimental studies: New procedures and recommendations **Shrout-Bolger-2002**

Patrick E. Shrout and Niall Bolger. "Mediation in experimental and nonexperimental studies: New procedures and recommendations". In: *Psychological Methods* 7.4 (2002), pp. 422–445. DOI: 10.1037/1082-989x.7.4.422.

Abstract: Mediation is said to occur when a causal effect of some variable X on an outcome Y is explained by some intervening variable M. The authors recommend that with small to moderate samples, bootstrap methods (B. Efron & R. Tibshirani, 1993) be used to assess mediation. Bootstrap tests are powerful because they detect that the sampling distribution of the mediated effect is skewed away from 0. They argue that R. M. Baron and D. A. Kenny's (1986) recommendation of first testing the $X \to Y$ association for statistical significance should not be a requirement when there is a priori belief that the effect size is small or suppression is a possibility. Empirical examples and computer setups for bootstrap analyses are provided.

Taylor et al.: Tests of the three-path mediated effect **Taylor-MacKinnon-Tein-2007**

Aaron B. Taylor, David P. MacKinnon, and Jenn-Yun Tein. "Tests of the three-path mediated effect". In: *Organizational Research Methods* 11.2 (July 2007), pp. 241–269. DOI: 10.1177/1094428107300344.

Abstract: In a three-path mediational model, two mediators intervene in a series between an independent and a dependent variable. Methods of testing for mediation in such a model are generalized from the more often used single-mediator model. Six such methods are introduced and compared in a Monte Carlo study in terms of their Type I error, power, and coverage. Based on its results, the joint significance test is preferred when only a hypothesis test is of interest. The percentile bootstrap and bias-corrected bootstrap are preferred when a confidence interval on the mediated

effect is desired, with the latter having more power but also slightly inflated Type I error in some conditions.

van Buuren et al.: Fully conditional specification in multivariate imputation **vanBuuren-Brand-GroothuisOudshoorn-etal-2006**

Stef van Buuren et al. "Fully conditional specification in multivariate imputation". In: *Journal of Statistical Computation and Simulation* 76.12 (Dec. 2006), pp. 1049–1064. DOI: 10.1080/10629360600810434.

Abstract: The use of the Gibbs sampler with fully conditionally specified models, where the distribution of each variable given the other variables is the starting point, has become a popular method to create imputations in incomplete multivariate data. The theoretical weakness of this approach is that the specified conditional densities can be incompatible, and therefore the stationary distribution to which the Gibbs sampler attempts to converge may not exist. This study investigates practical consequences of this problem by means of simulation. Missing data are created under four different missing data mechanisms. Attention is given to the statistical behavior under compatible and incompatible models. The results indicate that multiple imputation produces essentially unbiased estimates with appropriate coverage in the simple cases investigated, even for the incompatible models. Of particular interest is that these results were produced using only five Gibbs iterations starting from a simple draw from observed marginal distributions. It thus appears that, despite the theoretical weaknesses, the actual performance of conditional model specification for multivariate imputation can be quite good, and therefore deserves further study.

Yuan et al.: Three likelihood-based methods for mean and covariance structure analysis with nonnormal missing data **Yuan-Bentler-2000**

Ke-Hai Yuan and Peter M. Bentler. "Three likelihood-based methods for mean and covariance

structure analysis with nonnormal missing data". In: *Sociological Methodology* 30.1 (Aug. 2000), pp. 165–200. DOI: 10.1111/0081-1750.00078.

Abstract: Survey and longitudinal studies in the social and behavioral sciences generally contain missing data. Mean and covariance structure models play an important role in analyzing such data. Two promising methods for dealing with missing data are a direct maximum-likelihood and a two-stage approach based on the unstructured mean and covariance estimates obtained by the EM-algorithm. Typical assumptions under these two methods are ignorable nonresponse and normality of data. However, data sets in social and behavioral sciences are seldom normal, and experience with these procedures indicates that normal theory based methods for nonnormal data very often lead to incorrect model evaluations. By dropping the normal distribution assumption, we develop more accurate procedures for model inference. Based on the theory of generalized estimating equations, a way to obtain consistent standard errors of the two-stage estimates is given. The asymptotic efficiencies of different estimators are compared under various assumptions. We also propose a minimum chi-square approach and show that the estimator obtained by this approach is asymptotically at least as efficient as the two likelihood-based estimators for either normal or nonnormal data. The major contribution of this paper is that for each estimator, we give a test statistic whose asymptotic distribution is chisquare as long as the underlying sampling distribution enjoys finite fourth-order moments. We also give a characterization for each of the two likelihood ratio test statistics when the underlying distribution is nonnormal. Modifications to the likelihood ratio statistics are also given. Our working assumption is that the missing data mechanism is missing completely at random. Examples and Monte Carlo studies indicate that, for commonly encountered nonnormal distributions, the procedures developed in this paper are quite reliable even for samples with missing data that are missing at random.