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Published on: 01 Dec 1992 - Applied Psychological Measurement (Sage Publications)

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Testing Hypotheses About Methods, Traits, and Communalities in the Direct-Product Model

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The direct-product model has been suggested as a procedure for estimating multiplicative effects of traits and methods in multitrait-multimethod matrices. Research on the direct-product model is extended in two ways. First, hierarchically nested models are derived for explicitly testing the overall and specific patterns of method and trait factors. Second, formal tests are developed for the pattern of communalities. These procedures are illustrated with data from Lawler (1967). *Index terms: direct-product model, method factors, multiplicative model, multitrait-multimethod matrix, trait factors.*

Method factors may interact with trait factors multiplicatively in the multitrait-multimethod (MTMM) matrix (e.g., Campbell & O'Connell, 1967, 1982; Schmitt & Stults, 1986). Building on a model proposed by Swain (1975), Browne (1984) formally represented the interaction of traits and methods in a direct-product model (DPM) and developed the program MUTMUM, which estimates parameters and tests the general model (Browne, 1991). The DPM can be reformulated as a linear model (Wothke & Browne, 1990); therefore, the DPM can be fitted with programs such as EQS (Bentler, 1989; Bentler, Poon, & Lee, 1988) and LISREL (Jöreskog & Sörbom, 1989).

Given the frequent use of MTMM designs and the availability of these programs, it would seem likely that many researchers would employ the DPM in construct validation studies. However, the DPM has been used infrequently by applied researchers—very few studies could be found in the psychology literature (e.g., Bagozzi & Yi,

1990; Cudeck, 1988). Undoubtedly, the relative newness of the model accounts for its infrequent application to date. Further, the procedures for analyzing and interpreting the DPM are not straightforward for many researchers performing substantive investigations.

Although many contributions have been made to the theoretical formulation and estimation of the DPM in the psychometric literature, relatively little attention has been given to its practical application. Consequently, the literature provides little guidance on how to use the DPM in analyzing MTMM data. For example, applications to date have focused only on the appropriateness and fit of the overall model (e.g., Bagozzi, 1991; Bagozzi & Yi, 1990, 1991; Bagozzi, Yi, & Phillips, 1991; Cudeck, 1988; Lastovicka, Murry, & Joachimsthaler, 1990). More detailed hypotheses about traits and methods need to be specified, and formal tests of hypotheses of construct validity should be developed.

The present paper develops procedures for specifying and testing meaningful hypotheses regarding construct validity when traits and methods interact. Specifically, two extensions in the use of DPMS are presented. First, a series of hierarchically nested models for testing hypotheses of specific trait and method patterns are derived. This approach is analogous to Widaman's (1985) taxonomy of structural models for the linear formulation (i.e., confirmatory factor analysis), but because of the nature of the multiplicative interaction between traits and methods, the derivation and interpretation of the DPM are not straightforward. Second, formal tests of some meaningful hypotheses about

APPLIED PSYCHOLOGICAL MEASUREMENT
Vol. 16, No. 4, December 1992, pp. 373-380
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0146-6216/92/040373-08\$1.65

communalities are developed. These procedures are illustrated with data from Lawler (1967), which previously has been used to introduce researchers to the DPM (e.g., Wothke & Browne, 1990).

The Direct-Product Model

Swain (1975) proposed the DPM to represent the multiplicative interaction of traits and methods in the MTMM matrix:

$$\Sigma = \Sigma_M \otimes \Sigma_T, \quad (1)$$

where Σ is the covariance matrix of the observed variables;

Σ_M and Σ_T are method and trait covariance matrices, respectively; and

\otimes indicates a right direct (Kronecker) product.

However, because this model does not allow for measurement errors or for different scales for different variables, the applicability of the model is limited in many MTMM studies. Browne (1984, 1989) extended the DPM to overcome these limitations (see also Cudeck, 1988):

$$\Sigma = Z(P_M \otimes P_T + E)Z, \quad (2)$$

where Z is a non-negative definite diagonal matrix of scale constants;

P_M and P_T are non-negative definite method and trait correlation matrices, respectively; and

E is a diagonal matrix of non-negative unique variances.

This model, which is called a heteroscedastic error model, allows for measurement error for different variables (Wothke & Browne, 1990). Note that Equation 2 decomposes test scores into common factor score and error score components. Thus, the common factor correlation (corrected for attenuation) has a direct-product structure,

$$P_C = P_M \otimes P_T. \quad (3)$$

One useful version of the DPM is defined by adding a restriction (i.e., $E = E_M \otimes E_T$, with E_M and E_T diagonal) that yields

$$\Sigma = Z(P_M \otimes P_T + E_M \otimes E_T)Z. \quad (4)$$

This is called a composite error model (Wothke & Browne, 1990). Thus, there are two versions of the DPM: the more general heteroscedastic error model given in Equation 2, and a composite error model given in Equation 4. The program MUTMUM (Browne, 1991) estimates the parameters in the DPM.

Testing Hypotheses for Methods and Traits

To introduce a set of procedures for formally testing hypotheses concerning the effects of traits and methods, it is useful to consider the simple case with three traits and three methods. (These procedures are applicable to other MTMM matrices.) Suppose the correlation matrices among methods and among traits can be written, respectively, as

$$P_M = \begin{bmatrix} 1 & & \\ \rho_{m21} & 1 & \\ \rho_{m31} & \rho_{m32} & 1 \end{bmatrix}, \quad (5)$$

and

$$P_T = \begin{bmatrix} 1 & & \\ \rho_{t21} & 1 & \\ \rho_{t31} & \rho_{t32} & 1 \end{bmatrix}. \quad (6)$$

Five useful hypotheses about methods are:

- H_1 : Method correlations follow a Toeplitz pattern;
- H_2 : All methods are equally correlated;
- H_3 : All methods are completely unrelated;
- H_4 : All methods are equivalent; and
- H_5 : Some methods are equivalent.

H_1 is especially suitable for multitest-multi-occasion data in which methods represent occasions. It posits that the method correlation matrix is a Toeplitz matrix of the form

$$P_M = \begin{bmatrix} 1 & & & \\ \rho_1 & 1 & & \\ \rho_2 & \rho_1 & 1 & \\ \rho_3 & \rho_2 & \rho_1 & 1 \end{bmatrix}. \quad (7)$$

If the occasions are equally spaced, the correlation between occasions (i.e., methods) depends on the interval between them. In applications to typical multitest-multioccasion data, $\rho_1 \geq \rho_2 \geq \rho_3$ would be obtained. For the MTMM data with three methods, H_1 yields the restriction $\rho_{m21} = \rho_{m32}$.

H_2 posits that all methods are equally correlated. H_2 implies that all nondiagonal elements of \mathbf{P}_M are equal. Thus, H_2 yields the restriction $\rho_{m21} = \rho_{m31} = \rho_{m32}$ ($=\rho$). According to H_2 , whether a method is shared or not influences heterotrait correlations. For example, the common factor correlations involving Traits 1 and 2 would be ρ_{121} within each method, whereas they are $\rho_{m21}\rho_{121} = \rho_{m31}\rho_{121} = \rho_{m32}\rho_{121} = \rho\rho_{121}$ across different methods (see Equation 3). That is, once different methods are used, any combination of methods leads to the same effect.

H_3 suggests that all methods are orthogonal or that all nondiagonal elements of \mathbf{P}_M are 0. That is, H_3 implies the restriction $\rho_{m21} = \rho_{m31} = \rho_{m32} = 0.0$. H_4 posits that all methods are equivalent (i.e., $H_4: M_1 = M_2 = M_3$). H_4 implies the restriction that all methods are perfectly correlated: $\rho_{m21} = \rho_{m31} = \rho_{m32} = 1.0$. Thus, H_4 represents complete redundancy in methods; that is, a single method factor is sufficient to represent method effects. A formal test can be conducted by comparing the full DPM with the restriction $\rho_{m21} = \rho_{m31} = \rho_{m32} = 1.0$. Note that H_3 and H_4 are nested versions of H_2 .

When H_4 is rejected, it is still possible that one or more pairs of methods might not be equivalent (H_3). For example, a researcher could investigate whether any methods used in a pretest are redundant in order to avoid unnecessary duplication in subsequent research, so that the length of a survey as well as the potential boredom effect among respondents could be reduced. Thus, whether a particular pair of methods is equivalent could be tested. For instance, it may be hypothesized that Methods 1 and 2 are equivalent (i.e., $M_1 = M_2$). This requires the restriction that the two methods be

perfectly correlated (i.e., $\rho_{m21} = 1.0$). However, this restriction implies another restriction—both methods must be equally correlated with the other methods (i.e., $\rho_{m2r} = \rho_{m1r}$, $r \neq 1, 2$); otherwise, \mathbf{P}_M will not be positive definite or semidefinite (Browne, 1991). Thus, the hypothesis of equivalence between Methods 1 and 2 ($M_1 = M_2$) can be tested with the following restrictions: $\rho_{m21} = 1.0$ and $\rho_{m23} = \rho_{m13}$.

Four useful hypotheses regarding traits are:

- H_6 : All traits are equally correlated;
- H_7 : All traits are completely unrelated;
- H_8 : All traits are equivalent; and
- H_9 : Some traits are equivalent.

H_6 posits that all traits are equally correlated. This hypothesis implies that all trait correlations are the same; that is, $\rho_{112} = \rho_{113} = \rho_{123}$ ($=\rho$). Thus, whether a common trait is involved or not affects heteromethod correlations. For example, the correlations involving Methods 1 and 3 under each trait would be ρ_{m31} , whereas those across different traits are $\rho_{121}\rho_{m31} = \rho_{131}\rho_{m31} = \rho_{132}\rho_{m31} = \rho\rho_{m31}$. That is, any combination of traits leads to the same effect when different traits are involved.

H_7 says that all traits are completely orthogonal. Thus, this hypothesis yields the restriction $\rho_{121} = \rho_{131} = \rho_{132} = 0.0$. H_8 posits that all traits are equivalent. This hypothesis suggests that all traits are the same (i.e., $T_1 = T_2 = T_3$), or that traits do not make a difference in the heteromethod correlations.

When H_8 is rejected, it is meaningful to test whether some traits are equivalent (H_9). For instance, it may be hypothesized that Traits 2 and 3 are equivalent (i.e., $T_2 = T_3$). This hypothesis requires the restriction that the correlation between the two traits be unity (i.e., $\rho_{123} = 1.0$). Again, this restriction implies another restriction that both traits be equally correlated with the other traits (i.e., $\rho_{12r} = \rho_{13r}$, $r \neq 2, 3$). Thus, the hypothesis of equivalence between Traits 2 and 3 ($T_2 = T_3$) can be tested with the restrictions $\rho_{132} = 1.0$ and $\rho_{131} = \rho_{121}$.

An Illustration

Method. Lawler's (1967) data were used to illustrate these hypotheses. The MTMM matrix is given in Table 1. Three traits are represented: quality of job performance, ability to perform on the job, and effort put forth on the job. The traits were measured with three methods: superior ratings, peer ratings, and self-ratings.

MUTMUM (Browne, 1991) was used to investigate DPMs. Although LISREL or EQS could be used by following Wothke & Browne's (1990) parameterization of the DPM as a linear model, MUTMUM was selected for the following reasons. MUTMUM estimates the trait and method correlation matrices simultaneously and provides standard errors for both trait and method correlations. In contrast, a particular LISREL or EQS run only computes standard errors for trait or method correlations; the model then must be reparameterized and the program run again to yield both estimates. Also, MUTMUM accommodates equality constraints simultaneously on both trait and method correlation matrices; this cannot be done with LISREL or EQS under the DPM. Furthermore, LISREL sometimes results in empirical underidentification, but MUTMUM is not as sensitive to such occurrences (e.g., Bagozzi & Yi, in press). MUTMUM also automatically imposes inequality constraints for some parameter

estimates; for example, trait and method correlations are bounded between -1 and +1 (Browne, 1991, p. 4). These inequality constraints result in maximum likelihood estimates in some circumstances in which the likelihood function would be unbounded otherwise.

Results. The full DPM specified in Equation 4 first was estimated (see Model A in Table 2). The model fit was satisfactory (this model also was estimated with LISREL following the procedure by Wothke & Browne, 1990, and the results were the same as those obtained by the MUTMUM analysis). Next, a series of restricted DPMs were fit to investigate the pattern of individual method factors. χ^2 tests then were used to test the overall hypotheses as well as specific hypotheses about differences between methods (see Table 2).

H₁ was tested by comparing the full model (Model A) and the restricted model with a Toeplitz pattern (Model B). The χ^2 difference test (test of Model A vs. Model B in Table 2) indicated that H₁ could be rejected. H₂ posited that all method correlations were equal (Model C). The χ^2 difference test (Model A vs. Model C) was significant at the .001 level. Thus, H₂ could be rejected. H₃, which posited that all methods were completely unrelated, was tested by comparing Models A vs. D; the χ^2 difference was significant at the .001 level, suggesting that H₃ be rejected. H₄ is an omnibus hypothesis that all methods

Table 1
 Lawler's (1967) Managerial Job Performance Data (N = 113)
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Rater and Variable	Su-Q	Su-A	Su-E	P-Q	P-A	P-E	Se-A	Se-A	Se-E
Superior (Su)									
Quality (Q)	1.00								
Ability (A)	.53	1.00							
Effort (E)	.56	.44	1.00						
Peer (P)									
Quality (Q)	.65	.38	.40	1.00					
Ability (A)	.42	.52	.30	.56	1.00				
Effort (E)	.40	.31	.53	.56	.40	1.00			
Self (Se)									
Quality (Q)	.01	.01	.09	.01	.17	.10	1.00		
Ability (A)	.03	.13	.03	.04	.09	.02	.43	1.00	
Effort (E)	.06	.01	.30	.02	.01	.30	.40	.14	1.00

Table 2
 Results of χ^2 Goodness-of-Fit Tests for Models and χ^2 Difference Tests
 for Hypotheses About Methods, Traits, and Communalities

Model and Test	<i>df</i>	χ^2	Approximate <i>p</i> value
Method Model			
A. Trait \times Method Model	25	28.94	.27
B. Toeplitz-Pattern Model	26	54.56	< .001
C. Equally Correlated Methods	27	59.55	< .001
D. Completely Unrelated Methods	29 ^a	137.38	< .001
E. All Equivalent Methods	30	185.39	< .001
F. Methods 1 & 2 Equivalent	28	65.14	< .001
G. Methods 2 & 3 Equivalent	28	150.27	< .001
H. Methods 1 & 3 Equivalent	28	148.80	< .001
Test of			
Toeplitz-Pattern Method			
Correlations (A vs. B)	1	25.62	< .001
Equal Method Correlations (A vs. C)	2	30.61	< .001
Unrelated Methods (A vs. D)	4	108.44	< .001
$M_1 = M_2 = M_3$ (A vs. E)	5	156.46	< .001
$M_1 = M_2$ (A vs. F)	3	36.20	< .001
$M_1 = M_3$ (A vs. G)	3	121.33	< .001
$M_2 = M_3$ (A vs. H)	3	119.86	< .001
Trait Model			
I. Trait \times Method Model	25	28.94	.27
J. Equally Correlated Traits	27	34.14	.16
K. Completely Unrelated Traits	30 ^a	201.35	< .001
L. All Equivalent Traits	30	92.02	< .001
M. Traits 1 & 2 Equivalent	28	66.11	< .001
N. Traits 2 & 3 Equivalent	28	60.16	< .001
O. Traits 1 & 3 Equivalent	28	71.73	< .001
Test of			
Equal Trait Correlations (I vs. J)	2	5.20	> .05
Unrelated Traits (I vs. K)	5	172.41	< .001
$T_1 = T_2 = T_3$ (I vs. L)	5	63.08	< .001
$T_1 = T_2$ (I vs. M)	3	37.17	< .001
$T_1 = T_3$ (I vs. N)	3	31.22	< .001
$T_2 = T_3$ (I vs. O)	3	42.79	< .001
Communality Model			
P. Unrestricted E	21	28.83	.12
Q. $\mathbf{E} = \mathbf{E}_M \otimes \mathbf{E}_T$	25	28.94	.27
R. $\mathbf{E}_M = \mathbf{I}$	27	31.88	.24
S. $\mathbf{E}_T = \mathbf{I}$	27	32.29	.21
T. Equal diagonal elements of E	29	34.53	.22
Test of			
$\mathbf{E} = \mathbf{E}_M \otimes \mathbf{E}_T$ (P vs. Q)	4	.11	> .99
$\mathbf{E} = \mathbf{I} \otimes \mathbf{E}_T$ (Q vs. R)	2	2.94	> .20
$\mathbf{E} = \mathbf{E}_M \otimes \mathbf{I}$ (Q vs. S)	2	3.35	> .10
Equal diagonal elements of E (Q. vs. T)	4	5.59	> .25

^aThe degrees of freedom were modified because the MUTMUM program automatically imposes inequality constraints on parameter estimates (Browne, 1991, p. 4).

are equivalent; the χ^2 difference test (A vs. E) suggested that H_4 be rejected.

H_5 posited that some of the methods might be equivalent. Tests of individual methods also were conducted by comparing the full trait \times method model with restricted models. The results for the model with the equivalence constraint for Methods 1 and 2 (Model F) are provided in Table 2. The results indicated that the hypothesis of equivalent Methods 1 and 2 should be rejected (Model A vs. Model F). The hypotheses of equivalence for Methods 2 and 3 (Model G) and equivalent Methods 1 and 3 (Model H) also were tested. Both hypotheses were rejected (see tests of Model A vs. Model G and Model A vs. Model H in Table 2).

Table 2 also includes the results for testing hypotheses about traits. As for methods, the trait \times method model χ^2 is a general goodness-of-fit index for the DPM. A series of restricted DPMs were fit to test hypotheses about trait patterns. χ^2 difference tests then were used to test the significance of overall as well as individual patterns of traits.

H_6 was tested by comparing the full DPM (Model I) and the restricted model with all equal trait correlations (Model J). The χ^2 difference test (I vs. J) was not significant at the .05 level. H_7 posited that all traits were completely unrelated. The χ^2 difference test (Model I vs. K) was significant at the .001 level. H_8 is an omnibus hypothesis that all traits are equivalent. The χ^2 difference test (Model I vs. L) suggested that H_8 be rejected. H_9 tested the possibility that some traits might be equivalent (Models M, N, and O). The χ^2 difference test results of Model I vs. M indicated that the hypothesis of equivalent Traits 1 and 2 (Model M) should be rejected. Other hypotheses were tested similarly, but neither Traits 2 and 3 (Model I vs. N) nor Traits 1 and 3 (Model I vs. O) were found to be equivalent.

Testing Hypotheses for Communalities

Hypotheses about the error matrix E also may be considered, because the patterns of E gen-

erate corresponding patterns for communalities. Some useful hypotheses about errors are:

- H_{10} : E is unrestricted;
- H_{11} : $E = E_M \otimes E_T$;
- H_{12} : $E = I \otimes E_T$;
- H_{13} : $E = E_M \otimes I$; and
- H_{14} : All diagonal elements of E are the same;

where I is the identity matrix. H_{10} implies a basic DPM, as in Equation 2, and imposes no structure on E . That is, E is not restricted under H_{10} . H_{11} defines a useful version of the DPM by adding the restriction $E = E_M \otimes E_T$. This restriction implies that trait communalities have the same rank order within each method and that method communalities have the same rank order within each trait (Browne, 1991).

H_{12} causes the communality of each trait to be equal across methods. This hypothesis can be tested through the restricted model by fixing the diagonal matrix of errors corresponding to methods to unity; that is, $E_M = I$ (see the expression in Equation 4). Similarly, H_{13} implies that the communality of each method is equal across traits. Thus, this hypothesis yields the restriction that E_T is an identity matrix.

H_{14} posits that all diagonal elements of E are the same. This hypothesis implies that trait communalities remain the same under all methods and that method communalities remain the same under all traits.

An Illustration

Table 2 also summarizes the results for testing hypotheses about communalities based on Lawler's (1967) data. As for the methods and traits hypotheses, a series of restricted DPMs were fit to test hypotheses about communality patterns, and χ^2 difference tests then were used to test the hypotheses.

H_{10} and H_{11} imply two versions of the DPM: a heteroscedastic error model and a composite error model, respectively. The latter model is a special case of the former, because H_{11} imposes a restriction of composite errors on E . Table 2 shows the results for the general model (Model

P) and for the restricted model with the composite error structure (Model Q). The χ^2 difference test (Model P vs. Q) was not significant at the .99 level. Thus, H_{11} could not be rejected, and the composite error model was suitable for the data.

H_{12} predicts that trait communalities remain the same under all methods, and it requires the restriction $E_M = I$ (Model R in Table 2). The χ^2 difference test (Model Q vs. R) was not significant at the .20 level. Thus, H_{12} could not be rejected, and there is evidence that trait communalities were constant across methods.

H_{13} posits that method communalities remain the same under all traits. This hypothesis was tested by examining the restriction $E_T = I$ (Model S) vs. Model Q; the χ^2 difference test was not significant at the .10 level. H_{14} requires that all diagonal elements of E are the same (Model T). The χ^2 difference test (Model Q vs. T) suggested that this hypothesis could not be rejected. This finding suggests that trait communalities remained the same under all methods and that method correlations remained the same under all traits.

Conclusions

This paper has shown how the overall and specific patterns of traits, methods, and communalities can be formally tested with the MUTMUM program. Empirical underidentification problems, which are frequently observed in MTMM analyses (Schmitt & Stults, 1986), were not encountered in analyzing the data from Lawler (1967). These problems were avoided, perhaps because the program imposes constraints on the parameter space to avoid ill-defined solutions. In general, however, it is possible that parameters constrained at the boundaries point to misspecification errors such as when negative or zero uniqueness arises. The results also provided some useful information—the trait correlations appeared to be equal, and method and trait communalities were constant for the Lawler data. Such information could be useful in practical applications of the direct-product model.

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Acknowledgments

The authors thank the editor and two anonymous reviewers for helpful suggestions on an earlier version of this article. An anonymous reviewer suggested testing hypotheses for communalities. The financial support of the Michigan Business School is also gratefully acknowledged.

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