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ASSESSING LINEARITY IN STRUCTURAL EQUATION MODELS THROUGH GRAPHICS

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Abstract
While Structural Equation Models (SEMs) generally assume linear linkages between variables, it is a well-worn issue that this may not adequately describe the complexity and richness of social phenomena. For this reason, nonlinear SEMs that include interaction effects between latent factors have been developed.
However, while a large literature is available on methods for their estimation, few efforts have been devoted to the development of adequate diagnostic tools. In particular, the use of graphics has been rather limited so far, probably because of the partial information provided by the SEM residuals.
Hence, with this paper we introduce a graphical device which aims to evaluate the SEM linearity assumption, without any previous estimation of nonlinear models. Specifically, we define a series of plots based on the individual latent variable scores in order to investigate nonlinear effects involving latent variables. In doing so, we also highlight the potential for graphical tools within SEM when factor scores for each individual in the sample are visualized.
We call our graphical device the latent joint effect plot, as it displays the joint effect of two latent variables on some other response variable. The idea is presented through both simulated data and an illustrative example regarding the determinants that lead high school students to drop out of the Italian education system.

Keywords

Graphical diagnostic, Interaction term, Latent joint effect plot, Nonlinear effects

1. Introduction

Over the past few decades, Structural Equation Models (SEMs) have been increasingly applied in order to analyze causal relationships between theoretical latent concepts in many research areas.
Generally speaking, SEM analysis can be summarized in the following steps. First, the researcher specifies a tentative initial model. Then, if it does not fit the data, the model is modified taking into account both the data and its substantive meaning. Several models may be tested in this process, where the specification of each model may be theory or data driven.
Within this context, Joreskög (1993) described a possible strategy for data analysis: *i)* specify an initial model; *ii)* estimate the measurement and then its structural equation part; *iii)* evaluate the model's goodness-of-fit; *iv)* modify it according to the goodness-of-fit results (setting some parameter equal to zero if the model is over fitted, or looking for some model modification that leads to a better fit); repeat steps *i)-iv)* until a reasonable model is found.
In this trial-and-error process, one possibility is to verify whether or not the assumption of linear linkages between the latent variables holds. The idea is that the model may not fit the data because the relationships between the social phenomena under study are substantially not linear.
Nonlinearities may be modelled in many ways, and in this paper we focus on interaction effects within the structural part of SEMs. That is, we consider the case of two latent variables interacting with each other when explaining the pattern of some endogenous variable.
In some case, interaction effects are assumed on the basis of theoretical sociological hypotheses. An interaction model is estimated, and the existence of nonlinearity is evaluated through statistical tests.
However, before estimating an interaction model, one may wonder if the interaction is in some way justified by the data: a modus operandi that may be particularly profitable in view of the lack of consensus in the literature on the approach which provides the optimal method of estimation. Marsh *et al.* (2004) reported a trade-off between accessibility, simplicity, bias, precision, power, and Type I error rate when choosing an estimation method for interaction models.

For this reason, in this paper we present a graphical device which aims to evaluate the linearity assumption, without any previous estimation of nonlinear models. We present a series of plots, which we call *latent joint effect plots*, that make it possible to check for the presence of interaction effects between latent variables.
Offering this new graphical tool to SEM users is more than worthwhile: with our proposal we aim at encouraging social researcher to a larger use of graphics in SEM. We not only believe that statistical graphics is an undeveloped area in sociological practice (as claimed by Becker 2000), but more specifically that the SEM community may profitably develop and employ proper graphical tools if it learns to exploit latent variable factor scores to visually analyze SEM model outputs.
The paper is organised as follows. In section 2 the approaches dealing with nonlinear latent variable relationships are briefly reviewed, while in section 3 our graphical tool is presented and discussed with simulated data. In sections 4 and 5 respectively, an illustrative example and some concluding remarks are reported.

2. Testing linearity against nonlinearity in SEMs

In brief, SEMs combine a causal model between latent variables with a measurement model of latent factors through their observed indicators (Joreskög, 1970; Bollen, 1989). Formally, the causal relationships between latent factors are described by the equation:

$$\boldsymbol{\eta} = \mathbf{B}\boldsymbol{\eta} + \boldsymbol{\Gamma}\boldsymbol{\xi} + \boldsymbol{\zeta} \quad (1)$$

where $\boldsymbol{\eta}$ is the vector of latent endogenous variables, $\boldsymbol{\xi}$ is the vector of latent exogenous variables, **B** is the coefficient matrix for the effects of $\boldsymbol{\eta}$ on every other latent endogenous variable, **Γ** is the coefficient matrix that shows the influence of $\boldsymbol{\xi}$ on $\boldsymbol{\eta}$ and $\boldsymbol{\zeta}$ is the disturbance terms vector.
The measurement part for the observed exogenous and endogenous indicators is defined through the following two equations:

$$\mathbf{y} = \boldsymbol{\Lambda}_y \boldsymbol{\eta} + \boldsymbol{\varepsilon} \quad (2)$$

$$\mathbf{x} = \boldsymbol{\Lambda}_x \boldsymbol{\xi} + \boldsymbol{\delta} \quad (3)$$

where **y** and **x** are the vectors of observed indicators that measure the latent variables $\boldsymbol{\eta}$ and $\boldsymbol{\xi}$, respectively; $\boldsymbol{\Lambda}_y$ and $\boldsymbol{\Lambda}_x$ are the coefficient

matrices relating **y** to η and **x** to ξ; ε and $\boldsymbol{\delta}$ are the measurement error vectors for **y** and **x**.

An SEM model is specified following some hypotheses. In this paper, we focus on the assumption of linear relationships between latent variables. Specifically, we consider the case of two (or more) latent variables interacting with each other when explaining the pattern of some endogenous variables.

The classic approach to verify whether a model with latent interaction terms fits the data relies on hypothesis testing theory and a null linear model is tested against some alternative interaction effect model. The statistical significance of each interaction parameter and/or the overall fit of the model can be evaluated. In particular, chi-square test and fit indexes are used to verify whether the interaction hypotheses are supported.

However, two open issues arise. First, there is no agreement on how to estimate an SEM model with latent interaction effect. Secondly, these models implicitly violate the normality assumption (products of normally distributed variables do not have a normal distribution), and hence the test statistic distributions need to be adapted to nonlinearity.

Several strategies to estimate latent interaction effect are discussed in the SEM literature. Kenny and Judd (1984) suggested modelling interactions between latent variables by means of the product of observed indicators. This idea has been further investigated by many authors. Jaccard and Wan (1995) extend Kenny and Judd's procedure by defining a multiple product indicators approach, while Jöreskog and Yang (1996) make a proposal to rely on a single product indicator (see also: Saris *et al*., 2007). Others exploit a two-step technique in order to estimate interaction terms (Ping, 1996; Bollen, 1996; Bollen, Paxton 1998) or a multi-group approach if one or both of the latent interacting variables are discrete (Rigdon *et al.*, 1998; Reinecke, 2002). Alternatively, Jonsson (1998) and later Jöreskog (2000) suggest analyzing the interaction directly by the product of the exogenous latent variable scores. The latter approach has been compared with the traditional product indicant technique in Schumacker (2002), and has been used as a starting point for clustering municipalities in an applied study in regional development framework (Cziraky *et al.*, 2006). If only a single indicator for each

latent variable is defined, the corrected covariance matrices approach is also available (Bollen, 1989, chap.9).
Once an interaction model has been estimated, the second issue arises. Classic test statistic distributions are based on the multivariate normality assumption of the indicators. However, the presence of latent interaction effects implies a departure from this specification hypothesis (Moosbrugger *et al.,* 1997; Raykov, Penev 1997; Tomarken, Waller 2005). Estimation methods, based on the multivariate normality assumption (such as maximum likelihood), provide non-robust results for non-normal data (Bollen, 1989), while the asymptotically distribution-free estimation procedure (Browne, 1984; Satorra, 1990) requires large sample size to exploit asymptotical unbiasedness. In response, the latent moderated structural equations estimation method has been developed dealing with the methodological problems of non-normally distributed variables in latent interaction models (Klein, Moosbrugger 2000). It provides unbiased estimates of standard errors, although some drawbacks remain when many interacting variables and many observed indicators are involved in the model. Klein and Muthén (2007) developed the Quasi Maximum Likelihood estimation method to deal with computational effectiveness in case of complex model. However, the corresponding quasi-likelihood ratio test also relies on asymptotic results.
In brief, while latent interactions are a very active area of research (Batista *et al.* 2004; Song, Lee 2006; Little *et al.*, 2006; Saris *et al*., 2007), little effort has been devoted to the development of strategies for the assessment of their presence from a diagnostic perspective.

3. A graphical tool to evaluate linearity in SEMs: the latent joint effect plot

As mentioned above, we agree with the Becker's 2000 claim that although graphical methods play an important role in all aspects of data analysis, statistical graphics are still an undeveloped area in sociological practice (Becker 2000). In particular, we noticed that graphical tools are not often exploited in SEMs.
One of the reasons may be that graphical devices in SEM are based on the covariance residuals, that is on the difference between the observed covariances and those implied by the model. These

residuals signal if the estimated model does not fit the data, but they are unable to lead the researcher to easily discover ways of improving the model fit.
Alternatively, we suggest to introduce graphical devices based on the factor scores for each individual in the sample, which may identify more exploitable information. As an example, in this paper we offer a graphical tool, the *latent joint effect plot*, which is based on the scores of the latent variables for individual observations and allows a visual evaluation of the linearity assumption in the structural part of an SEM.
The device we propose is in line with the graphical diagnostics used in the framework of multiple linear regression (Cook, Weisberg, 1989, 1999; Cook, 1998). In particular, the plot belongs to the framework of the conditional plot (known also as 'coplot', Cleveland, 1993: chapters 4 and 5), and is included in the class of the graphs used for model adequacy and assumption verification, according to the taxonomy provided by Snee and Pfeifer (2006).
Finally, we note that several methods are available for estimating the values of factor scores in SEMs, each of which may provide different values for each individual. In practice, however, estimates obtained using the different estimation methods are highly correlated (Bollen, 1989; p. 105), and hence any of them can be safely used for diagnostic purposes. For simplicity's sake, in this work, we compute the factor scores according to the method described in detail in Joreskog (2000) and implemented in Lisrel 8.30.

3.1 The joint effect plot for two latent covariates

The *latent joint effect plot* is a general device that works for any number of latent variables in a model. However, for the sake of illustration, we first present it for a model with two exogenous latent variables, ξ_1 and ξ_2, and one endogenous latent variable η_1.
Let us assume, then, that η_1 depends only on ξ_1 and ξ_2, and we wish to examine the presence of an interaction effect between ξ_1 and ξ_2 in explaining η_1. Furthermore, let $\hat{\eta}_i$ and $\hat{\xi}_j$ be the estimated factor scores for η_i and ξ_j, respectively.
Our *latent joint effect plot* will then be drawn according to the following steps:

1. Choose which latent exogenous variable is to be considered as a moderator variable (say ξ_2);
2. Draw the scatterplot of $\hat{\eta}_1$ against $\hat{\xi}_1$;
3. Divide the moderator latent variable scores $\hat{\xi}_2$ into an appropriate number *k* of groups;
4. Estimate *k* regression lines of $\hat{\eta}_1$ against $\hat{\xi}_1$, one for each group defined for $\hat{\xi}_2$;
5. Superimpose the *k* regression lines estimated at step 4 onto the scatterplot of $\hat{\eta}_1$ against $\hat{\xi}_1$ obtained at step 2.

The steps described before produce a *latent joint effect plot* of ξ_1 and ξ_2 over $\eta_{1:}$ a scatterplot with some superimposed regression lines appears. If some interaction is present, the regression lines will intersect, having different intercepts and slopes. Vice versa, if the interaction is not present (i.e. the linearity assumption holds), these regression lines will be parallel, differing only in the intercepts. Finally, coincident lines in the plot suggest that the moderator variable should be excluded from the model. This fact can be easily proved, following the scheme given in Porzio and Vitale (2006, Appendix A).
In order to exemplify this, two different simulated datasets have been generated with two exogenous latent variables, ξ_1 and ξ_2, each measured by three observed indicators normally distributed. In the first dataset, the endogenous latent variable η_1 is defined as a linear combination of the two exogenous latent variables (Equation 4):

$$\eta_1 = \alpha_1 + \gamma_{11}\xi_1 + \gamma_{12}\xi_2 + \zeta_1 \qquad (4)$$

where α_1 is an intercept term, γ_{11}, γ_{12} are the two coefficients related to the linear effects of ξ_1 and ξ_2 on η_1 and ζ_1 is a normal distributed disturbance term.
Figure 1a shows the *latent joint effect plot* performed by the first simulated dataset. In particular, the plot highlights the scatterplot of the factor scores $\hat{\eta}_1$ against the factor scores $\hat{\xi}_1$, with four regression lines estimated over four groups of the $\hat{\xi}_2$ scores. The first group accounts for the first 25% of the scores, the second for the scores between the 25-th and the 50-th percentiles, and so on. In line with

the generated data, the parallel lines in Figure 1 emphasize that in this case linearity holds.

In the second simulated dataset, keeping ξ_1 and ξ_2 from the previous example, the endogenous latent variable η_2 is generated according to the model:

$$\eta_2 = \alpha_2 + \gamma_{21}\xi_1 + \gamma_{22}\xi_2 + \delta\ \xi_1\xi_2 + \zeta_2 \qquad (5)$$

where α_2 is an intercept term, γ_{21}, γ_{22} are the two coefficients related to the linear effects of ξ_1 and ξ_2 on η_2, δ is the product term's coefficient and ζ_2 is a normal distributed disturbance term. Figure 2 shows the *latent joint effect plot* performed by this second dataset. The four regression lines clearly intersect, correctly suggesting the presence of a nonlinear relationship between ξ_1 and ξ_2 in the explanation of the η_2 pattern.

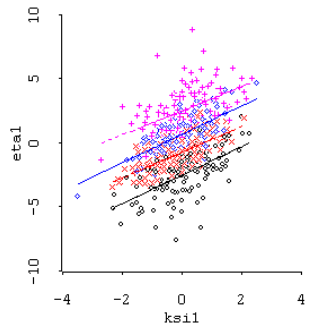

Figure 1. *Latent joint effect plot* with two latent covariates ξ_1 and ξ_2 and one endogenous variable η_1, each measured by three observed continuous indicators. Scatterplot of the factor scores $\hat{\eta}_1$ against the factor scores $\hat{\xi}_1$, with four regression lines estimated over four groups of the moderator $\hat{\xi}_2$. Parallel lines signal that interaction between ξ_1 and ξ_2 in the explanation of the η_2 pattern is absent.

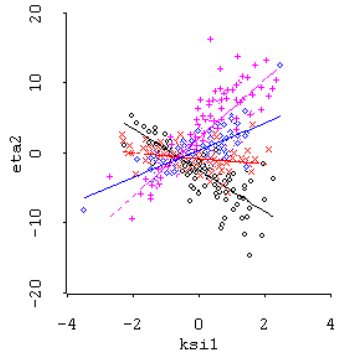

Figure 2. *Latent joint effect plot* with two latent covariates ξ_1 and ξ_2 and one endogenous variable η_2, each measured by three observed continuous indicators. Scatterplot of the factor scores $\hat{\eta}_2$ against the factor scores $\hat{\xi}_1$, with four regression lines estimated over four groups of the moderator $\hat{\xi}_2$ scores. Intersecting lines signal that some interaction is present between ξ_1 and ξ_2 in the explanation of the η_2 pattern.

3.2 The latent joint effect plot for more than two latent covariates

When the number of latent variables increases, the simple plot described in Section 3.1 is not appropriate for our purposes. If the model includes more than two covariates, the whole latent factor joint distribution must be taken into account. A kind of 'net effect plot' (Cook, 1998, chap. 13) needs to be defined, so that the interaction effect of two covariates can be evaluated given the effect of the other remaining variables.

In order to achieve this, the factor scores have to be displayed in a residual space. Specifically, let R be the set of all latent covariates included in the model that explains η_i except the ones (say ξ_j and ξ_{j+1}) for which an interaction effect is suspected. Then, our residual space will be spanned by the residual of the regression of η_i against R - $e(\eta_i/R)$, and the residual of the regression of ξ_j against R - $e(\xi_j/R)$. In brief, with $\hat{R}$ the estimated factor scores corresponding to R, the *latent joint effect plot* will be drawn according to the following steps:

1. Choose which latent covariate is to be considered as the moderator variable (say ξ_j);
2. Compute the OLS residuals $e(\hat{\eta}_i/\hat{R})$ from the linear regression of $\hat{\eta}_i$ vs. $\hat{R}$, and the OLS residuals $e(\hat{\xi}_j/\hat{R})$ from the linear regression of $\hat{\xi}_j$ vs. $\hat{R}$;
3. Draw the scatterplot of $e(\hat{\eta}_i/\hat{R})$ against $e(\hat{\xi}_j/\hat{R})$;
4. Divide the latent variable scores $\hat{\xi}_{j+1}$ into an appropriate number *k* of groups;
5. Estimate *k* regression lines of $e(\hat{\eta}_i/\hat{R})$ against $e(\hat{\xi}_j/\hat{R})$, one for each group of $\hat{\xi}_{j+1}$;
6. Superimpose the *k* regression lines estimated at step 5 onto the plot obtained at step 3.

The regression lines estimated on different grouped scores of the moderator variable ξ_{j+1} will highlight the presence of any interaction effect ξ_j and ξ_{j+1} on η_i: intersecting lines will suggest interaction.
For the sake of illustration, an example is offered to the reader. A simulated data set has been generated in order to specify a model with three exogenous variables, ξ_1, ξ_2, and ξ_3 and one endogenous variable η_3, each measured by three observed continuous indicators. The endogenous variable is derived so that the latent exogenous variables and an interaction term involving ξ_1 and ξ_2 enter the structural equation (Equation 6):

$$\eta_3 = \alpha_3 + \gamma_{31}\xi_1 + \gamma_{32}\xi_2 + \gamma_{33}\xi_3 + \delta\xi_1\xi_2 + \zeta_3 \qquad (6)$$

The corresponding *latent joint effect plots* are displayed in Figure 3. According to the simulated data, the presence of an interaction effect is only visualized in the *latent joint effect plot* displayed in Figure 3a, which shows the effect of ξ_1 and ξ_2 on η_3, fixing the effects of ξ_3: the intersecting lines clearly highlight some nonlinearity. In the other plots (Figures 3b and 3c), which evaluate respectively the joint effect of ξ_1 - ξ_3 and ξ_2 - ξ_3 in the explanation of η_3, parallel regression lines point out that no more interactions are present.

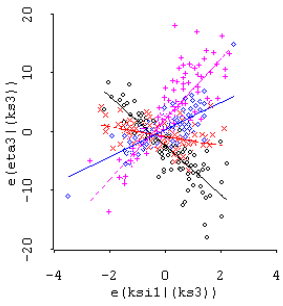

Figure 3a. Scatterplot of the OLS residuals $e(\hat{\eta}_3/\hat{\xi}_3)$ against the OLS residuals $e(\hat{\xi}_1/\hat{\xi}_3)$, with four regression lines estimated over four groups of the moderator $\hat{\xi}_2$ factor scores. The intersecting lines clearly highlight some nonlinearity between ξ_1 and ξ_2 on η_3, given the effect of ξ_3.

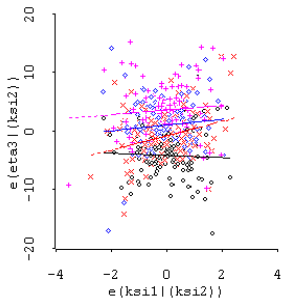

Figure 3b. Scatterplot of the OLS residuals $e(\hat{\eta}_3/\hat{\xi}_2)$ against the OLS residuals $e(\hat{\xi}_1/\hat{\xi}_2)$, with four regression lines estimated over four groups of the moderator $\hat{\xi}_3$ factor scores. The almost parallel lines signal that interaction is absent between ξ_1 and ξ_3 on η_3, given the effect of ξ_2.

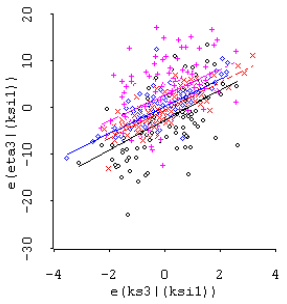

Figure 3c. Scatterplot of the OLS residuals $e(\hat{\eta}_3/\hat{\xi}_1)$ against the OLS residuals $e(\hat{\xi}_3/\hat{\xi}_1)$, with four regression lines estimated over four groups of the moderator $\hat{\xi}_2$ factor scores. The almost parallel lines signal that interaction is absent between ξ_2 and ξ_3 on η_3, given the effect of ξ_1.

4. An illustrative example

In order to illustrate how the proposed graphical procedure may work in practice, we analyze a causal model which aims to describe how some latent factors lead high school students to drop out of the Italian education system. We note that there is not a single measure available for measuring high school dropping out in Italy. Hence, dropping out is by itself a latent variable.

To this end, we analyze a sub-model of the SEM developed by Ragozini and Vitale (2006). We include the following latent factors: *family structure, socio-economic context*, *education system, high school dropping out*. The statistical units under examination are the Italian Provinces (i.e. administrative units). Each of the four latent variables are measured by three observed indicators. The socio-economic context is measured by two indicators of wealth and one of schooling; the family structure through indicators related to separations and divorces; the education system by some measures of

teacher experience and turn-over; the dropping-out by some student failure and delay indicators. Further details are in Ragozini and Vitale (2006).
In Figure 4, we present the hypothesized structural relationships among the latent factors in our sub-model. *Dropping out* (*Dropout*) depends directly and positively upon inexperienced teachers (*EduSystem*), and family break-up (*Family*), while the socio-economic context (*Context*) has both a negative direct and indirect effect on dropping out.
If linearity is assumed, the corresponding structural equations will be:

$$EduSystem = \alpha_1 + \gamma_{11} Context + \zeta_1 \quad (7)$$

$$Dropout = \alpha_2 + \gamma_{21} Context + \gamma_{22} Family + \beta_{21} EduSystem + \zeta_2 \quad (8)$$

We will then use our *latent joint effect plot* to evaluate this assumption. Given the hypothesized relationships, three plots suffice to investigate the presence of any interaction effect, as only the second structural equation may admit interactions, and that it has three latent terms. Figures 5a, 5b and 5c show these *latent joint effect plots* for the interaction of education system and family, context and family, education system and context, respectively[1].
The intersecting regression lines in Figure 5a, estimated over the two groups of the moderator variable family, highlight the presence of some interaction effects.
In Figure 5b, the lines are substantially parallel, while Figure 5c suggests some possible interaction. In brief, a stronger interaction between education system and family, and a smaller interaction between education system and context appear.
Finally, we perform a confirmative analysis to investigate to what extent the detected nonlinear relationships exist. For the sake of simplicity, we estimate path models on the factor scores. First, a full model that adds three latent product terms to the model in equation (8) is estimated: only the product term coefficient of education system and family turns out to be significant on the basis of the corresponding

[1] In the Figures 5a, 5b and 5c the continuous lines are estimated over the lower values of the moderator variable, while the dashed line over the higher values.

t-statistic. A likelihood ratio test is then performed to further investigate this interaction effect. The model with this interaction term and the three additive terms has χ^2= 14.42, df= 11, while the model without the interaction has χ^2= 22.36, df= 10. The Chi-square difference supports the interaction revealed by the *latent joint effect plot* of Figure 5a.

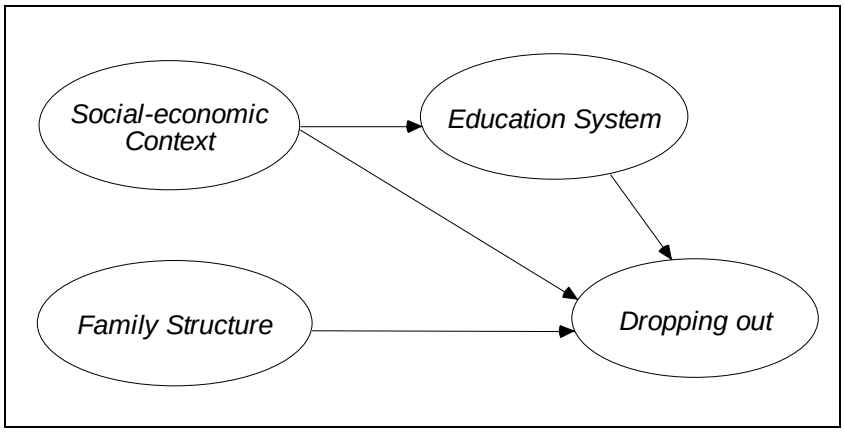

Figure 4. Theoretical path diagram for dropping out in high school.

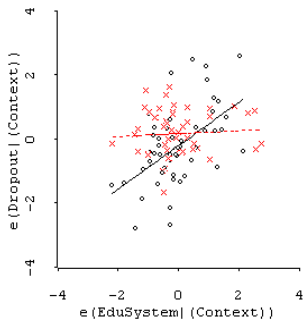

Figure 5a. *Latent joint effect plot* of Education System and Family on Dropout, after the effect of Context. Scatterplot of the OLS residuals e(*Dropout/Context*) against the OLS residuals e(*EduSystem/Context*), with regression lines estimated over two groups of the moderator variable Family. The intersecting regression lines highlight the presence of some interaction effects.

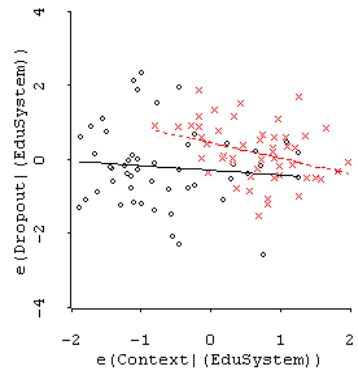

Figure 5b. *Latent joint effect plot* of Context and Family on Dropout, after the effect of Education System. Scatterplot of the OLS residuals e(*Dropout/EduSystem*) against the OLS residuals e(*Context/EduSystem)*, with regression lines estimated over two groups of the moderator variable Family. The parallel lines signal that interaction is absent.

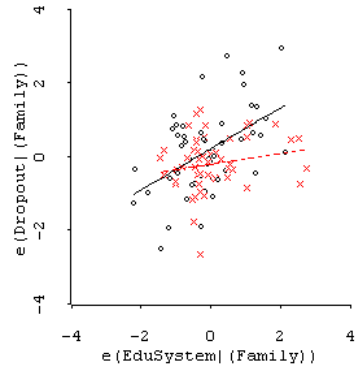

Figure 5c. *Latent joint effect plot* of Education System and Context on Dropout, after the effect of Family. Scatterplot of the OLS residuals e(*Dropout/Family*) against the OLS residuals e(*EduSystem/Family*), with regression lines estimated over two groups of the moderator variable Context. The quite parallel lines suggest some possible interaction.

5. Concluding Remarks

Graphical tools based on factor scores can profitably support the specification phase of an SEM. In particular, in this paper we have illustrated how to detect the presence of interaction effects through the *latent joint effect plot*, a graphical diagnostic device we introduced. The plot is designed to evaluate whether the linearity assumption on the relationship between latent variable holds. In particular, it makes it possible to check for the presence of any interaction effect between latent covariates. Besides its effectiveness, this tool has the advantage of assessing linearity without the previous estimation of any nonlinear model.

There are some precursors to the graphical device discussed in this paper. In multiple linear regression, plotted regression lines over different values of the moderator variable may highlight interaction between pairs of predictors (see e.g. Jaccard *et al*, 1990a, 1990b; Aiken and West 1991). However, these plots do not take into account the presence of others terms in the regression equation. In path models, Porzio and Vitale (2006) introduced a *joint effect plot* as an exploratory tool to evaluate whether non linear linkages between observed variables are actually present. In SEMs, Klein and Stoolmiller (2003), within an application on behavioural research, screened the data for an interaction effect through a series of scatterplots based on some observed indicators. However, their idea is suitable if the model involves few variables, and the nonlinear effect can be foreseen by a research hypothesis.

Finally, we note that the name *latent joint effect plot* recalls the *effect display* proposed by Fox (1987). However, our plot is a diagnostic device to be used while specifying a model, whereas Fox's plot is a tool for displaying the results of an analysis, *given* that a model has been correctly specified.

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