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Exploratory factor analysis revealing complex structure ☆

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ABSTRACT

The study introduces varimin, a novel factorial rotation which, unlike Thurstone's principle of simple structure, attempts to model complexity. Varimin-rotated factors are conceived as components of functional structure. Simple structure- (e.g., varimax-) rotated factors are conceived as representing indeterminate clusters of those components. An exploratory factor analysis was performed on decathlon scores from Olympic Games 1948–1988 of 233 decathletes. I expected that an interpretation of factors of transparent physical variables, modeled by complex structure, should outdo an interpretation of factors modeled by simple structure. Results of factor transformations by varimin and varimax were compared. Varimin factors of the 10 decathlon events pointed to components contributing jointly, with varying degrees, to the decathletes' performances revealing the following components, F_1: general athletic energy, F_2: pacing of energy expenditure (speed vs. endurance), and F_3: location of prime energy expenditure (upper vs. lower body parts). Varimax factors clustered the sports events without consistency, functional features of physical activities were not revealed. An analysis of complex structure is deemed appropriate to revive, on a broader scale, exploratory factorial research which, due to questionable output in the past, has long since lost its earlier challenge.

1. Introduction

Discontent with exploratory factor analysis prevails as a common thread in its long history. Harsh judgments were made by Revelle (1983): "*Factors are fictions*"; by Eysenck (1992): "*Morass of factor analysis*"; Schönemann (1996): "*Psychopathology of factor indeterminacy*." Disappointment has become evident, more noticeably than elsewhere, by factorial investigations into athletic performance (Büsch, Hagemann, & Thielke, 2001; Teipel, 1988, p. 341 ff.). The poor factorial validity of sports motor tests has been summarized by Bös (1987, p. 141). "*Doubts regarding the acceptability of factorial results exist since long.*" (p. 461). Unfortunately, researchers neglected to ask why conventional procedures did not meet initial expectations despite decade-long application.

I did make an attempt at solving the problem (Ertel, 2009a, in press). It seemed to me that the principle of simple structure, introduced by Thurstone (1935, 1947) as a guideline for factor rotation, was the main cause of flawed factorial results. The aim of transforming factors to simple structure has almost never been questioned. Rather it has been regarded, ever since Thurstone's introduction, as self-evident and thus comparable to Lakatos' hard core of suppositions.

At this point, Thurstone's parsimony needs reconsideration. His principle ignores the fact that manifest variables, multifaceted as they are, generally arise by joint contributions of co-variance sources. Units of observation are generally engendered by functional interactions. Thurstone's mathematical principle lacks, what might be called, 'combinational prudence'. The mathematical simplicity of simple structure, destroying factorial combinations, is imposed, tacitly and blind, on seemingly solitary observational entities ("variables") while the underlying components of these entities are entirely ignored. Simple structure rotation forces variables into clusters while the sources of clustering remain obscure. Empirical research demands an unveiling of relations among functional components, but this demand is obstructed by Thurstone's doubtful methodical decision.

Consequently, I replaced the standard procedure of factor rotation, varimax, with varimin, a novel procedure for rotating factor coordinates with the aim of letting manifest variables (items, test scores, etc.) be loaded with as many factors as the co-variance data permit. Varimin searches and maximizes the initial complexity of extracted factors. Varimax rotation maximizes the variance of squared factor loadings across variables ("the varimax criterion"). Varimin does the opposite, the variance of squared factor loadings is minimized. Varimin thus aims at modeling complex structure, the antithesis to simple structure. (See Harman, 1968, p. 144, his formula 14.25 represents the Varimax criterion which is not

☆ A longer German version of this paper and with confirming results of a questionnaire presented to decathletes may be obtained on request.

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altered except that the goal of maximizing V is replaced with that goal of minimizing V.)

$$V = n\sum_{p=1}^{m}\sum_{j=1}^{n}(b_{jp}/h_j)^4 - \sum_{p=1}^{m}\left(\sum_{j=1}^{n}(b_{jp}^2/h_j^2)^2\right)$$

At first sight, this approach might appear maverick (for an elaborate discussion see Ertel, 2009a, 2009b). Simple structure transformations, Kaiser's beloved "Little Jiffy", can hardly be abolished by theoretical reasoning alone. Appropriate empirical results are required in order to find out whether varimin transformations are not merely admissible, they might be better than varimax transformations or even be indispensable. Previous results of varimin applications on personality traits (Ertel, unpublished) and intelligence test performance (Ertel, in press) are encouraging.

An appropriate domain for testing the new methodological approach is athletics. Factors of motor behavior, performed under common rules, should be easier to comprehend than factors obtained from, say, intelligence test performance. In what follows, an account of factorial analyses of decathlon data is given which should merely exemplify the kind of results expectable for data subjected to the new procedure.

In a decathlon, each athlete competes in 10 events whose performance is distributed over 2 days: Various physical capacities and skills are required for winning scores on day 1 in 100 m race, long jump, shot put, high jump, 400 m race, and on day 2 in 110 m hurdles, discus, pole vault, javelin, and 1500 m race. Point scores are awarded on the basis of times (track events) and distance (field events). The athletes' scores correlate among each other (Table 1), factor analysis is expected to uncover considerably less than 10 latent determinants.

Previous factorial analyses of decathlon data.

Two earlier factor analyses of decathlon data were found, both aiming at simple structure. Karvonen and Niemi (1953) analyzed data of 62 decathlon competitors of the Olympic Games 1938, 1948, and 1952. A "multiple factor analysis" was applied "according to Thurstone". "*The rotations were performed graphically*" (p. 129). More methodical details are not conveyed. Poor results of earlier factorial studies on athletic performance might have discouraged researchers to continue factor analyses in this field. Despite published decathlon data from Olympic Games and world-wide interest in international sports competition I did not unearth, since 1977, from our literature any report on factor analyses of decathlon data.

Individual differences among decathletes should reveal one general physical component ('g') in the first place, just as one general intellectual component is almost always revealed from individual differences among intellectual performers. Overall genetic physical predispositions as well as training histories vary among athletes and should become manifest by one broad source of variance. A rotation to complex structure should reveal, in addition, 'g'-modifying factors which should specify particular physical functions.

Complex structure modeling hardly encounters the problems as they usually arise with simple structure. A varimax rotation – to take the most popular procedure for analyzing intellectual performance – removes 'g', although 'g' announces itself as an initial (unrotated) factor (Jensen, 1998). Varimax rotation dissolves the initial first factor, its loadings are redistributed among seemingly independent factorial "primaries". Highmore and Taylor (1954) lament factorial results of sports data: "*...the basic factor, representing general athletic ability (in which we are primarily interested), necessarily disappears, and the group factors [of simple structure rotation] show little relation to the classification indicated by the [initial] bipolar matrix*" (p. 4).

Now, since 'g' cannot be dismissed, theoretically, it must eventually be recovered from those "primaries". A "reunification" of variance is performed on a so-called second order level – a last-minute repair, as it were, with the help of artful mathematical operations (Schmid-Leiman transformation). A simple question arises which should have bothered statisticians since long: Why should 'g', present with an initial factorial solution, be removed at all? Varimin, by contrast, preserves 'g', improves its pattern together with patterns of additional factors while its contribution to the total variance is slightly diminished (to be demonstrated below). Additional factorial components will be aligned by varimin on the same first order level of factorial representation. They should emerge by itself without arbitrarily and riskily modeling them in advance.

2. Method

2.1. Data

Four sources of decathlon data were found and used: Intercorrelation matrices in Linden (1977), accessible by Basilevsky (1994), as well as individual scores for the 10 events from an internet source (2004), data from Kunz (1980) and from Zarnowski (1989). The largest number of athletes is provided by Zarnowski (N = 233), his athletes participated at 11 Olympic Games (1948–1988). The diversity within the sample is also the largest (49 participating nationalities). Zarnowski's data were therefore used for our factorial analysis.

2.2. Procedure

The 10 Zarnowski decathlon variables were intercorrelated. The intercorrelation matrix was subjected to Principal Component

Table 1
Intercorrelations of decathlon scores, taken from Zarnowski.

	1 100 m-run	2 Long jump	3 Shot put	4 High jump	5 400 m-run	6 110 m hurdles	7 Discus throw	8 Javelin throw	9 Pole vault	10 1500 m-run
1	1.00									
2	.66	1.00								
3	.51	.56	1.00							
4	.45	.64	.50	1.00						
5	.66	.60	.39	.54	1.00					
6	.62	.67	.55	.63	.58	1.00				
7	.43	.48	.80	.44	.37	.49	1.00			
8	.48	.61	.56	.70	.59	.63	.52	1.00		
9	.34	.46	.59	.40	.44	.41	.51	.52	1.00	
10	.09	.21	.09	.35	.53	.21	.12	.37	.24	1.00

Note: Source Zarnowski (1989): performances at the Olympic Games 1948–1988.
Negative time measures were used to obtain positive achievement correlations.

Table 2
Varimin-, varimax- and initial factor loadings of 10 decathlon events (source Zarnowski: $N = 233$ decathletes).

	Event	Varimin solution				Varimax solution				Initial solution			
		F_1	F_2	F_3	h^2	F_1	F_2	F_3	h^2	F_1	F_2	F_3	h^2
1	**100 m-run**	**.49**	**.61**	**.42**	.79	**.22**	**−.03**	**.86**	.79	**.73**	**−.07**	**.50**	.79
2	Long jump	.66	.47	.30	.75	.36	.15	.77	.75	.82	−.01	.27	.75
3	Shot put	.69	.51	−.37	.86	.86	−.01	.35	.86	.77	−.46	−.22	.86
4	High jump	.74	.18	.23	.64	.37	.40	.59	.64	.78	.17	.03	.64
5	**400 m-run**	**.75**	**.06**	**.46**	.78	**.17**	**.54**	**.67**	.78	**.77**	**.41**	**.13**	.78
6	**110 m hurdles**	**.65**	**.47**	**.30**	.75	**.36**	**.15**	**.76**	.75	**.81**	**−.01**	**.27**	.75
7	Discus throw	.66	.43	−.42	.79	.85	.02	.26	.79	.71	−.45	−.30	.79
8	Pole vault	.82	.16	.10	.67	.50	.44	.52	.67	.82	.12	−.11	.67
9	Javelin throw	.73	.11	−.35	.71	.74	.31	.15	.71	.66	−.15	−.45	.71
10	**1500 m-run**	**.65**	**−.65**	**.23**	.89	**.02**	**.94**	**.06**	.89	**.39**	**.76**	**−.40**	.89
	% Variance	47.2	17.2	11.2	76.0	27.2	16.7	32.0	76.0	54.4	12.4	9.2	76.0

Note: For better inspection, the data of the four race events are printed bold.

Analysis (PCA). With applying the conventional Kaiser–Guttman criterion and Cattell's scree test, three factors appeared suitable for rotation. The factors were rotated to varimin and varimax structure. An attempt was made to interpret and compare the two rotated solutions as well as the initial solution.

3. Results

The varimin, varimax, and initial (unrotated) factor loadings are shown in Table 2.

3.1. Interpreting varimin factors

Varimin F_1: General athletic energy.

F_1 is the expected general factor 'g' of track and field performance. Its validity is apparent by correlating F_1 loadings with decathlon total scores. Total scores are weighted points summed over the 10 events, the physical performance measures are transformed by sports experts into points following official standard rules.[1] The points' total, provided by Zarnowski, which had not been included here as a variable in the factorized data base, serves as an independent external criterion for testing the validity of varimin factor F_1. The correlation is sufficiently high ($r = .95$, $N = 233$). The validity of F_1 (general athletic energy) may thus be regarded as confirmed.

Some events show higher F_1 loadings than others and, accordingly, somewhat lower F_2 and/or F_3 loadings. It makes sense to suppose that events having comparatively higher F_1 loadings require more balanced motor skills (e.g., pole vault) than events with lower F_1 and higher F_2 and/or F_3 loadings (e.g., 100 m-run). Kunz (1980) already noticed conspicuous correlations between pole vault and various specialized events such as running, jumping and throwing. He concludes that pole vault is an "exceptionally many-sided event" (Kunz, 1980, p. 166). Many-sidedness implies dependence on multiple athletic faculties whose joint functioning is revealed, apparently, by high F_1 loadings and lower loadings on additional less broad factors.

Varimin F_2: Pacing of energy expenditure: Explosive speed vs. endurance.

Varimin F_2 is a bipolar factor, its highest loading, negative in sign, has long run 1500 m ($r = -.65$). No other event has a negative F_2 loading. An interpretation of F_2 may be obtained by *minimal pair comparison* (see Ertel, in press). Minimal pairs are pairs of variables which differ in only one feature. Two variables, e.g. two words or semantic units, such as *brother* and *sister*, may be equal in every respect except in one, gender in this case. We find minimal pairs of decathlon events, e.g., long run 1500 m and short run 100 m (see Table 3). The loadings for the two run events are almost equal for F_1 and F_3, but they contrast with F_2, thus forming an optimal *minimal pair*. Minimal pairs of variables are particularly useful and often necessary for factor interpretation.

Table 3
Minimal pair comparison of factor loadings between two run events (an example).

	Varimin factors		
	F_1	F_2	F_3
1500 m-run	.65	**−65**	.23
100 m-run	.49	**.61**	.42

The meaning of F_2 is elucidated by asking: How do physical demands differ between long and short run? Apparently, the pacing of energy expenditure is essential. Short runs require explosively fast, more concentrated, and long runs more enduring modes of energy expenditure. This interpretation applies for F_2 loadings of some other decathlon events. 110 m hurdles requires, as does 100 m-run, temporally concentrated effort expenditure (F_2: .47) while 400 m-run (F_2: .06), apparently, requires an optimum of both, speed and endurance.

Distinctions between temporally more extended vs. more concentrated effort expenditure can also be found among throw events. Shot put requires an explosion of strength, as does the discus throw ($F_2 = .51$), while for the javelin throw the temporal energy expenditure (.11) is less tight. Kunz called the javelin throw a "many-sided event", "probably extremely demanding" (Kunz, 1980, p. 167). The requirements of the other two throw events, shot put and discus, are more "one-sided" in that they require, in the first place, a maximum of strength output within seconds or fractions of seconds.

The proposed F_2 interpretation also applies to differences among jump events. It makes sense to expect concentrated effort expenditure with the long jump ($F_2 = .47$). The high jump ($F_2 = .18$) requires, in addition, skillful and coordinated body movements, not merely peaks of energy expenditure. The same holds with pole vault ($F_2 = .16$). In sum, F_2 seems to indicate demands of energy expenditure varying on a bipolar scale between the extremes of explosive output and extended endurance. This might remind intelligence researchers of an analogous distinction. For some tests, intellectual effort needs to be expanded fast (for "speed tests"), other tests require enduring effort within less limited time periods ("power tests") (Eberle, 1980).

A comment on bipolarity is due. Bipolarity of factor loadings in ability fields has been disregarded ever since Thurstone declared: "*It is ... natural to postulate that when a unique simple structure is*

[1] An official system for summarizing the 10 decathlon event scores has been issued in 1985 by the International Association of Athletics Federations (IAAF). Present-day competition rules are accessible via http://www.iaaf.org/index.html.

found for a battery of tests of mental abilities, then the non-vanishing entries in the factorial matrix are positive" (Thurstone, 1947, p. 341). Bemeyer (1957) remarked: "*The different methods of [factor] analysis [of mental aptitudes] yield factors which have negative loadings . . . Such factors, so Thurstone contends, must be devoid of 'scientific meaning'. They do not permit us to 'interpret the various tests as functions of the mental aptitudes which those tests elicit*'" (p. 23). Cyril Burt shared this view (Burt, 1954, p. 18). These authors did not realize that factorial metrics are arbitrary, not conceivable as scales with zero points (i.e., as ratio scales, see an extensive discussion in American Psychologist, 61, 2006, on the notion of arbitrariness of scaling in psychological domains).

Varimin F_3: Locus of prime energy expenditure: Physical force may be generated primarily by upper or lower body parts. F_3 is another bipolar factor which makes distinctions, by signs of loadings, between events requiring predominant energy expenditure of the upper or lower extremities. Muscle power of the arms is demanded for throw events (discus throw, $F_3 = -.42$, javelin throw, $F_3 = -.35$, and shot put, $F_3 = -.37$). Muscle power of the legs is demanded for run events 400 m ($F_3 = .46$), 100 m ($F_3 = .42$), and 110 m hurdles ($F_3 = .30$). The long run 1500 m does not seem to require particular leg strength ($F_3 = .23$), endurance of energy expenditure (F_2) seems to be more important.

Discussing varimin results. An interpretation of varimin factors of decathlon scores is straightforward, not complicated as one might expect for a complexity model. Each event is characterized by 'g', (1) a general disposition, by (2) the predominant source of the demanded muscle power (upper vs. lower body parts) and (3) by a temporal pacing of energy expenditure (concentrated vs. enduring).

The general model of complexity thus provides a pattern onto which sources of variance or co-variance, pertaining to the empirical domain under investigation, are mapped. For each variable a profile of independent componential contributions is thus revealed. By contrast, simple structure models try to squeeze variables into unique factorial "boxes".

Another advantage of modeling complex structures is that the variables under investigation appear connected with each other. Every event may be compared with every other event using the three components. Once events are placed into single boxes of simple structure, they are separated from each other, events pertaining to different factors cannot be compared.

Conceiving of sports activities as manifestations of interacting sources is in accord with common sense and with sports-physiological facts. An important practical question whether training for particular events leads to gains for untrained events, is better predicted by using a complex structure model which mirrors relations among events in conceptually organized ways.

3.2. Interpreting varimax factors

Varimax rotation of decathlon data does not generate a general factor 'g'. Another contrast to varimin rotation is that the resulting varimax factors are unipolar as are varimax factors of intelligence test data, due to the "positive manifold" of intercorrelations. Varimax factor scores of $N = 233$ athletes correlate with their decathlon scores (total points) as follows: $r = .60$ for F_1, $r = -.45$ for F_2 und $r = -.64$ for F_3. The correlations are highly significant, but inconsistent. Two of the three correlations have negative sign, but signs of factor loadings, being arbitrary, do not necessarily indicate directions of factorial validity. The fact that an initial 'g' variance has been redistributed among three rotated varimax factors explains their relations with total points, but confuses their possible meanings. How to interpret the varimax factors?

Varimax F_1: F_1 shows highest loadings for shot put (.86), discus throw (.85), and javelin throw (.74). The F_1 cluster of variables might be termed "throw events". However, the pole vault loading on F_1 (.51) is no throw event. In addition, long and high jump events with considerable F_1 loadings do not have anything in common with throw events.

Varimax F_2: Varimax F_2 with its highest loading on 1500 m-run (.94) appears to represent endurance. But how to explain high F_2 loadings of pole vault (.44) and high jump (.40)?

Varimax F_3: It is difficult to make sense out of varimax F_3. Run and jump events appear to be related by F_3 which can hardly be explained.

3.3. Interpreting initial factors

Conventional factorists might doubt that varimin is useful, for a seemingly obvious reason: Initial (unrotated) factor solutions are complex in the first place. How can the rotation of an initial complex structure towards *more* complex structure improve the result? Varimin rotation should prove its usefulness by showing that its results may differ from initial factor solutions and that, if they differ, surpass initial solutions by meaningfulness and other desirable features such as stability.

This can be tested for the present data set using factorial congruences (similarities). The Tucker congruence φ between initial and varimin F_1 is large (.98). Varimin and initial F_1 thus hardly differ. However, the congruence between varimin F_2 and initial F_2 is low (|.62|) (the sign need not be considered). Between varimin F_3 and initial F_3 the congruence is also low: .69. Congruences below .90 are generally considered as low and insufficient. Thus, the factor structures of initial and varimin solutions of the decathlon data, beyond F_1, are different.

Initial F_1: Initial F_1 structure matches varimin F_1 structure considerably, hence its interpretation may be regarded as identical (F_1: general athletic energy, 'g').

Initial F_2: At first glance, the meaning of initial F_2 seems to correspond to that of varimin F_2: endurance. The highest loading of initial F_2 has the 1500 m-run (−.76). In addition, shot put (.46) and discus throw (.45), both polar opposites to the long run, have opposite (positive) sign. However, the loading of initial F_2 for 100 m-run is moderate, it should be larger. 1500 m-run and 100 m-run should form a minimal pair for F_3. They do not form a minimal pair. Furthermore, initial F_2 for 110 m hurdles is too moderate, this event should also contrast with 1500 m-run. Thus, initial F_2 does not make sense consistently.

Initial F_3: An interpretation of initial F_3 is not in view. *Varimin* F_3 reflects distinctions between sources of muscle strength located at upper or lower body parts. But *initial* F_3 does not indicate this distinction. F_3 for javelin throw (initial $F_3 = -.45$), e.g., should not indicate more arm strength than for shot put (−.22), nor can 1500 m-run ($F_3 = -.40$) be characterized by arm strength. In sum, varimin factor structures are not pre-empted by initial structures.

4. Discussion

Varimin factor solutions of decathlon data proved to be more stable than varimax solutions. Each event was factorially conceivable as demanding athletic energy (F_1), a prime locus of producing energy (upper or lower limbs or more balanced energy demands, F_2), and a particular pacing of energy expenditure (more explosive vs. more enduring or more balanced) (F_3). The validity of varimin F_1 became evident in view of a high correlation between F_1 factor scores and decathlon total points (on which medal awarding norms are based). The objection, that varimin solutions might be superfluous because initial solutions are already complex, lacks empirical support. In this study, initial factors, beyond F_1, were disappointing or even confusing.

4.1. Varimin results and non-factorial findings

Varimin results of the present study can be easily linked with findings of other provenance. Properties of athletic activity, here uncovered by complex structure rotation, have been claimed by Szopa, Chwała, and Ruchlewicz (1998) whose approach was non-factorial, but multi-method oriented. The researchers used 42 tests of motor performance, participants were 143 men and 91 women. The authors summarized their results by distinguishing five main motor abilities, the first three match perfectly with the varimin factors. Szopa et al.'s "*ability to develop global strength*" reminds of varimin F_1, an "*ability to develop local strength* (*of lower or upper extremities*)" represents varimin F_3, and an "*ability of muscular endurance*" seems to represent one polar characteristic of varimin F_2.

The bipolarity of energy pacing (explosive vs. enduring), as indicated by varimin F_2, finds support by physiological facts: *"The energy at muscular activity can be supplied either (a) anaerobically, as it is during short bursts of activity of high intensity with an accumulation of lactic acid as a result, or (b) aerobically, as during more prolonged work, when oxygen intake balances the oxygen demand... In aerobic work, respiration and circulation will play a dominant role...*" (Astrand, 1956, p. 307). According to Milhorn, 1982, the basic physiological condition for bodily endurance is cardiovascular fitness.

Dissatisfying results have generally been obtained by simple structure transformations in the sports domain. Manning (1987) summarizes deplorable outcomes from anaerobic power tests: "*Results showed no single factor emerged and that unrelated aspects existed among these tests and that they were not measuring similar qualities...*".

Results of varimin rotation thus surpass those of varimax rotation in many ways. The question arises whether varimin results might be achieved by other means, for example by practicing more tolerance for complexity with simple structure models. Quartimax rotation was one of the attempts within the framework of simple structure. I recommend to undertake such attempts, but I doubt they will succeed. Replacing simple structure with complex structure is hardly associated with losses of benefits that one would want to make up.

Looking at varimin results, additional manipulative efforts influencing rotation does not appear necessary. Can varimin results be improved by different methods of factor extraction, by using Principal Axis Factoring, Maximum Likelihood, etc.? This is conceivable, but very good results, obtainable by PCA, do not call for still better results. Nevertheless, all this might be tested.

Rotation to complex structure is not without problems. The most difficult question is how to select appropriate samples of variables. A functional domain should be selected first and then variables of the domain which are supposed to be interacting or interrelated. Subjective judgments of factor analysts cannot be dismissed.

Whatever the eventual limitations of complex structure modeling will be, it seems worthwhile to take the turn to complexity as a prime goal of interest and to resume, on a broader scale, exploratory factorial research which, due to questionable output in the past, has lost its former reputation. Apparently, despair of the most clear-sighted among psychologists and psychometricians in view of the failing paradigm of their art was justified (Barrett, 2005; Breiman, 2001; Gigerenzer, 2004; Koch, 1999; Lykken, 1991; Mitchell, 1997). But there is reason for hope.[2]

[2] Barrett (2005, p. 45): "*...The pressure for change is building – and it looks like a paradigm change* –." Borsboom's "attack of the psychometricians" is an attempt to bridge the self-inflicted "gap between psychometry and psychology" and an ensuing modeling without theoretical substance merely by an increased modeling with substance (Borsboom, 2006).

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