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Fluid and Crystallized Intelligence and the Berlin Model of Intelligence Structure (BIS)

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Summary: Assessment of intelligence is often based on fluid (g_f) and crystallized intelligence (g_c), and – in the German-speaking countries – the Berlin Model of Intelligence Structure (BIS). As yet, however, the two approaches have not been systematically related to each other. The present study therefore aims to identify possible relationships between the approaches. We hypothesize that g_f is related to "processing capacity" and "memory" in the BIS, whereas g_c is related to "fluency" and "knowledge" and, to a lesser degree, to "processing capacity." We also assume "processing speed" to be related to both g_f and g_c. All components of the BIS that are relevant to the present study were measured by means of the BIS-r-DGP test, which, together with "knowledge" scales, was administered to 9,520 persons in the context of personnel selection.
The following results were obtained: First, the BIS was replicated by factor analysis of the BIS-r-DGP test. Second, "knowledge" was shown to form an additional component. Third, g_f and g_c emerged clearly from hierarchical factor analysis. Finally, with the exception of the relation of "fluency" to g_c, all hypotheses were confirmed by confirmatory factor analysis.

Introduction

In the German-speaking countries, the Berlin Model of Intelligence Structure (BIS; Jäger, 1982, 1984; see Bucik & Neubauer, 1996; Süß, Oberauer, Schulze, Wilhelm, & Wittmann, in press; Wittmann, 1988) stimulated important contributions to intelligence research and assessment (e. g., Jäger, Süß, & Beauducel, 1997). Anglo-American research on intelligence and assessment, on the other hand, is strongly influenced by the Cattell-Horn model of fluid (g_f) and crystallized (g_c) intelligence (e. g., Carroll, 1993; Cattell, 1987; Flanagan, Genshaft, & Harrison, 1997). Each concept has its specific advantages. As far as the BIS is concerned, both the generality of the tasks analyzed and the replicability of the intended structure in different populations are noteworthy (Bucik & Neubauer, 1996; Jäger, 1982; Jäger & Tesch-Römer, 1988; Kleine & Jäger, 1987). The Cattell-Horn conceptions of g_f and g_c are especially important for life-span development (e. g., Baltes, Lindenberger, & Staudinger, 1998; Lindenberger & Baltes, 1997), cross-cultural psychology (e. g., Cattell, 1987), and in the context of Carroll's integrative approach to the structure of human abilities (Carroll, 1993). It would therefore be interesting and important to investigate the relationships between g_f and g_c on the one hand and the BIS on the other. Up to now, this topic has only been addressed in a single psychometric study: Gilardi, Holling, and Schmidt (1983) investigated the replicability of g_f and g_c in a subset of the BIS, but they did not correlate the abilities conceptualized in the BIS to g_f and g_c. Thus, the relationships between the

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abilities conceptualized in the BIS and the g_f–g_c model have yet to be explored. The present study investigates the theoretical relationships between the BIS and the g_f–g_c model and then formulates hypotheses for these relationships.

The Differentiation of g_f and g_c

First, it should be noted that there are considerable differences in the measurement of g_f and g_c (see Flanagan et al., 1997). Horn (1988, pp. 658–659), for example, described g_c as follows: "The measured factor is a fallible indicator of the extent to which an individual has incorporated, through the systematic influences of acculturation, the knowledge and sophistication that can be referred to as the intelligence of a culture." Here, the importance of knowledge (K) as an aspect of g_c is very clear. With respect to g_f, Horn (1988, pp. 660) wrote: "The factor is a fallible indicator of reasoning of several kinds, abstracting, and problem solving, when these qualities are acquired outside the acculturational process, through personal experience, and through learning that is not selectively restricted." Here, reasoning seems to be the most important aspect of g_f. In other words, tasks with a high loading on g_f involve primarily reasoning and, to a lesser degree, knowledge of the culture, whereas tasks with a high loading on g_c involve primarily cultural knowledge and, to a lesser degree, reasoning. This differentiation between reasoning and knowledge forms the basis for the g_f–g_c differentiation in a widely used German intelligence test "I-S-T 2000 R" (Amthauer, Brocke, Liepmann, & Beauducel, 2001). Yet, although the difference between reasoning and knowledge reflects an important aspect of the g_f–g_c differentiation, g_f and g_c can also be differentiated on the basis of several other aspects. For example, Lindenberger and Baltes (1997) based their differentiation of the mechanics and pragmatics of intelligence on reasoning and memory on the one hand (mechanics), and knowledge and fluency on the other (pragmatics). Moreover, in the studies conducted by Horn and Cattell (1966), Hakstian and Cattell (1978), and Gilardi et al. (1983), reasoning and memory load on g_f, whereas knowledge and fluency load on g_c. In this broader perspective, g_f cannot be reduced to "pure" reasoning and g_c cannot be reduced to knowledge alone. The importance of the differentiation between reasoning and knowledge is acknowledged, but it also is recognized that other abilities may be significant in the g_f-g_c differentiation.

The differentiation between g_f and g_c may be of particular interest in personnel selection procedures and in the prediction of job performance. It is well known that when hiring employees without previous job-related experience, the most valid predictor of future performance is intelligence (Schmidt & Hunter, 1998). Nevertheless, it may also be useful to differentiate between g_f and g_c in this context. Schmidt (1992, p. 1178) performed meta-analyses showing that the major impact of intelligence on job-performance capability is indirect: Higher ability leads to increased acquisition of job-related knowledge, which has a strong effect on job performance capability. It is conceivable that g_c could be a more important indicator of future job-related knowledge than g_f. This would make g_c tests attractive for personnel selection.

The Relationships of BIS Abilities to g_f and g_c

The BIS was developed in order to integrate several models of intelligence. The focus of the BIS is on generality, and the original studies were therefore based on a large sample of 2,000 intellectual tasks gathered from an extensive screening of the literature. The pool of tasks was then reduced by eliminating very similar tasks, while retaining the marker variables for important models of intelligence. A set of 191 tasks representing 98 different types of tasks was chosen for the initial empirical BIS studies (see Jäger, 1982). Since the BIS is based on such a large sample of tasks, it was expected to cover a broad range of intellectual abilities.

The BIS was originally developed by factor analysis of theoretically founded aggregates (parcels). This technique is based on Humphrey's (1962) ideas on the suppression of unwanted variance, and allows facets to be demonstrated by factor analysis. Thus, the BIS is a faceted model of intelligence with the following structure: A content facet for verbal, numerical, and figural abilities is differentiated from an operation facet for processing speed, memory, creativity, and processing capacity. The two facets form 12 "structuples" (4 operations × 3 contents), one for every operation-content combination. These structuples are not interpreted as ability constructs, however; rather, they serve only to classify the tasks in the BIS. A general intelligence component is assumed to form the highest hierarchical level (see Jäger, 1982, 1984; Wittmann, 1988; Bucik & Neubauer, 1996). Each operation factor (processing speed, memory, creativity, and processing capacity) is measured in three types of content (i. e., verbal, numerical, figural), and each type of content is measured with four types of operation. The model has been replicated several times (e. g., Bucik & Neubauer, 1996; Jäger, 1982; Jäger & Tesch-Römer, 1988) and in different countries (e. g., Kleine & Jäger, 1987).

As far as the operation facet of the BIS is concerned, the following relationships to g_f and g_c are expected: Processing capacity is very close to reasoning, which is usually related to g_f (e. g., Hakstian & Cattell, 1978). Carroll (1993, p. 64) directly relates the processing capacity described in Jäger (1967) to g_f. However, when knowledge is required for the solution of tasks (e. g., when the terms in analogies are not very common), parts of reasoning tasks can also be related to g_c (e. g., Horn, 1988). Thus, tasks representing processing capacity can be assumed to be related mainly to g_f and, to a lesser degree, to g_c. Horn and Cattell (1966), Hakstian and Cattell (1978), and Gilardi et al. (1983) found associative memory to be related to g_f. Therefore, associative memory is also expected to be related to g_f in the present context. With respect to creativity, no correlations with g_f or g_c have yet been reported. However, correlations have been reported between fluency, which can be regarded as a part of the BIS creativity construct, and g_c (Gilardi et al., 1983; Hakstian & Cattell, 1978; Horn & Cattell, 1966). Furthermore, in Lindenberger and Baltes (1997), fluency is seen as part of the pragmatics of intelligence, which is close to g_c. Of course, fluency is only a weak measure of creativity. Therefore, the results reported in the respective studies should not be generalized to the broad construct of creativity, although a correlation with g_c is assumed for the fluency part of the creativity construct. Since some speed and flexibility is necessary to produce words in fluency tasks, fluency could also be expected to be related to g_f; this, however, has not yet been reported in the literature on g_f and g_c. We therefore decided not to formulate an explicit hypothesis in this regard, but rather to explore the relation of fluency to g_f in a *post-hoc* analysis. According to Horn and Cattell (1966), relationships to g_c can also be assumed for processing speed, which is close to Carroll's (1993) broad cognitive speediness. Even though some differentiation is possible within the domain of processing speed, the BIS model, on which the present article is based, conceptualizes speed as a homogeneous dimension (Jäger, 1982). Simple skills (e. g., simple numerical calculations or reading speed) that are acquired within a culture are also trained within the cultural experience, so that the degree of automation is culture-dependent. Therefore, the speed of performance in such skills could be related to g_c (e. g., Lansman, Donaldson, Hunt, & Yantis, 1982). Gilardi et al. (1983) found speed to have a main loading on g_c, although speed has also been found to be related to g_f (e. g., Hakstian & Cattell, 1978). The latter finding has been interpreted within the mental speed framework (e. g., Rabbitt, 1996). More specifically, individual differences in processing speed are linked to age-related differences in g_f (Fry & Hale, 1996; Salthouse, 1996). According to these findings, the correlation between speed and g_f should be age-dependent: In more homogeneous age groups, the correlation between speed and g_f should be considerably reduced.

Table 1. Expected relations between BIS operations and g_f and g_c.

	Processing capacity	Memory	Fluency	Processing speed
g_f	X	X		X
g_c	X		X	X

Notes. Expected relations are marked with an "X."

Altogether, the relationships of speed to g_f and g_c are complex. It is therefore assumed that speed is related to both g_f and g_c. The expected relationships between g_f, g_c, and the BIS operations are summarized in Table 1.

As far as the BIS content facet of verbal, numerical, and figural abilities is concerned, the relationships are less clear than for the operation facet: Verbal abilities are often assumed to be related to g_c (e. g., Carroll, 1993), whereas figural abilities (especially topographies and matrices) are thought to be related to g_f (see Cattell, 1987). However, these tendencies do not follow directly from Horn's (1988) descriptions of g_f and g_c cited above. The degree of acculturation can be assessed with verbal tasks, although verbal tasks are not always related to g_c. According to Cattell (1987), verbal reasoning tasks in which the words are familiar to the participants may be mainly related to g_f. Sternberg and Gastel (1989) used verbal reasoning tasks to measure g_f., and in Amthauer et al. (2001) verbal reasoning tasks had their main loadings on g_f. Therefore, the assumption that verbal abilities are mainly related to g_c holds only on the condition that the vocabulary or verbal knowledge required for the specific tasks is not familiar to all participants, and that only a low amount of reasoning is required. Figural abilities are assumed to be substantially related to g_f (e. g., Horn, 1988) and are generally not found to be related to g_c. This could be because of knowledge as a basis for g_c is generally assessed with verbal tests. In Amthauer et al. (2001) knowledge is assessed by means of verbal, numerical, and figural tests, and the figural knowledge tests also load on g_c, indicating that figural tests do not necessarily have to mark g_f. Numerical calculations are related to g_f when they require reasoning rather than mathematical knowledge (Horn, 1988). When they demand mathematical knowledge, numerical calculations load primarily on g_c. According to Horn (1988), broad mathematical ability can indicate g_f as well as g_c. Because numerical reasoning tasks usually involve high levels of both reasoning and knowledge, they will be assumed to be related to both g_f and g_c in this study. In sum, we follow the approach taken by Horn (1988) and regard g_f and g_c as differing mainly in the degree of acculturation involved in the tasks. Since the relationship of the content factors to acculturation is not clear, no unambiguous hypotheses can be stated on the relation of the content factors to g_f and g_c.

In the basic analyses of Horn and Cattell (1966) and Hakstian and Cattell (1978), and in Horn's (1988) description of g_c, knowledge was regarded as an important aspect of g_c. Moreover, in Horn and Cattell (1966) and Hakstian and Cattell (1978), knowledge scales load on the g_c factor. This is in line with Cattell's (1987) investment theory, since the investment of g_f should at least result in the acquisition of some testable knowledge (cf. Beauducel, Brocke, & Liepmann, 2001). Thus, knowledge can be regarded as a core of g_c (see Horn, 1988), but at the same time g_c could also comprise further aspects of acculturation, such as general problem-solving strategies. Since the BIS does not include a knowledge component, it was necessary to include knowledge as an additional component in the analysis in order to assess g_c properly. It was assumed that knowledge forms an additional component in line with the four BIS operation components.

Finally, it should be noted that both the BIS (Jäger, 1982) and Cattell's (1987) investment theory include general intelligence or "g" at the highest hierarchical level. Since the present study was designed to cover the most important parts of both models, it can be expected that a factor representing *g* will be found.

In sum, our predictions of the relationships between the BIS operations and knowledge, on the one hand, and g_f and g_c on the other were as follows:

1. "Processing capacity," which is close to reasoning, is mainly related to g_f and, to a lesser extent, to g_c.
2. Memory is related to g_f.
3. Fluency is related to g_c.
4. Processing speed may load on g_f as well as g_c.
5. Knowledge, which is not represented in the BIS, is related to g_c.

In order to investigate these relationships, both the BIS and the g_f–g_c model will first have to be replicated within the present study. If the BIS can be replicated, we will assess whether knowledge forms an additional component in the context of the BIS operations. Finally, we will test our hypotheses on the relationships of the BIS operations and knowledge with g_f and g_c, and investigate whether a factor for general intelligence can also be found.

Methods

Participants

The following analyses were based on data gathered from 9,520 high school graduates tested between August 1996 and April 1999 in a German civil service selection program. The participants were between 17 and 32 years old. The median age was 19 years, with a standard deviation of 4.2 years. The age distribution was right skewed, and 65% of the total group was younger than 21 years (see Fig. 2). There were 5,669 female (59.5%) and 3.851 male (40.5%) applicants.

The present group is more age-homogeneous than that of Horn and Cattell (1966). However, the analysis of age-heterogeneous groups has been criticized by Guilford (1980), who postulated that different tests related in the same way to age would correlate positively in age-heterogeneous samples. In the extreme, these correlations would merely represent a condition (i. e., age), rather than an ability. Thus, with respect to Guilford's (1980) critique, it may be important to explore whether g_f and g_c can actually be demonstrated in a more age-homogeneous sample.

This article focuses on the question of construct validity. However, for a subsample of 249 students applying for a position with the German financial civil service, criterion validities are reported for g_f and g_c, with training proficiency as the criterion (for details see Kersting, 1999).

Material and Procedure

Participants' abilities were assessed using the so-called BIS-r-DGP test. This test was constructed by Kersting and Beauducel (2001) on the basis of the BIS and is now used for the sole purpose of personnel selection. In contrast to the more comprehensive BIS test (Jäger et al., 1997), the BIS-r-DGP test does not assess creativity, including the flexibility of ideas, but assesses only fluency as a single component of creativity (for a description of the psychometric characteristics of the BIS-r-DGP test, see Kersting & Beauducel, 2001). Moreover, the BIS-r-DGP test features only 11 of the 12 BIS structuples or "cells"; the numerical fluency structuple is not included (for short labels of the BIS-r-DGP tasks see Table 5). In order to establish marker variables for g_c, knowledge was assessed with four scales: knowledge of community structures, literature, economics, and politics. Each knowledge scale consisted of 15 multiple-choice items. The tests were administered to groups of 2 to 50 participants. The complete test session took 4 hours and 30 minutes (including breaks).

Data Analysis

The BIS was initially confirmed by means of exploratory factor analysis of aggregates (parcels). Aggregates were

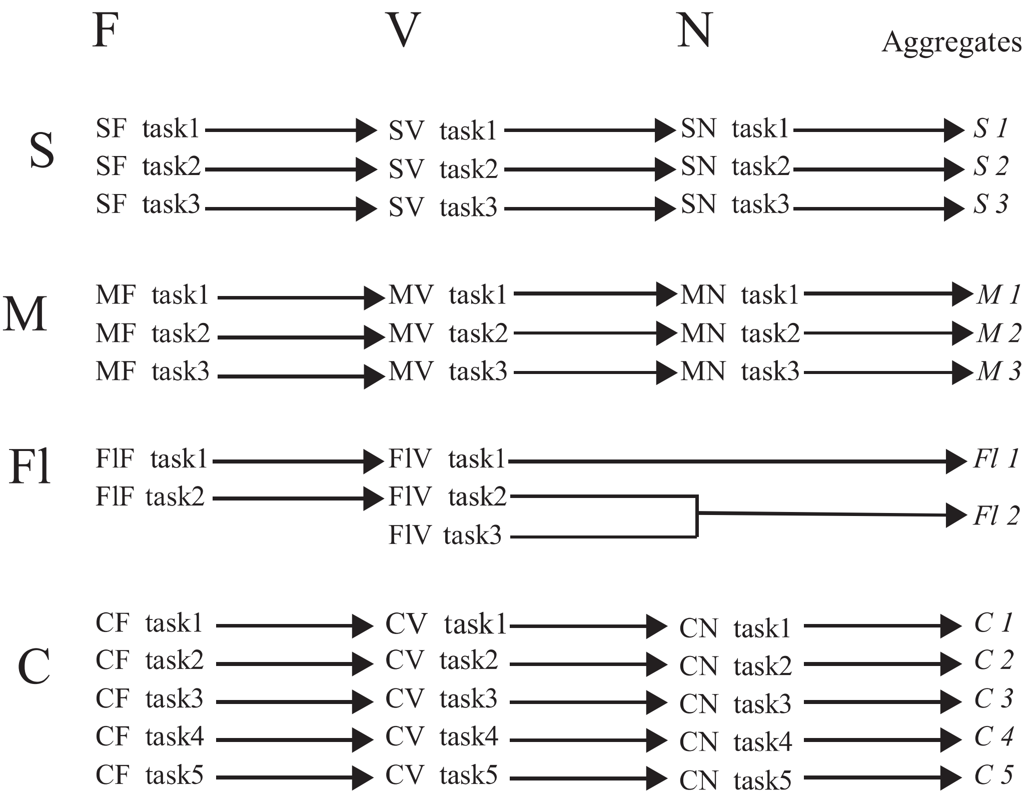

Figure 1. Process of aggregation for operation-homogeneous aggregates with BIS-r-DGP tasks; SV = processing speed verbal; SN = processing speed numeric; SF = processing speed figural; MV = memory verbal; MN = memory numeric; MF = memory figural; FlV = fluency verbal; FlF = fluency figural; CV = processing capacity verbal; CN = processing capacity numeric; CF = processing capacity figural.

formed in order to suppress unwanted variance (see Humphreys, 1962). For example, an aggregate intended to measure memory (M) was formed by the aggregation of a figural memory task (MF), a verbal memory task (MV), and a numerical memory task (MN). Figure 1 gives an overview of the aggregation of variables in the present context.

Thus, the unwanted variance of the BIS contents was balanced out by aggregation, whereas the wanted variance (e. g., of the memory operation) remains in the aggregate. With this method of controlled aggregation, Jäger (1982, 1984) was able to demonstrate a faceted structure using exploratory factor analysis (see also Wittmann, 1988). Since the BIS model was initially confirmed by this technique, exploratory principal axis factoring with aggregates was also performed in the present context using SPSS for Windows (Version 8).

The replication of g_f and g_c was performed with hierarchical exploratory factor analysis, as this was the method employed by Cattell and Horn in most analyses of g_f and g_c (e. g., Hakstian & Cattell, 1978). First, an exploratory principal axis factoring was performed for the BIS-r-DGP test and the knowledge scales. The number of factors to be extracted was estimated by means of parallel analysis (Horn, 1965), which has been shown to be superior to the Guttman-Kaiser criterion, the scree-test, and other criteria (Hubbard & Allen, 1987; Zwick & Velicer, 1986). In order to employ a method of factor rotation close to Cattell's (1978, 1987) ideas on hyperplanes and oblique rotation, we performed a new method of oblique hyperplane maximization called Trasid rotation (Beauducel, 1997). The number of irrelevant loadings on a factor, i. e., the number of loadings in the hyperplane or with very low absolute values (e. g., below .10), was one of the most important of Thurstone's (1947) original criteria for simple structure. Cattell and Muerle (1960) criticized the fact that most analytical methods of factor rotation do not maximize the number of very low (i. e., nonsignificant) absolute loadings per factor directly, but instead maximize related mathematical criteria, for which the correspondence to simple structure in the original sense is not perfect. In order to maximize the number of variables with extremely low absolute loadings directly, Cattell and Muerle developed the Maxplane rotation. Maxplane rotation, like Trasid, maximizes the number of variables with absolute values close to zero, i. e., the hyperplane count. However, Trasid has been shown to be superior to the Maxplane rotation in this regard (Beauducel, 1997). Thus, Trasid was used to maximize the hyperplane count directly. According to

Table 2. Principal axis factor pattern for operation-homogeneous aggregates (promax solution, $\kappa = 3$).

	C	S	M	Fl			
S1	–.01	*.83*	.03	.02			
S2	.07	*.85*	–.02	–.01			
S3	–.03	*.83*	.02	.02			
M1	.01	–.06	*.74*	–.01			
M2	.09	.09	*.68*	.00			
M3	–.03	.04	*.77*	.02			
Fl1	.02	–.01	.00	*.76*			
Fl2	–.02	.04	.00	*.76*			
C1	*.65*	.04	–.04	.06			
C2	*.67*	–.04	–.04	.00			
C3	*.68*	.03	.04	.02			
C4	*.62*	.02	.03	–.04			
C5	*.64*	–.01	.09	–.03			
Correlations	C	S	M				
S	.46						
M	.50	.51					
Fl	.23	.46	.29				
Eigenvalues: 4.88	1.75	1.28	1.06	.61	.58	.56	.48
Mean eigenvalues of random data: 1.06	1.05	1.03	1.03	1.02	1.01	1.00	.99

Notes. C = processing capacity, S = processing speed, M = memory, Fl = fluency; for the variables see Figure 1; loadings > .40 are printed in *italics.*

Cattell (1978) a small threshold value should be used for the hyperplane count when the sample size is large. Therefore, a threshold value of ±.05 was used with Trasid in the present study. In order to compare the results to a more common method of factor rotation, Promax rotation (with k = 3) was also performed. For the hierarchical factor analysis, the Schmid-Leiman (1957) transformation was used to represent the solutions (i. e., the oblique factors were then orthogonalized). The hypotheses on the relationships between the BIS operations, knowledge, and the g_f–g_c model were tested by means of confirmatory factor analysis (CFA) using LISREL 8 (Jöreskog & Sörbom, 1993).

Results

Exploratory Factor Analysis

In order to investigate whether the BIS-r-DGP test measures the parts of the BIS model relevant for the present investigation, principal axis factor analyses were performed with aggregates (as in Jäger 1982, 1984). As mentioned above, in contrast to the BIS model, the BIS-r-DGP does not measure creativity, but only a part of it: fluency. The results for the aggregates which are homogeneous with respect to the operation (i. e., processing capacity, memory, fluency, and processing speed) and heterogeneous with respect to content (i. e., verbal, numerical, and figural abilities) are presented in Table 2. Parallel analysis was performed on the basis of the means of the eigenvalues based on the correlations of 13 normally distributed random variables with 9,520 cases.

Four factors were identified by parallel analysis, i. e., four empirical eigenvalues were larger than the eigenvalues of the random data (see Table 2). These rotated factors correspond to the parts of the BIS which are relevant in the present context. The results for the aggregates which are homogeneous in content (i. e., verbal, numerical, and figural abilities) and heterogeneous with respect to the operation (i. e., processing capacity, memory, fluency, and processing speed) are shown in Table 3.

Parallel analysis based on nine normally distributed variables with 9,520 cases did not indicate the three-factor solution which was expected in accordance with the BIS. However, the first eigenvalue was extremely large; it represented 52.8% of the common variance. Turner (1998) and Beauducel (2001) demonstrated that parallel analysis tends to underestimate the number of factors to be extracted when there is a very large first eigenvalue. Therefore, and because a three-factor solution was expected theoretically, we computed a three-factor solution. The factors corresponded to the expected content

Table 3. Principal axis factors for content-homogeneous aggregates (Promax solution, $\kappa = 3$).

	N	V	F					
F1	.02	–.02	*.78*					
F2	.04	.20	*.59*					
F3	.06	.13	*.57*					
V1	.03	*.67*	.10					
V2	.11	*.68*	.02					
V3	.03	*.69*	.10					
N1	*.72*	.04	.08					
N2	*.84*	.00	–.03					
N3	*.47*	.15	.09					
Correlations	N	V						
V	.63							
F	.56	.69						
Eigenvalues:								
4.75	.97	.72	.55	.48	.41	.40	.39	.34
Mean eigenvalues of random data:								
1.05	1.03	1.02	1.01	1.00	.99	.98	.97	.95

Notes. N = numerical abilities, V = verbal abilities, F = figural abilities; loadings > .40 are printed in *italics.*

Table 4. Principal axis factors for operation-homogeneous aggregates and knowledge scales (Promax solution, $\kappa = 3$).

	C	S	K	M	FI							
S1	.00	*.83*	–.01	.02	.02							
S2	.05	*.85*	.04	–.01	–.02							
S3	.00	*.82*	–.04	.01	.02							
M1	.04	–.06	–.04	*.72*	–.01							
M2	.06	.09	.07	*.70*	.00							
M3	–.01	.04	–.01	*.76*	.02							
FI1	.02	–.01	.01	.00	*.76*							
FI2	–.02	.04	.02	.00	*.76*							
C1	*.61*	.05	.08	–.03	.05							
C2	*.58*	–.02	.18	–.02	–.01							
C3	*.74*	.02	–.09	.01	.02							
C4	*.55*	.03	.13	.04	–.05							
C5	*.69*	–.02	–.09	.07	–.02							
Community structures	–.08	.02	*.83*	.04	–.02							
Literature	.04	–.01	*.47*	.08	.04							
Economics	.04	.01	*.61*	–.07	.03							
Politics	.05	–.04	*.79*	–.03	–.02							
Correlations	C	S	K	M								
S	.46											
K	.39	.12										
M	.50	.51	.09									
FI	.22	.46	.09	.29								
Eigenvalues:												
5.16	2.48	1.58	1.16	1.05.	.73	.59	.57	.55	.51	.48	.45	.41
Mean eigenvalues of random data:												
1.07	1.06	1.05	1.04	1.03	1.02	1.01	1.00	.99	.98	.97	.96	.95

Notes. C = processing capacity, S = processing speed, K = knowledge, M = memory, FI = fluency; for the BIS variables see Figure 1; loadings > .40 are printed in *italics*.

Table 5. Schmid-Leiman transformed first-order hierarchical solution based on Promax factor patterns.

	3rd order	2nd order		1st order							
Tasks	*g*	gf	gc	S	K	M	CF	FI	CN	CV	
marking letters (SF)	.21	*.42*		*.51*						–.10	
comparing figures (SF)	.27	*.46*		*.51*							
placing signs (SN)	.25	*.38*		*.46*					.14		
classification (SV)	.27	*.40*		*.45*							
Marigold (SF)	.24	*.42*		*.45*					–.13		
incomplete words (SV)	.28	*.41*		*.43*							
part-whole (SV)	.28	*.38*		*.35*						.18	
divide by six (SN)	*.32*	*.36*	.14	*.33*					.26		
political knowledge	.28		*.53*		*.51*						
community structure knowledge	.28		*.52*		*.51*					–.12	
economic knowledge	.23		*.43*		*.40*						
literature knowledge	.24		*.32*		*.33*					.12	
text analysis (CV)	.28	.10	*.34*		.23				.26		
classify words (CV)	.25	.15	.24		.21		.14			.24	
fantasy language (MV)	.26	*.41*				*.47*				.14	
pairs of numbers (MN)	.21	.28				*.41*			.21		
remember words (MV)	.15	.30				*.39*					
recognize numbers (MN)	.16	.22					*.37*			.13	
two-digit numbers (MN)	.23	.29				*.36*			.20		
meaningful text (MV)	.30	*.34*	.13	.10	.11	*.33*	–.10			.14	
memorizing forms (MF)	.26	*.46*		.10		.29	.27		–.13		
pairs of figures (MF)	.24	*.42*				.29	.24				
orientation memory (MF)	.15	.25				.18	.21				
turning figures (CF)	.17	.17					*.41*		.11		
complex unwinding (CF)	.16	.18					*.35*				
analogies (figural) (CF)	.18	.25					.28		.12	.15	
choosing figures (CF)	.12	.14					.26				
letter series (CN)	.20	.27					.26		.19	.10	
Bongard (CF)	.14	.17					.22				
characteristics and abilities (FIV)	.18	.24						*.57*			
possibilities of application (FIV)	.18	.22						*.57*			
continuing sign (FIF)	.11	.24						*.56*			
creating objects (FIF)	.14	.26						*.50*			
Masselon (FIV)	.19	.23						*.36*		.13	
computation reasoning (CN)	.27		*.34*		.10		.16		*.45*		
estimating results (CN)	.27	.15	.29				.22		*.44*		
matrices of numbers (CN)	.23	.18	.18				.16		*.43*		
X-greater (SN)	*.33*	*.31*	.20	.29						*.38*	
tables & statistics (CN)	.22	.13	.22				.13		.29	.12	
conclusions (CV)	.26	.30	.10				.13			*.41*	
comparing conclusions (CV)	*.32*	.23	.26		.14					*.30*	
analogies (verbal) (CV)	.27	.23	.19				.21			.27	
Eigenvalues of unrotated primary solution:	7.85	3.39	2.36	1.81	1.68	1.41	1.10	.92	.91	.87	.84
Mean eigenvalues of random data corresponding to primary factor solution	1.13	1.12	1.11	1.10	1.09	1.08	1.07	1.06	1.06	1.05	1.05

Notes. CF = figural processing capacity, CN = numerical processing capacity, CV = verbal processing capacity, FI = fluency, K = knowledge; M = memory, S = processing speed; loadings < .10 were dropped. Loadings > .30 are given in *italics*.

factors for verbal, numerical, and figural abilities and had a clear simple structure (see Table 3). Thus, the first large eigenvalue could be regarded as a strong effect of general intelligence, but the intended structure was pronounced for the content factors. The strong impact of general intelligence could also be seen in the large correlations between the content factors. Altogether, the results showed that relevant parts of the BIS, i. e., processing capacity, memory, fluency, and processing speed, as well as verbal, numerical, and figural abilities can be measured by means of the BIS-r-DGP test. Moreover, the present results can be regarded as a further replication of important parts of the BIS.

The next step was to investigate whether general

Table 6. Schmid-Leiman transformed second-order hierarchical solutions for Promax and Trasid factor patterns.

	Promax K = 3			Trasid		
	3rd order	2nd order		3rd order	2nd order	
Factor	*g*	gf	gc	*g*	gf	gc
S	*.38*	*.62*	–.02	*.30*	*.69*	–.03
K	*.38*	–.06	*.66*	.18	–.10	*.49*
M	*.36*	*.59*	–.03	.27	*.55*	.04
CF	.29	*.45*	.00	*.31*	*.37*	*.33*
CN	*.32*	.08	*.42*	*.34*	.01	*.74*
CV	*.39*	*.40*	.22	.27	*.31*	.29
Fl	.24	*.37*	.01	.14	*.40*	–.10

Eigenvalues for unrotated second-order solutions:													
3.07	1.33	.90	.56	.47	.38	.29	2.82	1.40	.90	.65	.53	.43	.27
Mean eigenvalues of random data: 1.04						1.02	1.01	1.00	.99	.98	.96		

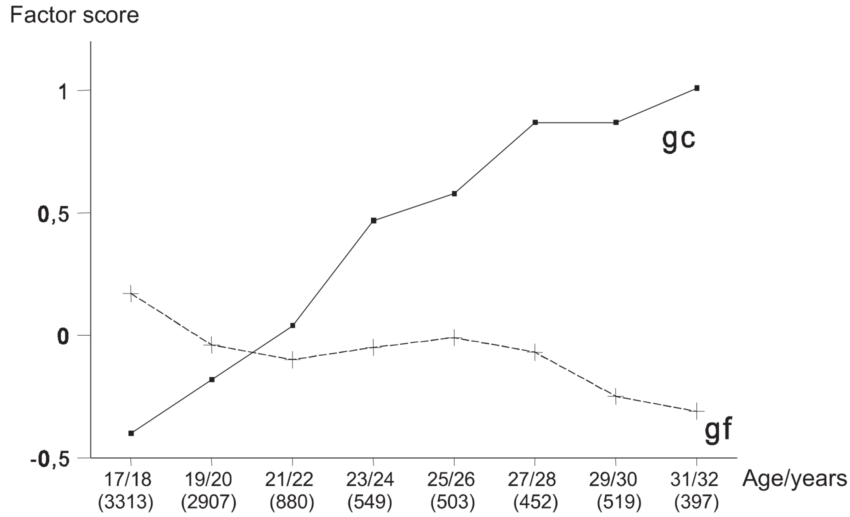

Figure 2. g_f and g_c factor scores of the promax solution across age groups. The number of participants in each age group is given in brackets.

knowledge represents an additional factor in line with the BIS operations. Therefore, principal axis factor analysis was performed with the four knowledge scales and aggregates which were homogeneous with respect to the BIS operations (see Table 4). Parallel analysis based on 17 normally distributed random variables with 9,520 cases indicated that five factors should be extracted. As expected, in addition to the four factors for the BIS operations, the knowledge factor emerged with a clear simple structure. As before, the correlations between the factors may be attributed to general intelligence. However, the correlation between the factors for fluency (Fl) and knowledge (K) was low, which contradicts the assumption that both factors load on a common factor for g_c.

Since the BIS model was substantiated on the basis of the present material, and since knowledge was demonstrated to represent an additional factor, the next step was to replicate g_f and g_c using the present material. Therefore, in addition to the 38 tasks of the BIS-r-DGP test, the four knowledge scales were included in first-order exploratory principal axis factor analysis of the tasks. The correlation matrix for the entire set of tasks is given in the Appendix. Parallel analysis was based on mean principal component eigenvalues for 50 sets of 42 normally distributed random variables with 9,520 cases. Parallel analysis suggested that six or seven factors should be extracted: Seven empirical eigenvalues were larger than the corresponding mean eigenvalues of random data (see Table 5). However, the seventh eigenvalue was almost the same size as the corresponding mean eigenvalue based on random data. Since overextraction is considered less problematic than underextraction (Gorsuch, 1983), we chose the seven-factor solution here.

In addition to the Promax rotation, the Trasid rotation was performed (Beauducel, 1997), thus directly maximizing the hyperplane count. As there were only slight differences between the Promax and Trasid factor patterns, only the first-order Schmid-Leiman transformed factor pattern for the hierarchical Promax solution is presented in Table 5.

The primary factors in Table 5 have some similarity with Thurstone's (1938) primary mental abilities, especially the memory and fluency factor. However, speed is not restricted to perceptual speed, but comprises all three areas of content, whereas reasoning or processing capacity is split up into verbal, numerical, and figural content. Moreover, a factor representing knowledge emerges. When a second-order factor analysis was performed on the basis of the seven primaries, parallel analysis indicated that two factors were to be extracted (see eigenvalues in Table 6). An additional Trasid rotation was performed, based on the Trasid rotated seven primary factor solution (see Table 6).

In both analyses g_f and g_c emerged and a factor for general intelligence could be shown (see Table 6). In both the Promax and the Trasid solution, the second-order factor representing g_f was formed by processing speed (S), memory (M), figural processing capacity (CF), parts of verbal processing capacity (CV), and fluency (Fl). With the exception of the loading of fluency, all primaries loading on the first second order factor in Table 6 were compatible with the interpretation of this factor as g_f. The loading of the speed factor on g_f is in line with the mental speed approach (Rabbitt, 1996). Knowledge (K), numerical processing capacity (CN), and parts of verbal processing capacity (CV) loaded on the second factor, which is interpreted as g_c. In the Trasid solution, an additional loading of figural processing capacity (CF) on g_c was found. The interpretation of the factors as g_f and g_c is further supported by the cross-sectional plot of the factor scores of the Promax solution for age (see Fig. 2).

The differences in g_f and g_c across age groups correspond to the expectations of the investment theory (Cattell, 1987), with g_c showing an age-related increase across participants aged between 17 and 32, and g_f showing a slow decrease with age. Thus, in the present study, it was possible to demonstrate g_f and g_c as well as the BIS with the same material. This indicates that at least some of the differences between the models were due to different strategies of data analysis, variable selection, and aggregation techniques used in the development of the models.

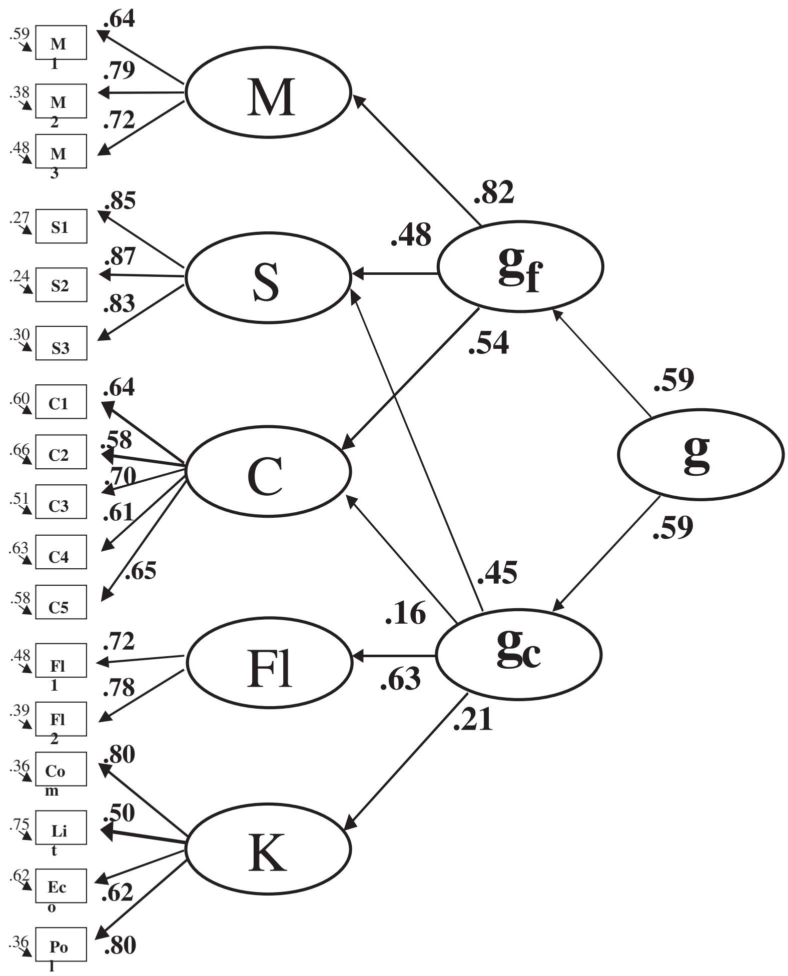

Figure 3. Completely standardized solution for BIS operations, knowledge, g_f, and g_c; factor labels: g = general intelligence, g_f = fluid intelligence, g_c = crystallized intelligence, C = processing capacity, Fl = fluency, K = knowledge, M = memory; S = processing speed; variable labels: Co = community structure knowledge, Li = literature knowledge, Ec = economic knowledge, Po = political knowledge; for the BIS variables see Figure 1; $\chi^2(111, N = 9520) = 3171.03$, $p < .001$, goodness of fit index = .96, adjusted goodness of fit index = .94, root mean square residual = .09, comparative fit index = .95.

Confirmatory Factor Analysis

In order to test the hypotheses on the relationships of the BIS operations and knowledge with g_f and g_c, and to demonstrate a factor for general intelligence more directly, CFA was performed. The model was based on the operation-homogeneous aggregates and the knowledge scales. Therefore, five first-order factors were postulated. The λ-path coefficients for the expected loading of each variable on one of the five endogenous variables were set free, and the remaining λ-path coefficients were set to zero. At the next hierarchical level, g_f and g_c were postulated as endogenous variables. According to our hypothesis, the β-paths for the loading of processing speed (S) on g_f and g_c were constrained to be equal and between .00 and 1.00. The β-paths for the loading of memory (M) and processing capacity (C) on g_f were set free. The β-paths for fluency (Fl), processing capacity (C), and knowledge (K) on g_c were also set free. At the third level, a g-factor was postulated and the γ-path coefficients for g_f and g_c were set free between .00 and 1.00. The model fit was acceptable (see Figure 3) and all path coefficients were significant.

However, in exploratory analyses there were low correlations between factors for knowledge and fluency (Table 4), and fluency did not load on g_c (Table 6). Therefore, in a *post-hoc* CFA analysis, we tested whether an additional β-path from g_f to the latent variable representing fluency would improve the model fit. The remaining parameters of the model presented in Figure 3 remained unchanged. The increase in fit was significant ($\chi^2_{diff} = 185.29$, $df = 1$, $p < .001$), indicating that fluency was also related to g_f. However, in this model, the β-paths of both g_f and g_c on fluency were significant.

g_f/g_c and Criterion Validity

The results clearly indicate that g_c predicts training proficiency more accurately than g_f. The correlation between g_c and the preliminary examinations was $r = .40$ (.46 when corrected for restriction of predictor range) compared to $r = -.04$ for g_f.

Discussion

The aim of the present study was to replicate the BIS and the g_f–g_c model with the same set of tasks and participants, and to investigate the relationships between BIS operations on the one hand and g_f and g_c on the other. It was possible to replicate important parts of the BIS using the BIS-r-DGP test. Knowledge (K) was established as an additional factor in line with the operations processing speed (S), memory (M), fluency (Fl), and processing capacity (C). Furthermore, g_f and g_c were replicated in hierarchical factor analysis. Since the Promax solution already had a pronounced simple structure, the Trasid solution for the primaries, which was maximized with regard to the hyperplane count, was similar to the Promax solution. However, in second-order analysis, a loading of the primary for figural processing capacity on g_c only occurred in the Trasid solution. This indicates that the method of oblique rotation may alter the results of second-order factor analysis, even when the changes in the primary loadings are not important. Moreover, the unusual loading of figural processing capacity on g_c indicates that care should be taken in identifying g_f and g_c with content factors.

The interpretation of g_f and g_c was supported by the cross-sectional age changes of the g_f- and g_c-factor scores, which were in line with Cattell's (1987) investment theory. This confirms the results of Gilardi et al. (1983), who also replicated g_f and g_c in a subset of BIS tasks. However, in the present study, g_f and g_c were replicated with test material comprising more BIS tasks than in Gilardi et al.'s study, and with additional knowledge scales. Thus, g_f and g_c were replicated within a context of tasks which was at least as large as in the original studies conducted by Cattell (1963), Horn and Cattell (1966), and Hakstian and Cattell (1978).

Compared to Horn and Cattell (1966), the age of the participants in the present study was quite homogeneous. Sixty-five percent of the total group were younger than 21 years. However, Cattell (1963) was able to demonstrate g_f and g_c in a sample that was younger and more age-homogeneous than the present sample. Moreover, Guilford (1980) criticized the use of age-heterogeneous groups in Horn and Cattell (1966). Therefore, the replication of g_f and g_c in a group which is relatively age-homogeneous is worthy of note.

As far as the relationships between the BIS operations and the g_f-g_c model are concerned, we had proposed the following hypotheses: (1) processing capacity, which is close to reasoning, is mainly related to g_f and, to a lesser degree, to g_c, (2) memory is related to g_f; (3) fluency is related to g_c, (4) processing speed may load on g_f as well as g_c, and finally, (5) knowledge, which is not a part of the BIS, is related to g_c. No hypotheses were formulated as to the relation of the BIS content factors to g_f and g_c. It emerged that the loading pattern of the second-order factors in the exploratory factor analysis was as expected, but the loading of the fluency factor on g_f was unexpected. The loading of the speed factor on g_f was in line with the assumptions of the mental speed approach (Rabbitt, 1996).

In further analyses using CFA, it was possible to confirm all hypotheses on the relationships of BIS operations to g_f and g_c: Processing capacity (C) was strongly related to g_f and more weakly related to g_c. Memory (M) was related to g_f only. Processing speed (S) was related to g_f and to g_c. Fluency (Fl), which was related to g_f in exploratory factor analysis, was related to g_c in CFA. However, the model fit could be improved by allowing an additional path between g_f and fluency. It is possible that the unexpected relation of fluency to g_f in exploratory factor analysis was mainly due to the high correlations between fluency and processing speed, which was, in turn, mainly related to g_f in the exploratory analyses. The present data were collected in the context of personnel selection. It may be that under strong pressure to succeed, the participants focused more on the quantity than on the quality of their solutions in fluency tasks. This may have enhanced the correlations of the fluency tasks with the speed tasks.

This view is supported by the CFA models; fluency was also related to g_c in the models in which speed was forced to load equally on g_f and g_c. However, the CFA models provide only weak support for the third hypothesis that fluency is related to g_c, since fluency was also related to g_f in the second model. It should be noted that the present results concerning fluency cannot be generalized to the much more global construct of creativity. Knowledge was shown to form an additional factor in line with the BIS operations, and was related to g_c in CFA as well as in the exploratory analysis.

General intelligence was demonstrated in CFA. The present demonstration of general intelligence differs from Gustafsson's (1984) results, where general intelligence was identical to g_f. In the present data, general intelligence did not correspond to g_f, since both g_f and g_c load equally on this factor. In contrast to Gustafsson's results, the present demonstrations of g_f and g_c were not only based on CFA, but also on exploratory factor analysis. This method invariance can be regarded as an advantage of the present structure. Moreover, in the present CFA, the primary factors were the BIS operations and even in the exploratory factor analysis, the primaries were mainly BIS operations, whereas Gustafsson (1984) had many content factors at the level of primary factors. Therefore, his secondary factors were probably more closely related to the content of tasks (figural and verbal). Amthauer et al. (2001) and Beauducel et al. (2001) demonstrated that g_f and g_c tests might be related to content factors, and that this relation causes problems in the validity of g_f and g_c assessments. Since the BIS operations were used as primary factors in the present study, contamination of g_f and g_c with content factors was probably avoided. This shift in the variance contributions of primaries to g_f and g_c may explain the difference between the present results and those of Gustafsson. Nevertheless, in the exploratory analysis with Promax rotation, more primary factors loaded on g_f than on g_c. This might indicate that g_f could be a core element of general intelligence. However, with Trasid rotation, g_c had more loadings than with Promax (see Table 6). This demonstrates that factor rotation may influence the relative loadings of primary factors on g_f and g_c. Moreover, when the relative importance of g_f and g_c is addressed, criterion validities should also be considered. In our study, the criterion validity of g_c was clearly larger than the criterion validity of g_f. This result should be of interest for the field of psychological assessment, and is not out of line with the repeated demonstration of high criterion validities for *g* (e.g., Schmidt & Hunter, 1998). The differing criterion validity of g_f and g_c suggests that it would be of interest to perform large-scale studies on the criterion validity, not – as has been done in the past – of *g* only, but also of g_f and g_c. The large criterion validity of g_c in the present study could be related to the large criterion validity of job-related knowledge tests (Schmidt & Hunter, 1998). Schmidt (1992) was able to show that intelligence is related to job performance by its important role in the acquisition of job-related knowledge. Further studies with large batteries of instruments, and especially extensive knowledge tests and criterion measures, would be necessary to further investigate these relationships.

The present findings on the relationships of the BIS operations to g_f and g_c could be interpreted in terms of a hierarchical concept, with the BIS operations and knowledge at the bottom, general intelligence at the top, and g_f and g_c in between (see Figure 3). This view would also be in line with the concept of the pragmatics of intelligence comprising knowledge and fluency, and the mechanics of intelligence comprising reasoning and memory (Baltes et al., 1998; Lindenberger & Baltes, 1997). The present hierarchical integration of the operation facet of the BIS and the g_f–g_c model demonstrates that at least some of the differences between the models may be attributed to the different methods of data analysis used in the development of the models (i. e., hierarchical factor analysis versus controlled aggregation) and to the fact that knowledge scales were included in the g_f–g_c analyses but not in the original BIS analysis. On the other hand, the level of primary factors was not usually elaborated to any great extent within the g_f–g_c model, whereas the BIS model has a broad and replicated structure at this level. Since the BIS was based on a very large sample of intelligence tasks, it might be advantageous to integrate the BIS structure of primary factors into the g_f–g_c model. Of course, the suitability of the resulting first-, second-, or third-order factors for prediction is probably also dependent on the type of criterion used (see Wittmann, 1988).

The role of the content facet in this context is not clear, however. It is possible that the hierarchical structure only holds in the operation facet and not in the content facet. In order to investigate the role of the content facet more closely, it would be helpful to assess knowledge not only in the verbal, but also in the numerical and figural domain (Amthauer et al., 1999; Beauducel et al., in press), as this would exclude a systematic contamination of g_c with verbal abilities. Nevertheless, the hierarchical structure identified for the BIS operations, g_f-g_c, and general intelligence provides a first crude map for the integration of the two models.

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Appendix: Pearson correlations for the 42 variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	28	39	40	41
1 marking letters (SF)																																									
2 comparing figures (SF)	53																																								
3 placing signs (SN)	45	47																																							
4 classification (SV)	42	47	47																																						
5 marigold (SF)	54	46	38	44																																					
6 incomplete words (SV)	40	49	49	43	42																																				
7 part-whole (SV)	36	41	38	43	33	40																																			
8 divide by six (SN)	38	47	39	37	32	40	35																																		
9 political knowledge	–06	–00	00	03	–01	03	05	13																																	
10 community structure knowledge	–05	02	04	07	00	05	06	17	65																																
11 economic knowledge	–02	02	05	07	–02	05	06	14	49	51																															
12 literature knowledge	01	05	03	10	08	07	11	12	43	38	29																														
13 text analysis (CV)	02	07	12	13	07	15	18	15	35	33	34	26																													
14 classify words (CV)	06	09	06	13	12	12	17	14	28	24	21	27	28																												
15 fantasy language (MV)	19	22	17	22	22	24	23	21	02	03	–00	14	15	16																											
16 pairs of numbers (MN)	13	15	18	14	13	20	15	21	04	08	04	06	11	08	32																										
17 remember words (MV)	13	15	11	14	14	13	15	15	–04	–02	–04	04	06	10	39	21																									
18 recognize numbers (MN)	13	13	13	11	10	14	13	17	03	07	04	06	07	03	28	30	23																								
19 two-digit numbers (MN)	17	21	19	17	16	22	16	26	07	12	04	07	13	12	28	37	25	26																							
20 meaningful text (MV)	19	25	23	27	25	29	28	27	17	20	13	21	22	20	41	27	29	22	29																						
21 memorizing forms (MF)	29	32	24	27	31	27	26	23	–00	–01	00	08	09	16	43	27	30	18	26	31																					
22 pairs of figures (MF)	24	30	21	21	24	23	23	22	–00	–02	–02	06	10	12	39	26	30	20	25	26	49																				
23 orientation memory (MF)	12	15	10	12	14	12	15	12	01	00	–00	04	06	08	21	21	14	14	18	17	28	27																			
24 turning figures (CF)	10	13	08	07	09	11	09	13	11	08	06	07	11	16	08	10	05	06	12	08	20	17	13																		

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	28	39	40	41
25 complex unwinding (CF)	09	14	10	10	10	11	11	13	06	05	06	06	11	14	10	11	09	06	10	09	19	15	14	28																	
26 analogies figural (CF)	11	18	14	13	14	14	17	17	03	–01	–01	05	11	15	16	14	09	10	13	13	21	22	18	20	21																
27 choosing figures (CF)	06	11	07	08	09	09	08	10	06	04	03	05	06	11	08	09	06	03	09	08	16	14	11	15	15	14															
28 letter series (CN)	11	20	19	18	15	19	18	19	04	02	–00	04	11	13	18	17	12	10	21	19	24	22	18	19	20	24	14														
29 Bongard (CF)	07	11	09	12	10	09	11	11	04	03	04	06	07	11	11	12	08	07	11	13	16	14	13	17	13	18	12	19													
30 characteristic and abilities (FIV)	20	20	17	20	20	19	18	19	09	09	09	12	09	11	11	08	08	09	08	13	16	13	06	05	05	08	04	06	05												
31 possibilities of applications (FIV)	21	18	18	18	19	18	17	19	09	10	12	10	10	11	10	08	07	08	09	12	15	14	06	06	07	08	05	06	06	44											
32 continuing sign (FIF)	26	25	22	22	20	20	19	20	–06	–01	00	02	–01	00	07	07	07	08	08	09	13	13	07	–01	03	05	01	01	03	38	37										
33 creating objects (FIF)	22	23	20	22	23	20	18	17	–01	–01	03	03	04	05	11	08	08	08	09	13	18	17	08	07	08	09	06	06	05	36	34	43									
34 Masselon (FIV)	17	19	16	18	18	17	19	20	09	09	08	11	13	12	15	11	09	08	11	15	17	16	07	06	09	13	06	11	07	31	31	26	24								
35 computation reasoning (CN)	00	08	13	09	02	14	10	28	29	30	31	16	29	19	08	16	02	09	18	15	09	10	08	22	19	17	14	20	13	06	08	–02	03	09							
36 estimating results (CN)	06	14	18	12	08	17	13	32	25	25	24	15	22	18	10	19	04	10	20	14	14	15	11	21	20	20	16	26	16	07	09	00	05	09	46						
37 matrices of numbers (CN)	07	15	19	11	07	19	16	27	15	14	09	06	18	13	14	21	06	13	21	17	14	15	13	21	18	22	14	28	14	04	07	–00	04	10	34	37					
38 X-greater (SN)	32	34	40	33	30	39	37	47	18	21	16	14	22	13	20	23	09	18	24	28	20	18	10	15	13	17	11	19	12	17	16	12	13	17	34	34	35				
39 tables & statistics (CN)	06	11	13	08	07	15	12	20	20	18	15	14	20	14	10	14	03	09	16	15	10	11	10	19	16	17	10	18	12	07	08	00	03	11	32	30	25	27			
40 conclusions (CV)	12	18	15	20	20	20	24	22	09	03	03	13	24	21	24	14	12	09	14	23	24	24	16	19	17	26	10	24	16	14	12	06	11	18	18	21	18	21	24		
41 comparing conclusions (CV)	15	22	19	23	19	23	26	27	28	24	25	23	32	27	18	10	10	09	14	24	19	19	10	15	16	18	10	16	10	20	18	10	13	19	28	25	19	29	26	35	
42 analogies verbal (CV)	08	14	11	14	15	18	20	20	19	16	13	19	26	31	21	13	13	08	16	22	22	22	13	20	19	23	14	24	15	11	10	01	08	15	24	26	24	20	20	30	27

Notes. $N = 9520$; correlation coefficients with an absolute value of .021 or higher are statistically significant ($p < .05$)
SV = processing speed verbal; SN = processing speed numeric; SF = processing speed figural; MV = memory verbal; MN = memory numeric; MF = memory figural; FIV = fluency verbal; FIF = fluency figural; CV = processing capacity verbal; CN = processing capacity numeric; CF = processing capacity figural

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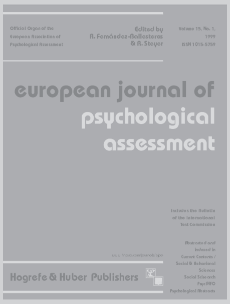

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