Examining the Components of Fluid Intelligence: Implications for STEM Education

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Abstract

Substantial empirical evidence illustrates the significance of spatial ability for STEM academic achievement. However, it is critical that research efforts continue to identify cognitive factors which are associated with STEM education to further increase the impact which cognitive interventions can have. Considering the cognitive factor of fluid intelligence as fundamental for STEM education due to its association with novel problem solving, this paper describes a study comprising of two experiments, one exploratory and one confirmatory, which aim to identify cognitive factors which may be components of fluid intelligence. The results identify that a synthesis of visualization, memory span, and inductive reasoning can account for approximately 40% of the variance in fluid intelligence. This paper offers a theoretical rationale for the importance of these factors in STEM education and advocates for their future consideration in cognitive interventions.

Cognition in STEM Education: The Need to Look Beyond Spatial Ability

One of the most significant findings from the perspective of cognition and individual differences in STEM education is the link between spatial ability and performance (Wai, Lubinski, & Benbow, 2009). However, it is well established that the factor structure of human intelligence is comprised of multiple individual factors across multiple cognitive faculties (Carroll, 1993; Schneider & McGrew, 2012). Therefore, despite the substantial wealth of evidence illustrating the association between spatial ability and STEM education, it is important to be cognizant of other potential factors which contribute to STEM achievement.

In Wai, Lubinski and Benbow's (2009) study for example, verbal and mathematical abilities are also shown to be associated with STEM academic achievement. Johnson and Bouchard Jr. (2005) present a model of intelligence with verbal, perceptual and spatial factors idetified as the only second-order factors again suggesting that other factors should be at least acknowledged. Finally, Lohman (1996), noted how other factors such as fluid and crystallised intelligence are better predictors of general education achievement than spatial ability further implicating the importance of considering the potential for more factors to underpin STEM achievement.

The factors of fluid and crystallised intelligence described by Lohman (1996) are the two core factors within the Gf-Gc theory (Cattell, 1943, 1963) which is described as "probably the best known and most widely accepted theories of intellectual factors" (Willis et al., 2011, p.44). Fluid intelligence is defined as "a facility in reasoning, particularly where adaptation to new situations is required" while crystallised intelligence is defined as "accessible stores of knowledge and the ability to acquire further knowledge via familiar learning strategies" (Wasserman & Tulsky, 2005, p.18). Considering the nature of STEM education and its agenda to facilitate students in ascertaining the skills to solve problems in a future society which does not yet exist, fluid intelligence appears as an auspicious cognitive faculty to explore in the context of STEM education. Fluid intelligence is recognized to comprise of more narrow and explicit factors (Ebisch et al., 2012) and considering its influence on novel problem solving, identifying narrow factors which have predictive power for it would provide an empirically derived model with a strong theoretical basis to examine in the context of STEM educational achievement.

Method

Approach

This study aspired to identify a selection of first-order cognitive factors which are statistically associated with fluid intelligence to provide a model for further exploring cognition and individual differences in STEM education. Two experiments were conducted which involved the administration of well-established psychometric tests to two separate cohorts with a similar demographic. The first experiment involved the administration of 17 psychometric tests, one of which was the Ravens Advanced Progressive Matrices Test (Raven, Raven, & Court, 1998) which is an established indicator of fluid intelligence, with the remaining 16 being indicators of various domain-free general factors and spatial factors. Based on the results of the first experiment, factors with a statistically significant loading on fluid intelligence were incorporated into a second experiment which acted as a confirmatory experiment for the results of Experiment 1. In Experiment 2, the variables of time taken to complete test items and mental effort exerted in these items were also considered.

For both experiments, descriptive statistics, correlation matrices, and multiple linear regression analyses are presented. The descriptive statistics present information pertaining to raw scores. This raw data was also used to generate the correlation matrices. New datasets were created for the multiple regression analyses which included the original data subsequent to screening for missing data and outliers. Missing data was computed using a full-information maximum likelihood (FIML) estimate within the AMOS software (v.21, IBM SPSS Statistics). This approach was selected to avoid the randomness introduced by imputation techniques (Dong

& Peng, 2013). As multiple linear regression analyses assume multivariate normal distributions and are sensitive to extreme outliers, the data was screened for both univariate and multivariate outliers prior to the conduction of these tests (Kline, 2016). Univariate outliers were identified as results which exceeded three standard deviations from the mean and were transformed to the value equal to three standard deviations from the mean (Kline, 2016). The criterion for identifying outliers with the Mahalanobis D statistic was $p < 0.001$ (Kline, 2016) and for the Cook's D statistic it was any instance greater than 1 (Cook, 1977). No data was identified as a multivariate outlier.

Experiment 1: Participants

A cohort of 3rd year undergraduate students (N=85) enrolled in an Initial Technology Teacher Education (ITTE) programme participated in this experiment. The cohort consisted of 80 males and five females. Their ages ranged from 19 to 31 with a mean of 21.19 and a standard deviation of 2.41. Participation in this study was voluntary.

Experiment 1: Psychometric Tests

Participants were invited to take a total of 17 psychometric tests with each one representing a unique first-order factor of human intelligence. These tests were predominantly adopted from the Educational Testing Services' (ETS) Kit of Factor Referenced Cognitive Tests (Ekstrom, French, Harman, & Derman, 1976a), however additional tests were utilised to reflect advances in psychometric research. The second order factors included in this study were fluid intelligence, visual processing (spatial ability), long-term memory, short-term memory, general reasoning, and processing speed. Table 1 provides a description of each test utilised within this study.

Participants engaged with the tests in five groups of approximately 17 people. The tests were administered over a course of four test sessions with one week passing between each session. No session lasted longer than 60 minutes in duration and tests were administered in a different order to each group to remove the potential for an order bias within the data.

Table 1. Psychometric tests utilized in Experiment 1

Test	Second-Order Factor	First-Order Factor
Ravens Advanced Progressive Matrices	Fluid Intelligence	
ETS Paper Folding Test	Visual Processing	Visualization
Mental Rotations Test	Visual Processing	Spatial Relations
ETS Card Rotations Test	Visual Processing	Speeded Rotations
Perspective Taking Spatial Orientation Test	Visual Processing	Spatial Orientation
ETS Gestalt Completion Test	Visual Processing	Closure Speed
ETS Hidden Patterns Test	Visual Processing	Flexibility of Closure

Test	Second-Order Factor	First-Order Factor
ETS Shape Memory Test	Visual Processing	Visual Memory
ETS Maze Tracing Speed Test	Visual Processing	Spatial Scanning
Transformation Test	Visual Processing	Imagery Quality
ETS Picture Number Test	Long-Term Memory	Associative Memory
ETS Toothpicks Test	Long-Term Memory	Figural Flexibility
ETS Auditory Number Span Test	Short-Term Memory	Memory Span
ETS Figure Classification Test	General Reasoning	Inductive Reasoning
ETS Nonsense Syllogisms Test	General Reasoning	Deductive Reasoning
ETS Finding A's Test	Processing Speed	Perceptual Speed *(Letters)*
ETS Identical Pictures Test	Processing Speed	Perceptual Speed *(Images)*

Experiment 1: Results and Discussion

Descriptive statistics of the raw scores from each of the tests are illustrated in Table 2. Skewness and kurtosis values for all tests are within acceptable limits of between ±2 (Gravetter & Wallnau, 2014; Trochim & Donnelly, 2006). Despite some of the α values being below the recommended value of .7 (Nunnally, 1978), all of the tests utilised in the study are well-established and have been previously validated so this was deemed acceptable.

Table 2. Descriptive statistics from Experiment 1

Task	n	M	SD	Range	Skewness	Kurtosis	α
1. Paper Folding	72	12.11	3.13	16.00	-.26	.13	.73
2. Mental Rotations	79	13.33	4.43	18.00	.13	-.85	.81
3. Card Rotations	65	114.29	24.33	95.00	-.04	-.66	.97
4. Perspective Taking	71	152.97	14.83	67.17	-1.04	.68	.63
5. Gestalt Completion	72	14.63	2.71	11.00	-.93	.45	.61
6. Hidden Patterns	72	217.65	55.75	286.00	-.49	.22	.98
7. Shape Memory	68	24.99	3.19	14.00	-.52	-.07	.56
8. Maze Tracing	82	30.35	6.58	33.00	.25	.42	.93
9. Transformation	82	20.56	2.94	13.00	-1.21	1.38	.63
10. Picture Number	75	25.13	9.35	34.00	-.38	-.91	.91
11. Toothpicks	74	10.07	5.27	21.00	.28	-.74	.63
12. Auditory Number Span	82	10.01	2.75	14.00	.25	.02	.71
13. Figure Classifications	75	130.49	32.88	145.00	-.18	-.58	.98
14. Nonsense Syllogisms	73	14.53	4.16	20.00	.06	-.16	.80
15. Finding A's	63	50.94	12.67	59.00	.63	.39	.92

Task	n	M	SD	Range	Skewness	Kurtosis	α
16. Identical Pictures	77	83.05	10.50	43.00	-.91	.31	.93
17. Ravens Advanced Matrices	73	23.43	4.97	25.00	-.61	.25	.87

A correlational analysis (Table 4) was conducted to provide an initial overview of factors which correlated with fluid intelligence as measured by the Ravens Advanced Progressive Matrices test. Four factors had moderate and statistically significant correlations including visual memory (Shape Memory Test) (r = .534, p < .01), visualization (Paper Folding Test) (r = .534, p < .01), inductive reasoning (Figure Classifications Test) (r = .453, p < .01), and associative memory (Picture Number Test) (r = .428, p < .01).

The final data analysis from Experiment 1 was the conduction of a stepwise multiple linear regression as an exploratory multivariate analysis to determine a potential model of factors with predictive power for fluid intelligence. The results (Table 3) indicate that the four factors with statistically significant and moderate correlations with fluid intellilgence formed a statistically significant model (F(4,80) = 15.269, p < .001), with a R^2 value of .433. Therefore, this model predicted 43.3% of the variance in fluid intelligence as described by performance on the Ravens Advanced Progressive Matrices test.

Table 3. Stepwise multiple linear regression results from Experiment 1

IV	Model 1			Model 2			Model 3			Model 4		
	B	SE B	β	B	SE B	β	B	SE B	β	B	SE B	β
1	.451	.085	.504**	.406	.080	.455**	.369	.079	.413**	.306	.083	.343**
2				.200	.054	.329**	.167	.055	.275**	.130	.056	.214*
3							.200	.085	.216*	.178	.084	.192*
4										.299	.141	.209*
		.254			.360			.401			.433	
		.245			.345			.379			.405	
		28.312**			13.559**			5.555*			4.473*	

Note: * p < 0.5. ** p < 0.1. Independent Variables (IV): 1 = Visualization (Paper Folding Test), 2 = Associative Memory (Picture Number Test), 3 = Inductive Reasoning (Figure Classification Test), 4 = Visual Memory (Shape Memory Test). Dependant Variable = Fluid Intelligence (Ravens Advanced Progressive Matrices test).

Table 4. Correlation matrix from Experiment 1

Task	Statistic	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. Paper Folding	Pearson's *r*	–																
	n																	
2. Mental Rotations	Pearson's *r*	.439**	–															
	n	70																
3. Card Rotations	Pearson's *r*	.334*	.531**	–														
	n	58	62															
4. Perspective Taking	Pearson's *r*	.303*	.322**	.285*	–													
	n	62	71	55														
5. Gestalt Completion	Pearson's *r*	.282*	.325**	.262*	.280*	–												
	n	72	70	58	62													
6. Hidden Patterns	Pearson's *r*	.255*	.026	.032	.143	.239*	–											
	n	72	70	58	62	72												
7. Shape Memory	Pearson's *r*	.453**	.275*	.031	.360**	.289*	.241	–										
	n	62	64	57	56	62	62											
8. Maze Tracing	Pearson's *r*	.418**	.175	.359**	.068	.144	.209	.168	–									
	n	69	76	62	68	69	69	68										
9. Transformation	Pearson's *r*	.401**	.382**	.177	.145	.318**	.247*	.204	.272*	–								
	n	69	76	62	68	69	69	68	82									
10. Picture Number	Pearson's *r*	.145	.078	.160	.134	.167	.140	.426**	.201	.152	–							
	n	65	71	59	63	65	65	62	73	73								
11. Toothpicks	Pearson's *r*	.350**	.400**	.313*	.141	.122	.222	.072	.332**	.347**	.085	–						
	n	63	71	59	63	63	63	58	72	72	67							
12. Auditory Number Span	Pearson's *r*	.182	.287*	.224	.157	.168	.142	.186	.035	.037	.200	.119	–					
	n	69	76	62	68	69	69	68	82	82	73	72						
13. Figure Classifications	Pearson's *r*	.274*	.241*	.175	-.086	.139	.437**	.322*	.362**	.386**	.279*	.351**	-.046	–				
	n	65	71	59	63	65	65	62	73	73	75	67	73					
14. Nonsense Syllogisms	Pearson's *r*	-.034	.162	.114	.041	.102	-.030	-.017	.181	.182	.162	.065	.213	.027	–			
	n	63	70	58	62	63	63	57	71	71	66	73	71	66				
15. Finding A's	Pearson's *r*	.024	-.029	.100	.007	.298*	.090	.083	.066	.064	.115	-.119	-.014	.254	-.100	–		
	n	57	60	58	52	57	57	59	61	61	57	58	61	57	57			
16. Identical Pictures	Pearson's *r*	.300*	.277*	.466**	.009	.421**	.140	.148	.489**	.370**	.294*	.342**	-.102	.326**	-.122	.181	–	
	n	70	74	62	66	70	70	65	74	74	69	68	74	69	67	61		
17. Ravens Advanced Matrices	Pearson's *r*	.533**	.218	.211	.181	.341**	.309*	.534**	.247*	.272*	.428**	.174	.122	.453**	.039	.126	.278*	–
	n	66	71	58	63	66	66	63	71	71	67	66	71	67	65	59	68	

Note: **. correlation is significant at the .01 level (two-tailed). *. correlation is significant at the .05 level (two-tailed).

Experiment 2: Participants

A cohort of 4th year undergraduate students (n=87) enrolled in the same ITTE programme as the 3rd year cohort from Experiment 1 participated in this experiment. The cohort consisted of 79 males and eight females. Their ages ranged from 21 to 33 with a mean of 22.63 and a standard deviation of 2.33. Participation in this study was voluntary.

Experiment 2: Psychometric Tests

Based on the results from Experiment 1, the five tests from the regression model (Table 3) were utilised with two additional measures (Table 5). This meant that there were two tests of visualization, two tests of memory span, and two tests of inductive reasoning to act as independent variables and the Ravens Advanced Progressive Matrices remained as the dependent variable.

Table 5. Psychometric tests utilized in Experiment 2

Test	Second-Order Factor	First-Order Factor
Ravens Advanced Progressive Matrices*	Fluid Intelligence	
ETS Paper Folding Test	Visual Processing	Visualization
ETS Surface Development Test*	Visual Processing	Visualization
ETS Shape Memory Test	Visual Processing	Visual Memory
ETS Picture Number Test	Long-Term Memory	Associative Memory
ETS Figure Classification Test*	General Reasoning	Inductive Reasoning
ETS Letter Sets Test	General Reasoning	Inductive Reasoning

Note: * Tests were adapted to include the Paas (1992) Cognitive Load Rating Scale after each item as a measure of mental effort. Participants also recorded the start and end times for each item. Two minutes were added to each test to facilitate these amendments.

Experiment 2: Results

Descriptive statistics for Experiment 2 are presented in Table 6. No test exceeded acceptable limits of skewness or kurtosis and all reliability coefficients were acceptable.

Table 6. Descriptive statistics for Experiment 2

Task	n	M	SD	Range	Skewness	Kurtosis	α
1. Ravens Advanced Matrices	87	19.00	5.28	25.00	-.40	-.09	.80
2. Paper Folding	87	13.40	2.67	12.00	-.47	-.08	.65
3. Surface Developments Test	87	46.06	9.31	42.00	-.73	.05	.91
4. Shape Memory	87	24.38	3.72	17.00	-.05	-.46	.65
5. Picture Number	87	24.85	8.88	41.00	-.29	-.57	.90
6. Figure Classifications	87	126.35	27.49	127.00	.18	-.34	.96

Task	n	M	SD	Range	Skewness	Kurtosis	α
7. Letter Sets Test	87	19.24	4.23	23.00	-.42	.49	.75

A correlational analysis was conducted on the data from Experiment 2. All performance scores had statistically significant correlations with the Ravens test except the Picture Number Test strengthening the reliability in the correlations found in Experiment 1.

Table 7. Correlation matrix for Experiment 2 including time and effort variables

	1	2	3	4	5	6	7	8	9	10	11	12
1. Picture Number Test	-											
2. Shape Memory Test	.30**	-										
3. Letter Sets Test	.24*	.15	-									
4. Paper Folding Test	-.01	.12	.33**	-								
5. Surface Development Time	-.08	.01	-.29**	-.41**	-							
6. Surface Development Score	.10	.19	.32**	.36**	-.54**	-						
7. Surface Development Effort	-.11	-.18	-.22*	-.19	.44**	-.53**	-					
8. Ravens Matrices Time	.30**	.37**	-.01	-.12	.31**	.00	-.05	-				
9. Ravens Matrices Score	.20	.35**	.34**	.39**	-.23*	.41**	-.20	.42**	-			
10. Ravens Matrices Effort	.17	.05	-.09	-.22*	.08	-.09	.37**	.14	-.11	-		
11. Figure Classifications Time	-.09	-.04	-.12	-.19	.33**	-.14	.04	.35**	-.04	.28**	-	
12. Figure Classifications Score	.13	.20	.20	.40**	-.19	.40**	-.20	.23*	.54**	-.18	-.16	-
13. Figure Classifications Effort	-.12	-.24*	-.22*	-.19	.13	-.32**	.46**	-.14	-.32**	.67**	.31**	-.46**

Note: Correlation coefficients describe Spearman's Rho (ρ) values. **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Three multiple linear regression analyses were subsequently conducted to examine the predictive power of the visualization (Paper Folding Test), inductive reasoning (Figure Classification Test), visual memory (Shape Memory Test) and associative memory (Picture Number Test) factors on performance, time taken and effort exerted during the Ravens Advanced Progressive Matrices test. A statistically significant regression equation was found between the four factors and performance ($F(4,82) = 14.226$, $p < .001$), with a R^2 value of .410. A statistically significant regression equation was also found between the four factors and time taken ($F(4,82) = 7.504$, $p < .001$), with a R^2 value of .268. Finally, a statistically significant regression equation was also found between the four factors and effort exerted ($F(4,82) = 3.200$, $p = .017$), with a R^2 value of .135.

Discussion and Conclusion

The results of Experiment 2 are similar to those from Experiment 1 and confirm the predictive power of the synthesis of visualization, visual memory, associative memory and inductive reasoning on fluid intelligence. All regression models were statistically significant with 43.3% of the performance variance being explained in Experiment 1 and 41% of the variance being explained in Experiment 2. It is important to consider the nature of each of these factors and the potential role they may play in problem solving in STEM education. The Picture Number Test measures associative memory which falls under the second-order factor of long-term memory however in the Kit of Factor Referenced Cognitive Tests (Ekstrom, French, Harman, & Derman, 1976b) it is described as a short-term memory process. Therefore, the three factors identified in this study as components of fluid intelligence are visualization, inductive reasoning, and what is arguably memory span being described by the two memory tests. It is posited that the strength and significance in the association between memory span and fluid intelligence stems from the increased capacity to hold relative information in the working memory while problem solving. This is further supported by the statistically significant regression models illustrating the predictive power of these factors on time taken and effort exerted in the Raven's test. In terms of the association with visualization, it is posited that this supports the ability to generate and manipulate the information within the working memory. Finally, inductive reasoning is posited to provide people with the capacity to make inferences from the information stored in the working memory.

There are many implications for these results. In considering the impact that the intervention described by Sorby (2009) has had on STEM educational achievement and retention, developing complementary interventions to support inductive reasoning and working memory capacity may further increase the positive effects such training can have for STEM students. In considering the work of Buckley, Seery and Canty (2017) who present a model of spatial skills synthesizing multiple factors from contemporary research, these results can guide which factors should be selected for consideration within STEM education research and practice.

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