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COGNITIVE PREDICTORS OF ACADEMIC ACHIEVEMENT AT HIGH SCHOOL AGE: CROSS-CULTURAL STUDY

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Abstract

The aim of the study is to investigate the role of cognitive characteristics (processing speed, working memory and sense of number) and general (nonverbal intelligence) in the individual differences in academic achievement on the samples of high school children from Russia and Kyrgyzstan. These countries are characterized, on the one hand, by similarities in the organization of the national education system, and, on the other hand, differences in socioeconomic status and effectiveness of public education. The study involved 514 schoolchildren at Grades 10 & 11 from two state educational institutions. The samples were balanced by the educational microenvironment. The Russian sample was represented by 205 pupils from 15.8 to 18.8 years (41.9% of boys). The Kyrgyz sample included 309 schoolchildren from 15.3 to 18.8 years (36.4% of boys). It is shown that both in Russia and in Kyrgyzstan, the best model fit was for the speed of information processing as a key predictor of intelligence, working memory and a number sense, which in turn explained variation in the academic achievement. At the same time, we found cross-cultural differences in the interrelationships between certain cognitive development factors and academic achievement. Thus, in less favorable socioeconomic conditions, the greatest functional weight was obtained for the correlation between the speed of processing information and academic achievement through working memory and nonverbal intelligence. On the contrary, under more favorable conditions, the contribution of cognitive characteristics to the development of individual differences in academic achievement was not significant.

Keywords: Processing speed, Non-verbal Intelligence, Working Memory, Number Sense, School Achievement, High school age

1. Introduction

The relevance of the study of the role of cognitive development factors shaping individual differences in the academic achievement is related to a clear practical request and is associated, in particular, with the development of individually-based learning systems.

The results of studies in the field of cognitive psychology demonstrate that academic achievement correlates with cognitive characteristics such as intelligence (Deary et al., 2007; Verbitskaya et al., 2017), various aspects of the number sense (Halberda, Mazzocco, Feigenson, 2008; Tikhomirova et al., 2015a; Tosto et al., 2014), spatial memory (Bull, Davidson, Nordmann, 2010; Tikhomirova, 2017) and processing speed (Semmes, Davison, Close, 2011; Tikhomirova et al., 2015b).

2. Problem Statement

The studies of the structure of the relationships between cognitive characteristics and individual differences in academic achievement in different sociocultural samples show directly opposite results (e.g., Tikhomirova et al., 2017a; Deary et al., 2007).

On the one hand, the cross-cultural specifics of these results may be due to cultural differences in reasoning, for example, East Asian (holistic cognition) and Western (analytical cognition) cultures (Nisbett et al., 2012), differences in the structure of language and writing, for example, Chinese hieroglyphs and the Russian alphabet (Rodic et al., 2015), the type of cultural communities (the ratio of the scales "collectivism - individualism" and "independence-interdependence") (Oyserman, Coon & Kemmelmeier, 2002).

On the other hand, it is repeatedly reported that the development of individual differences in intelligence depends on the macro-conditions that in most studies are associated with socioeconomic factors: the level of the country's economic development (Krapohl & Plomin, 2016; von Stumm & Plomin, 2015) in particular, the effectiveness of the public education system (Brinch & Galloway, 2012; Falch & Sandgren Massih, 2011; Nisbett et al., 2012). Thus, the significant positive impact of education on individual differences in cognitive functioning was obtained in a number of research projects.

First, this influence is established in natural experiments, when as a result of the reform of the educational system additional years of education are introduced or, alternatively, the duration of compulsory education is shortened (Brinch & Galloway, 2012, Nisbett et al., 2012). It was found, in particular, that pupils who miss 1 year of schooling, then show slightly lower results in the intelligence test (Ceci, 1991). Moreover, the studies recorded a "seasonal" decrease in the test scores of the intellect, which is associated with prolonged school holidays in the absence of planned educational impact (Nisbett et al., 2012).

Second, the influence of education on the cognitive functioning of schoolchildren is investigated in studies involving peer children who for different reasons begin schooling for 1 year sooner or later. These papers report the best results of performing tests of non-verbal intelligence by children enrolled in school one year earlier, compared to their peers who started their studies at school (Cahan, Cohen, 1989).

Third, the positive impact of education is documented in studies of eolder people (Schneeweis, Skirbekk & Winter-Ebmer, 2014). It is shown that the duration of schooling at school age contributes to later cognitive aging.

3. Research Questions

The differences in the effectiveness of the national education systems can lead to differences in the relationship between cognitive functioning and academic achievement. It has been shown that the large heterogeneity and low efficiency of the educational environment lead to a decrease in the role of cognitive indicators in the success of schooling (Tucker-Drob, Bates, 2016).

In the present study, the analysis of the structure of the relationship between the cognitive development factors and academic achievement is investigated on the samples of high school students from Russia and Kyrgyzstan. These countries have a similar organization of education systems (like the former Soviet republics), but differ in social and economic status (they are part of the groups of countries with high and medium development levels according to the Human Development Report of the United Nations Development Program, http://hdr.undp.org/en/2016-report) and the level of academic achievement of 15-year-old schoolchildren (according to the International Achievement Assessment Program, http://www.oecd.org/pisa/aboutpisa).

4. Purpose of the Study

The purpose of the study is to analyze cross-cultural aspects of cognitive factors such as the processing speed, working memory, number sense, nonverbal intelligence, and the development of individual differences in the academic achievement across various school disciplines. We aim to investigate universal and culturally-specific predictors of academic achievement at high school age.

5. Research Methods

5.1. Participants and procedure

The study included 514 students studying in Grades 10 & 11 from two general education institutions in Russia and Kyrgyzstan with similar educational conditions in terms of the quality of education, qualifications and structure of the teaching staff, departmental affiliation and educational programs implemented at school. The Russian sample is represented by 205 students from 15.8 до 18.8 years (41.9% male); the Kyrgyz sample included 309 students from 15.3 до 18.8 years (36.4% male).

We received individual written consent from the parents of participants. Students completed the tasks in a computerized test battery to determine the level of cognitive development in terms of the speed of processing information, working memory, sense of number. On both cultural samples, identical test procedures were conducted with instructions in Russian and strictly in accordance with the protocols. Data collection was conducted in educational institutions at the time of lessons strictly following the protocol under the constant supervision of a researcher. Indicators of academic success in school subjects were recorded with the consent of participants and their parents on the basis of class journals.

5.2. Measured variables: cognitive characteristics

Each participant completed the tasks of Web-based test battery (Tosto et al., 2013). The analysis of the results was carried out on the basis of anonymous personal data with prior written consent from the parents of the participants. The participants completed the following tasks.

- *Test «Choice Reaction Time», processing speed.* In the test the numbers 1, 2, 3, 4, appear 10 times each in randomized order with random interval between 1 and 3 seconds. The task consists in pressing the key corresponding to the number appearing on the screen as fast and accurately as possible. The task starts with instructions and a practice trial consisting of 6 items. The practice trial can be repeated. Time out for responses is 8 seconds. If no response is given during this time the next trial follows. The program records accuracy and reaction time on correct response.

- *Test 'Corsi Tapping Block', working memory.* Participants are presented with a block were cubes glow one at the time, in established patterns. The task consists in reproducing the correct pattern clicking on the boxes with the mouse. The test starts with 4 items (or tappings of the cubes) in each sequence. There are 2 sequences in each level, 9 levels therefore a total of 18 trials. The test starts with visual instructions and one practice trial of 3 items that can be repeated until the participant is familiar with the task. During presentation of the stimuli, the box glows for 1 sec. An interval of 1 sec separates the glowing of the boxes. The program records correct responses and reaction time on correct response.

- *Test 'Number Sense', ability of quantity and numerosity estimation.* Participants are presented with arrays of yellow and blue dots, mixed together and varying in size and numbers. The task requires to judge whether the array contains more yellow or blue dots by pressing the responding keys on the keyboard. The stimuli are 150 static pictures with the arrays of yellow and blue dots varying between 5 and 21 dots of each colour and ratios of the arrays in the two colours between 1:3 and 6:7. The presentation order is the same for all participants. The stimulus flashes on the screen for 400 ms, maximum response time is 8 sec. The task contains a set of instruction, a practice trial, with two items and an option to repeat the practice. The task is divided in blocks of 50 trials. The program records accuracy and reaction time on correct trials.

- *Test 'Raven's Progressive Matrices', non-verbal intelligence.* Pen-and-paper version of the test are used (Raven, 2000). It consists of 60 tasks grouped in 5 series. In series A, participants have to complement the missing part of an image. In series B they are asked to find correspondence between pairs. In series C the tasks are related to geometrical principles in figure changes. In series D the participants have to find the structure in shuffling of figures. Series E requires the ability to analyze figures and add the missing parts. Each correct answer was counted as 1 point. Total scores were calculated.

5.3. Measured variables: academic achievement

Academic achievement was indicated by semi-annual grades in Math, Language and Science. Grades are given by teachers and vary from 2 (low achievement) to 5 (high achievement) points. In the statistical analysis the mean of the grades was used.

5.4. Data analysis

At the first stage, the analysis was made to show the structure equivalence of cognitive development indicators and academic success using the principal components analysis (PCA) with Varimax rotation.

At the second stage, descriptive statistics were calculated for the analyzed indicators in each sample. A one-factor ANOVA was run on the indicators of cognitive development to assess the effect of cultural affiliation.

At the third stage, a correlation analysis of the relationship between all cognitive indices and academic success on each of the samples was performed.

At the fourth stage, the structure of cognitive characteristics and academic achievement was studied in each of the analyzed samples using the structural equation modeling method (SEM, OpenMX package). To assess the model's compliance with empirical data, the following criteria were used: $RMSEA \leq 0.06$; 95% confidence intervals – $RMSEA low = 0.00$ and $RMSEA high < 0.08$; $CFI > 0.95$; $TLI > 0.90$ (Hu & Bentler, 1999). During the process structural modeling, a number of theoretical models explaining the relationship between cognitive characteristics and success at each level of general education were tested.

- *Model 1*: cognitive characteristics affect the success rates in learning through the latent variable of the overall cognitive ability "*g*";
- *Model 2*: cognitive characteristics – processing speed, working memory, number sense and non-verbal intelligence – contribute to the factor of overall academic achievement "*e*" ("*education*");
- *Model 3:* the information processing speed is a key predictor of nonverbal intelligence, working memory and number sense, which, in turn, contribute to the factor of overall academic achievement "e".

6. Findings

6.1. Equivalence analysis

In accordance with the cultural and comparative studies methodology, an equivalence analysis was carried out (Berry et al., 2002). Factor analysis of the indicators on the samples of Russia and Kyrgyzstan revealed an invariant factor structure of cognitive functioning and academic success indicators, extracting two factors and explaining 63.4% and 55.6% of the indices variance in both samples respectively. This is the condition of structural equivalence of data. On both cultural samples, identical test procedures were conducted with instructions in Russian. They consisted of instructions with numbers and geometric forms

in strict accordance with the protocols. This fact eliminates the need for analysis of the differential item functioning (DIF) in tests.

Thus, the quantitative differences between the patterns of cognitive functioning can be compared in a cross-cultural context. At the same time, cross-cultural comparison of academic success on the basis of teachers' assessments is impossible even in countries with similar educational systems. At the same time, within single population, the mark-based analysis of academic achievement is acceptable.

6.2. Descriptive statistics & ANOVAs

In the cross-cultural study, the indicators of number sense, working memory, information processing speed, non-verbal intelligence and academic achievement were analyzed. Descriptive statistics of indicators – means, as well as minimum and maximum (in parentheses) – are presented in Table 01.

Table 01. Descriptive statistics of cognitive characteristics and academic achievement

	Russia	**Kyrgyzstan**
Non-verbal intelligence	51.47 (32 – 60)	46.09 (21 – 58)
Processing speed	0.48 (.32 – 1.12)	0.74 (.49 – 1.39)
Working memory	5.1 (1 – 10)	5.1 (1 – 10)
Number sense	109.7 (76 – 134)	108.9 (66 – 133)
Math	3.9 (3 – 5)	3.7 (3 – 5)
Russian	3.9 (3 – 5)	3.6 (3 – 5)
Biology	4.0 (3 – 5)	3.9 (3 – 5)

Table 01 presents the average value of the correct answers for indicators of non-verbal intelligence, working memory, sense of number. For the information processing speed indicator, the average response time for the correct answers in seconds is shown. Consequently, the smaller the average value, the higher the processing speed of information. The minimum and maximum number of scores for indicators of nonverbal intelligence is from 0 to 60, working memory – from 0 to 12, number sense – from 0 to 150. The range of success indicators in learning mathematics, the Russian language and biology varies from 2 to 5.

According to Table 01, slightly higher averages were obtained from a sample of Russian high school students compared to their Kyrgyz counterparts for all indicators of cognitive development, except for the working memory. For example, the average number of correct answers for the RPM on the Russian sample was 51.47, and in Kyrgyz – 46.09. Russian high school students were also on average more "speedy" compared to Kyrgyz: the average reaction time for Russians is 0.48 versus 0.74. On the contrary, the average value of working memory was similar on the samples of high school students from Russia and Kyrgyzstan.

The indicators of academic success generally do not differ between the two samples analyzed. For example, the average value of the success in studying mathematics is 3.9 on the Russian and 3.7 on the Kyrgyz sample.

The findings suggest cross-cultural differences in the variability range of indicators of non-verbal intelligence, information processing speed and number sense. In particular, in the Kyrgyz sample the minimum values were lower than in the Russian sample. For example, the minimum value of non-verbal intelligence indicator in Russian sample is 32, and in Kyrgyz – 21. The range of variability in academic success as well as working memory is similar for both cultural samples.

To determine the statistically significant cross-cultural differences in cognitive performance, a one-way ANOVA was carried out. Table 02 presents the results of a single-factor ANOVA, where the categorical factor used was the country of residence – Russia or Kyrgyzstan.

To test the hypothesis that all distributions of dependent variables for the compared samples have the same variances, the criterion for the equality of Levene's variances was used. For all test indicators, the significance level was greater than 0.05, which indicates the equality of variances in two populations.

Table 02. The country of residence factor influence upon the cognitive characteristics

Test measure	Square sums (SS)	Fischer's F (F)	P-value (*p*)	Effect size (η^2)
Non-verbal intelligence	2147.67	47.94	.00	.14
Processing speed	1.56	30.34	.00	.05
Working memory	16.66	4.02	.07	.00
Number sense	16.58	21.20	.14	.00

Table 02 shows that the effect of the country of residence factor was statistically significant for two indicators of cognitive functioning – non-verbal intelligence and processing speed. According to the data in Table 01, Russian students demonstrate significantly better results in tests of non-verbal intelligence and information processing speed than their Kyrgyz peers. In this case, a significantly larger effect size was obtained for non-verbal intelligence ($\eta^2 = 0.14$; $p < 0.001$). These results are consistent with the available data on cross-cultural differences in non-verbal intelligence and information processing speed (e.g., Brouwers, Van de Vijver, Van Hemert, 2009; Hedden et al., 2002). According to the research, non-verbal intelligence is the most common subject of cross-cultural research: a number of studies have shown cross-cultural differences in test scores of nonverbal intelligence (see, for example, a meta-analysis with a sample of 244,316 subjects (Brouwers, Van de Vijver, Van Hemert, 2009). Cross-cultural differences in the information processing speed are studied in close connection with age characteristics: cross-cultural differences are mostly recorded in children and young men (Hedden et al., 2002).

Thus, as a result of variation analysis, we have shown that at the full level of general education there are cross-cultural differences in the indices of non-verbal intelligence and processing speed. A direct correlation between the mean values of these cognitive characteristics and the socio-economic development level of the country of residence was revealed.

6.3. The interrelationships between cognitive characteristics and academic achievement: correlation analyses

We used correlation analysis to study the structure of the relationships between cognitive characteristics – processing speed, working memory, number sense and non-verbal intelligence – and academic achievement. Spearman correlation coefficients were used (SPSS 20.0 software).

Table 03 presents the correlation coefficients between processing speed (PS), working memory (WM), number sense (NS), non-verbal intelligence (NI), and academic achievement in mathematics (M), Russian (R) and biology (B) separately for the Russian (upper line) and Kyrgyz (lower line) samples.

Table 03. Spearman correlation coefficients between cognitive characteristics and academic achievement

	PS	WM	NS	NI	R	M
WM	-.34** -.11	1				
NS	-.32** -.03	.39** .17**	1			
NI	-.08 -.11	.32** .23**	-.06 .35**	1		
R	.06 .10	.14** .04	.06 .11	.18** .19**	1	
M	.04 .00	.12 .11	.07 .15*	.14 .24**	.92** .39**	1
B	.01 .04	.11 .02	.10 .12	.08 .14	.76** .34**	.76** .55**

Note: ** $p < .01$; * $p < .05$

According to Table 03, only non-verbal intelligence was related to academic achievement in both cultural samples among the analyzed indicators of cognitive development. In the Russian sample non-verbal intelligence was only associated with Russian language attainment (r = 0.18; $p < 0.01$), while in the Kyrgyz sample it was associated with academic achievement in both Russian language (r = 0.19; $p < 0.01$) and mathematics (r=0.24; $p < 0.01$). Working memory was associated with Russian language attainment only in the Russian sample (r = 0.14; $p < 0.01$). Number sense was weakly associated with academic achievement in mathematics only in the Kyrgyz sample (r = 0.15, $p < 0.05$).

The relationship between the analyzed cognitive characteristics is more pronounced in the Russian sample (0.32 < r < 0.39; $p < 0.01$) than in Kyrgyz (0.17 < r < 0.35; $p < 0.01$). It should be noted that in the Kyrgyz sample, information processing speed was not associated with any of the indicators of cognitive development.

In general, the structure of the relationships between cognitive characteristics and academic achievement differed in the Russian and Kyrgyz samples. This was to be expected, since cross-cultural differences in similar interrelationships were already observed in our previous study involving Russian and British senior students (Tikhomirova et al., 2014).

6.4. The role of cognitive characteristics in individual differences of academic achievement: structural equation modeling

Next, we studied the structure of the relationships between cognitive characteristics and academic achievement using structural equation modeling (R, OpenMX package).

We proposed three models for this analysis. Model 1 was based on the hypothesis that cognitive characteristics would influence academic achievement through a general "g" factor. Model 2 assumed that the information processing speed, working memory, number sense and non-verbal intelligence - contribute to the factor of overall academic achievement "*e*" ("*education*"). Both models fit the data poorly in both samples (RMSEA > 0.08; CFI < 0.95; TLI < 0.90; χ^2 was significant ($p < 0.05$)). Finally, with Model 3 we hypothesized that information processing speed would be the key predictor for non-verbal intelligence and number sense, which in turn would influence factor "*e*" of academic achievement. Model 3 showed good fit to the data in both samples (see Table 04).

Table 04 presents the Model 3 fit statistics obtained from both our samples – the samples of Russia and Kyrgyzstan.

Table 04. Model 3 fit statistics

Sample	AIC	BIC	CFI	TLI	RMSEA	RMSEA low	RMSEA high
Russia	995.50	-3274.59	1.006	1.013	.000	.000	.000
Kyrgyzstan	2673.10	-4199.99	1.009	1.020	.000	.000	.000

Note: RMSEA low and RMSEA high refer to the 95% confidence intervals of the RMSEA fit statistic.

Figure 01 shows the model of the structure of the interrelations of cognitive characteristics (RT-processing speed, Raven – non-verbal intelligence, WM – working memory, NS – Number Sense) and academic achievement in mathematics (Math), Russian (Rus) and science disciplines (Bio) in Russia. Non-significant loadings ($p > 0.05$) are represented by dotted lines.
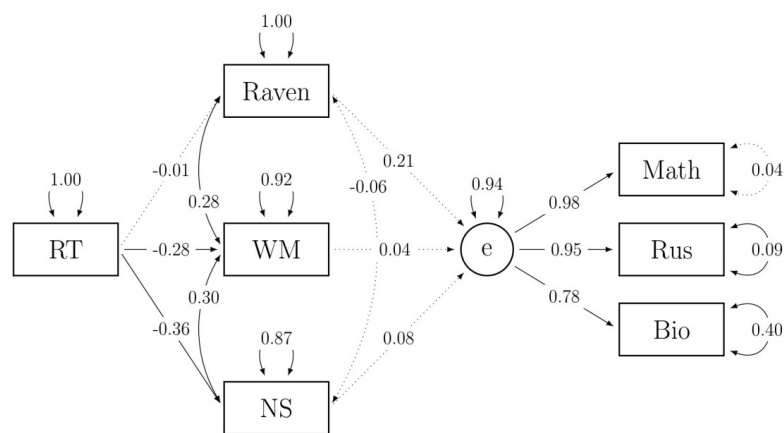
Figure 01. The relationship between cognitive characteristics and academic achievement in Russia
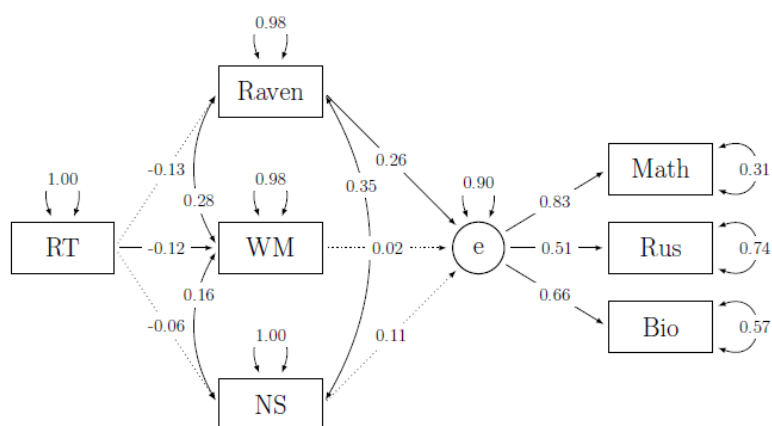
On the Russian sample of high school age students, a comparative analysis of the standardized structural coefficients of the model shows that information processing speed has a moderate effect on

number sense (β = -0.36), slightly less on the working memory (β = -0.28) and is not related with non-verbal intelligence ($p > 0.05$). The standardized coefficient between nonverbal intelligence and working memory reaches a value of 0.28, and between number sense and spatial memory is 0.30. The relationship between the intellect and the number sense not reach statistical significance ($p > 0.05$).

It should be especially noted that at the full level of education, none of the cognitive characteristics analyzed has a statistically significant effect on the factor of academic success ($p > 0.05$).

Among the indicators of success, the success in training mathematics (β = 0.98) and, to a lesser extent, the success in the Russian language (β = 0.95), is the most heavily weighted on the factor of academic success. The indicator of success in learning biology is less loaded – 0.78.

Figure 02 shows the model of the structure of the interrelations of cognitive characteristics (RT-processing speed, Raven – non-verbal intelligence, WM – working memory, NS – Number Sense) and academic achievement in mathematics (Math), Russian (Rus) and science disciplines (Bio) in Kyrgyzstan. The standardized structural coefficients ($p < 0.05$) obtained in the course of structural modeling are indicated. Dotted lines indicate statistically insignificant relationships ($p > 0.05$).

Figure 02. The relationship between cognitive characteristics and academic achievement in Kyrgyzstan

In the Kyrgyz sample of high school age students, a comparative analysis of the standardized structural coefficients of the model shows that information processing speed affects only working memory (β= -0.12) and is not related to the number sense and non-verbal intelligence ($p > 0.05$). The standardized ratio between non-verbal intelligence and working memory reaches a value of 0.28, and between number sense and the working memory is 0.16. The relationship between the intellect and number sense is significant ($p < 0.05$), with a coefficient of 0.35.

Among the analyzed cognitive characteristics, only nonverbal intellect has a statistically significant effect on the academic achievement (β = 0.26; $p < 0.05$). The greatest functional weight has the interrelation "processing speed − working memory − non-verbal intelligence − academic achievement". The regression weight of this path is -0.02.

Among achievement indicators, the achievement in mathematics (β = 0.83) and, to a lesser extent, in biology (β = 0.66), is the most heavily weighted on the factor of academic achievement. The indicator of success in the Russian language is less loaded – 0.51.

Thus, the theoretical model, which assumes that information processing speed is a key predictor of intelligence, working memory and number sense, which in turn contribute to individual differences in academic achievement, best describes the empirical data obtained on Russian and Kyrgyzstan samples. The obtained results are in good agreement with the existing studies of the structure of the interrelationships conducted in Europe and the USA. According to the literature, the nonverbal intelligence is one of the most significant indicators of cognitive development, which form individual differences in academic achievement across a whole spectrum of disciplines (Deary et al., 2007; Taub et al., 2008). At the same time, a number of studies have shown that academic achievements are largely related to the individual characteristics of elementary cognitive processes – processing speed, working memory and number sense (Tikhomirova et al., 2015b; Tikhomirova et al., 2014; Luo, Thompson & Detterman, 2006; Rohde, Thompson, 2007). These basic processes underlie cognitive processes of a higher order (Ackerman, Beier & Boyle, 2005; Colom et al., 2006). According to the authors, the connection between elementary cognitive processes and academic achievement is mediated precisely by non-verbal intelligence (Rindermann, Neubauer, 2004).

At the same time, we found cross-cultural differences in the links between cognitive development indicators and academic achievement on the samples of senior pupils of Russia and Kyrgyzstan. In particular, the greatest functional weight was obtained for the relationship between information processing speed and academic achievement through working memory and non-verbal intelligence for low socio-economic indicators. On the contrary, in more favorable socio-economic conditions, the contribution of cognitive characteristics to the development of individual differences in academic achievement was not significant. This fact can be explained by the more stringent criteria for the selection of schoolchildren for high school education in Russian schools, including the achievement criteria (Tikhomirova et al., 2017b; Tikhomirova et al., 2015b). In this case, on the sample of Russian high school students, the range of variability of cognitive development indicators is most narrowly narrowed, which may be the reason for a statistically insignificant contribution to the development of individual differences in academic success.

7. Conclusion

In this paper the cognitive basis of academic achievement was operationalized through the elementary cognitive characteristics: processing speed, working memory and number sense, as well as the overall cognitive index – the non-verbal intelligence.

It is shown that both in Russia and in Kyrgyzstan, the theoretical model that is best describing the empirical data is the one with the information processing speed is a key predictor of intelligence, working memory and number sense, which in turn form individual differences in academic achievement.

At the same time, during the senior school age, there are cross-cultural differences in the relationships between different cognitive development indicators and academic achievement. So, in countries of residence with low socio-economic indicators, the greatest functional weight is obtained for

the interconnection between information processing speed and academic success through working memory and non-verbal intelligence. On the contrary, in more favorable socioeconomic conditions, the contribution of cognitive characteristics to the formation of individual differences in academic success is not significant.

Further research in this area is required to study the structure of the links between cognitive development and academic success, including samples that belong to other cultural communities and age groups.

Acknowledgments

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