Processing speed and intelligence as predictors of school achievement: Mediation or unique contribution?

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The relationships between processing speed, intelligence, and school achievement were analyzed on a sample of 184 Russian 16-year-old students. Two speeded tasks required the discrimination of simple geometrical shapes and the recognition of the presented meaningless figures. Raven’s Advanced Progressive Matrices and the verbal subtests of Amthauer’s Intelligence Structure Test were used as intelligence scales. The teacher-assigned grades in six school subjects that were aggregated into two scales represented real-life school achievement. Latent processing speed and intelligence as individual predictors each accounted for about 18% of the variability in scholastic performance. Taken together, they explained about 28% of the variance of school achievement. Although significantly correlated, each had a unique impact on school achievement; zero-constraining each of the two paths to school achievement resulted in a significantly worsened fit of a model. A mediation effect $\text{processing speed} \rightarrow \text{intelligence} \rightarrow \text{school achievement}$ was bootstrapped to obtain an estimate of its statistical significance and was found to be non-distinguishable from zero. The results are inconsistent with the causal hypothesis that states that processing speed is a predictor of real-life scholastic performance because of the impact of processing speed on higher-order cognitive ability, which in turn underlies school achievement.

1. Introduction

Since intelligence tests were originally meant to determine children with potential difficulties in school education (Binet, 1905) and the first measurement of general intelligence included analysis of school examination scores (Spearman, 1904), the association between intelligence and scholastic performance is one of the best-established associations and is often referred to in the literature on cognitive ability. The relationship between intelligence scores and school performance that are commonly found in studies are moderate to strong (e.g., Bartels, Rietveld, Van Vaal, & Boomsma, 2002; Brody, 1992; Jencks, 1979; Jensen, 1998; Neisser et al., 1996). These results largely depend on the kind of indexes of school achievement that were examined and whether intelligence was analyzed at a manifest or a latent level. For instance, the observed magnitude of correlation with intelligence varies for different subjects and measures of performance. Achievement in mathematics and sciences tends to be better predicted by cognitive ability than achievement in the languages (e.g., Deary, Strand, Smith, & Fernandes, 2007; Krumm, Ziegler, & Buehner, 2008; Lu, Weber, Spinath, & Shi, 2011), with a portion of predicted variability in such subjects as arts being the lowest (e.g., Deary et al., 2007). Another issue is the measure of school achievement used in the analysis: achievement test scores are more highly correlated with intelligence than are teacher-assigned grades, probably because the latter tend to reflect, to some extent, not only real performance, but also some of the other characteristics of the child like effort or personal traits (e.g., see Jensen, 1998). On the side of cognitive ability, intelligence modeled...
at a latent level generally serves as a better predictor of scholastic performance than single test scores; test-specific variance adds much less to the explanation of the variability in school performance. In other words, the variance of school achievement that is predictable by intelligence scores is mostly accounted for by \( g \), and not by the other factors that determine the scores on the different tests (Jensen, 1998).

At the same time, a large number of studies that were published in the last decades demonstrated that \( g \) could, in turn, be predicted by a number of basic cognitive processes. Processing speed and working memory are probably the best-established candidates to explain higher-order individual differences in cognitive ability (e.g., Colom, Abad, Quiroga, Shih, & Flores-Mendoza, 2008; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Fry & Hale, 1996; Jensen, 1998; Kail & Salthouse, 1994). Correlations between single measures of processing speed and intelligence that are commonly reported in the literature are low to moderate; when measures of processing speed are based on response times from different speeded tasks, their correlations with intelligence approach those typically observed between psychometric tests (Grudnik & Kranzler, 2001; Jensen, 2006; Kranzler & Jensen, 1989; Sheppard & Vernon, 2008; Vernon, 1988).

Thus, the next logical step would be to relate these basic processes directly to scholastic achievement. However, studies addressing this problem are still relatively rare. Discussing this issue, Luo, Thompson, and Detterman (2003a) mentioned that the failure of early studies (e.g., Cattell & Farrand, 1890) to observe significant relationships between elementary cognitive processes and scholastic performance has influenced the field. Recent studies seem to come back to this problem; however, research interest has more often focused on the working memory construct as the explanatory factor for school achievement (e.g., Alloway, 2009; Krumm et al., 2008; Lu et al., 2011). The relationship between processing speed and scholastic performance remains much less explored, although processing speed was shown to be almost as a powerful predictor of school achievement as working memory is, in at least one study that analyzed two large datasets (Luo, Thompson, & Detterman, 2006).

A study on the relationship between processing speed and scholastic achievement in fact can address different questions. First, processing speed can be examined as a single predictor of scholastic achievement in fact can address different questions. First, processing speed can be examined as a single predictor of school achievement. For example, Carlson and Jensen (1982) found that reaction time in a task designed in the Hick paradigm (Hick, 1952) and reading comprehension share about 30% of common variance. Very similar results were reported by Luo, Thompson, and Detterman (2003b). In their study, about 30% of the variance of scholastic performance was accounted for by the mental speed factor; the relationship between mental speed and school achievement was found to be invariant across different knowledge domains. Moreover, the latter study addressed another question, namely the etiology of these relationships. The covariance between mental speed and scholastic achievement was found to be mostly genetically mediated (similarly, other studies report that mental speed has a substantial genetic covariation with psychometric \( g \) (Baker, Vernon, & Ho, 1991; Rijsdijk, Vernon, & Boomsma, 1998) and intelligence has a mostly genetic covariation with school achievement (Kovas, Haworth, Dale, & Plomin, 2007; Petrill & Thompson, 1993; Thompson, Detterman, & Plomin, 1991; Wadsworth, DeFries, Fulker, & Plomin, 1995; Wainwright, Wright, Geffen, Luciano, & Martin, 2005)).

The next question that can be addressed is the question on the comparative strength of processing speed and intelligence as possible predictors of school achievement. Luo et al. (2006) formulated a very similar problem in terms of the criterion validity of tasks of basic cognitive processes. In the analyses of two datasets, which are the Woodcock-Johnson III Cognitive Abilities and Achievement Tests normative data and the Western Reserve Twin Project data (with a total of more than 5500 participants), the authors observed zero-order correlations between latent processing speed and achievement factors, which are similar or even higher than the correlations between conventional cognitive ability and achievement factors. In their earlier study, the same authors reported very similar results of almost equal zero-order shared variance between processing speed and scholastic performance, on the one hand, and intelligence and scholastic performance, on the other hand (Luo et al., 2003a). Similarly, Rindermann and Neubauer (2000) observed a correlation between processing speed and school performance \((r = .37)\) that was only slightly lower than a correlation between intelligence and school performance \((r = .43)\). Results reported by Luo and Petrill (1999) also suggest that “the predictive power of \( g \) will not be compromised when \( g \) is defined using experimentally more tractable [elementary cognitive tasks] ECTs” (p. 157). However, the relative strength of processing speed as a single predictor of school achievement (as compared to intelligence) still remains doubtful, as some studies report significantly lower association between processing speed and school achievement than between intelligence and school achievement. For example, Rindermann and Neubauer (2004) reported the associations with school achievement of \( \beta = .09 \) and \( \beta = .53 \) for processing speed and intelligence, respectively. Colom, Escorial, Shih, and Privado (2007) observed only low zero-order correlations between school grades and processing speed as measured by simple short-term recognition tasks. Of nine school subjects, grades in mathematics showed highest correlations with the measures of processing speed, although even these correlations were quite low \((r = -.12 \text{ and } r = -.17)\). In the latter study, latent processing speed was not a significant predictor of academic performance, while a combined latent variable for fluid intelligence and memory span capacity accounted for about 29% of variance of school achievement.

Finally, the most intriguing issue on the relationships between processing speed, intelligence, and school achievement is their consistency with the causal mental speed hypothesis. From this point onward, certain theoretical assumptions start playing a major role, as any kind of testing of mediation effects is completely senseless in the absence of strong theoretical and methodological backgrounds. The mental speed theory provides a strong background for this kind of study (Brand, 1981; Deary, 1995; Jensen, 1982, 2006, 2011); it suggests that processing speed is a basic factor that underlies higher-order cognitive ability, which in turn influences one’s success or failure in school. This theoretical model results in another set of questions that can be addressed through empirical studies. The first question concerns the relationship between intelligence and school achievement, with processing speed
as another explanatory variable. Indeed, as soon as processing speed not only underlies intelligence but also serves as a predictor of school achievement, could intelligence add anything else to the explanation of scholastic performance beyond processing speed? In other words, after controlling for processing speed, does the observed relationship between intelligence and school achievement still hold? The recent studies that addressed this issue reported inconsistent results. Luo et al. (2003a), who were the first to use structural equation modeling for the analysis of the unique impact of intelligence on school achievement beyond processing speed, concluded that “the observed correlation between seemingly complex g and scholastic performance is indeed mostly mediated by a set of elemental cognitive functions” (p. 81). The authors compared the proportion of variability in school achievements explained by a single intelligence factor (about 30%) to the corresponding proportion of variability after controlling for processing speed (about 6%). Based on the observed drop of the correlation, Luo, Thompson, and Detterman claimed that processing speed explained a great deal of the common variability between cognitive ability and school achievement. At the same time, it is noteworthy that the higher-order shared variability between intelligence and school achievement was still important, as reducing the corresponding correlation between the residuals in the model resulted in significant chi-square changes. In the later study by Luo et al. (2006), two other methods were used to address the same issue. First, $R^2$ changes in a series of mathematically equivalent structural equation models with different number of predictors of school achievement were analyzed. Low $R^2$ increments in models where cognitive ability factors were predictors of school achievement, in addition to the factors of processing speed and working memory, provided the evidence that the unique contribution of intelligence to school achievement is relatively low. Second, $\chi^2$ change, which was caused by constraining the path between cognitive ability and achievement to zero, was evaluated. In both datasets analyzed in that study, such constraints did not result in significant $\chi^2$ change, thus demonstrating the non-significant unique impact of intelligence on school achievement beyond processing speed and working memory (the significance of the unique contribution of intelligence beyond processing speed as a single predictor was not analyzed so far in that study). In contrast, Rindermann and Neubauer (2004) reported high direct effect of intelligence on school achievement ($\beta_{direct} = .54$ from the total effect of $\beta_{total} = .63$, with additional specific indirect effects mediated by processing speed and creativity). Moreover, in the study reported by Rohde and Thompson (2007), the unique contribution of intelligence to scholastic performance differed depending on the measure of achievement. After controlling for working memory, processing speed, and spatial ability in the hierarchical multiple regression models, intelligence scores still accounted for additional 20% and 39% of variance in Wide Range Achievement Test III scores and SAT scores respectively, while its additional contribution to the explanation of the GPA was non-significant.

Yet another question that is much less frequently addressed is whether the entire effect of processing speed on school achievement is mediated by intelligence. In fact, the additional unique contribution of intelligence to scholastic performance discussed above is not in contradiction to the theoretically assumed sequence \textit{processing speed $\rightarrow$ intelligence $\rightarrow$ school achievement}; however, the unique impact of processing speed beyond intelligence would be more problematic for this theoretical model. In those rare studies that examined the direct effect of processing speed, methods very similar to those described above were used. Rindermann and Neubauer (2004) reported the low direct effect of processing speed on school achievement (their model assumed the specific indirect effects of processing speed that was mediated by intelligence and creativity). The authors constrained this direct path to zero and did not observe significant changes in model fit statistics, and hence concluding that “a direct path between processing speed and school performance is statistically not necessary” (p. 582). Vock, Preckel, and Holling (2011) recently reported very similar results. In their study, mental speed was a significant single predictor of scholastic performance ($\beta = .43$), but its direct effect on school achievement ($\beta = -.07$) was not significant when reasoning and divergent thinking were entered into the model as mediators. These results were regarded as an evidence of “a full mediation for the effect of mental speed on academic achievement” (p. 366).

At the same time, in the two large datasets analyzed by Luo et al. (2006), zero constraints on the path between processing speed and school achievement resulted in significantly higher $\chi^2$ values. In other words, the unique impact of processing speed on school performance, not mediated by its effect on intelligence, was important. In the study by Rohde and Thompson (2007), working memory, processing speed, and spatial ability additionally explained 1% to 8% of variance in school achievement, after controlling for intelligence scores. When verbal and math achievement scores were analyzed separately, the additional contribution of basic processes was low for verbal scores and relatively high for math scores, reaching up to 13% of the additionally explained variance (with a good portion of additionally explained variability in math scores due to processing speed).

Finally, the fact that intelligence mediates (at least partly) the relationship between processing speed and school achievement was either explicitly pronounced or implicitly suggested in the previous studies; however, this mediating role of intelligence is itself worthy of particular examination. Indeed, the presence of this mediation effect was previously demonstrated based on the comparison of the proportion of variability in school achievement that is accounted for by processing speed or intelligence as a single predictor, before and after controlling for the other predictor (in terms of the $R^2$s, zero-order and partial correlations or total and indirect effects). Together with the other analyses (like constraining the weights in the models and evaluating the $\chi^2$ changes), these methods served the purposes discussed above well. However, they in fact do not tell us much about the \textit{significance} of the mediation effect itself, making a conclusion about the presence of mediation quite problematic. From the statistical point of view, these methods are in fact modifications of the “causal steps approach” (Baron & Kenny, 1986; Hyman, 1955; Judd & Kenny, 1981), a method for testing mediation effects that has been criticized by a number of recent statistical-simulation studies for having the lowest power (Fritz & MacKinnon, 2007; MacKinnon, Lockwood, Hoffman, West, & Sheets, 2002). More sophisticated procedures, primarily bootstrapping, are strongly recommended for this
purpose (e.g., Lockwood & MacKinnon, 1998; MacKinnon, Lockwood, & Williams, 2004; Preacher & Hayes, 2004, 2008; Shrout & Bolger, 2002) since they allow the construction of confidence intervals for the mediating effect itself; this in turn makes it possible to judge whether this effect differs significantly from zero. Until now, to our knowledge, the significance of the mediation effect processing speed → intelligence → school achievement has not been tested.

Thus, the present study examines the relationships between processing speed, intelligence, and school achievement using several perspectives. First, processing speed and intelligence are analyzed as individual predictors of school achievement; their relative strength as predictors of school achievement is compared. Second, the unique contribution of each processing speed and intelligence, beyond and above the other predictor, is estimated. Third, the significance of the mediation effect processing speed → intelligence → school achievement is tested.

Three more remarks should be made here concerning the present study. First, the mediating role of intelligence in the association between processing speed and school achievement that is suggested by the causal mental speed hypothesis was analyzed based on cross-sectional data in this study. Therefore, all the limitations of studies with cross-sectional design for testing mediation effects must be borne in mind.

Second, teacher-assigned grades in school subjects were used to represent school achievement, as they provide a measure of a relevant real-life performance. Thus, lower relationships with cognitive variables were expected, as compared to those reported for achievement tests. However, this choice was assumed not to affect the relative strength of the observed effects, both direct and indirect, in any systematic way.

Third, a sample of Russian high-school students was analyzed. This fact does not seem to have any special impact on the outcomes of the cognitive tests since only commonly used intelligence tests (Raven’s Advanced Progressive Matrices and the subtests of the Amthauer’s Intelligence Structure Test) were administered. However, Russian educational program and grading system differ from those referred to by the studies in the literature. Some details on the grading system and a list of the subjects used in the analysis are described in the next section. Again, the impact of the country where the participants study, if any, was assumed to concern the absolute, but not the relative magnitudes of the effects of processing speed and intelligence on school achievement.

2. Methods

2.1. Participants

The participants were 184 Russian high school students. The study was conducted in nine public schools located in Moscow (in the Russian educational system, secondary education is mostly provided by public state schools). Participants’ mean age was 16.00 (SD = .67); 38% were male. Processing speed tasks were administered individually through the computers; intelligence was tested in groups. All tests were held in the schools where the participants studied.

School grades were collected from the participants’ final school report for the academic period when the tests were administered.

2.2. Materials

2.2.1. Processing speed measures

Two tasks were used to provide measures of individual speed of information processing. The Discrimination Time task (DT) required participants to determine, as quickly as possible, whether the figure that appeared on the screen was a triangle. The test consisted of 20 trials wherein five different geometric figures could appear on the screen. The participants had to press one key for the triangle and another key for any other figure.

The second task was the Recognition of Meaningless Figures Test (RMFT), described in detail in Dodonova and Dodonov (2011). Different meaningless figures consisting of four short lines were used as stimuli in this test. A white background screen was first presented (500 ms), followed by a probe figure (2000 ms), followed by the background screen (500 ms), and the test figure. Participants had to determine whether the test figure was exactly the same as the figure in the probe. The test consisted of 60 trials. Some examples of the stimuli are presented in Fig. 1 (all the stimuli for “No” responses can be found in Dodonova and Dodonov 2011).

In both speeded tasks, only latencies of correct responses were analyzed. For each participant, distance-weighted mean response time was calculated by:

$$DWM = \frac{\sum_{i=1}^{n} (w_i x_i)}{\sum_{i=1}^{n} w_i},$$

where

$$w_i = \frac{(n-1)}{\sum_{j=1}^{n} abs(x_i-x_j)}.$$

In other words, weighting coefficient for each response time $x_i$ was computed as the inverse mean distance between $x_i$ and the other data points. Therefore, possible outlying

![Fig. 1. Examples of the stimuli in the RMFT. Note. Probe stimuli are presented in the top row, with the corresponding test stimuli presented in the bottom row (“No” responses). Original size of the stimuli was 40 × 40 mm.](image-url)
values were downweighted in calculating individual response times.1

2.2.2. Intelligence scales

Two intelligence scales were used in this experiment. The first was Raven’s Advanced Progressive Matrices (APM, with 40-minute time limit). The second was the verbal scale of the Amthauer’s Intelligence Structure Test (v-IST), which included three subtests: sentence completion, finding analogies, and finding common categories. For each of the two scales, the total number of correct responses was calculated.

2.2.3. School achievement scores

Data on school achievement included school grades in six subjects: algebra, geometry, physics, Russian language, literature, and foreign language. Although a five-point grading scale is used in Russian schools, actual final grades in each subject varied from “3” to “5”, as “3” is the lowest passing grade (in the Russian grading system, higher grades indicate better school performance; “5” is the best possible grade). To allow for better differentiation between the participants, the school grades were aggregated into two classes: math and language. Score on math was calculated as the average grade in algebra, geometry, and physics; score on language was the average grade in Russian language, literature, and foreign language.

2.3. Missing values

The DT task was not administered to two participants (1.1% of the cases). Data on the RMFT and the APM were collected for all the participants. The IST was not administered to four participants (2.2%). Data on school performance were available for 13 participants (7.1%) due to the limited access to school records. Little’s MCAR test was not significant ($\chi^2 = 22.64, df = 17, p = .161$), indicating the randomness of the missing values. For further analyses, missing values were imputed using the EM estimation method in SPSS 17.0.

For discussion on this measure of central tendency in response-time data analysis, see Dodonov and Dodonova (2011). The R code for computing the distance-weighted estimator was:

$$d_{we} = \text{function}(x; y) = \|\text{is.na}(x)\|; a = y; b = y; p = \text{outer}(a, \text{function}(b, a) \text{abs}((b-a))); n = \text{colSums}(p) / \text{length}(y); w = 1/n \times \text{sum}(y \times w) / \text{sum}(w)).$$

3. Results

Descriptive statistics for response times, intelligence scores, and school grades are presented in Table 1. To estimate reliabilities of processing speed measures, distance-weighted mean response times were calculated separately for odd and even trials in each task. Odd–even correlations adjusted by the Spearman–Brown formula were $r_{ob} = .89$ and $r_{ob} = .95$ for DT and RMFT, respectively.

Further analyses were conducted on unstandardized residual scores with age and sex variances removed. Correlations between the variables are shown in Table 1. Two measures of processing speed were significantly correlated. Of these two measures, DT was more related to intelligence scores, than RMFT. Of the two correlated measures of intelligence, absolute values of correlation with processing-speed measures were slightly higher for the APM than for the v-IST. On the contrary, the v-IST was more related to the measures of school achievement, than the APM. It is noteworthy that both processing speed measures were significantly related to the indexes of school achievement in math and language.

Three mathematically equivalent models that were specified in this study are shown in Fig. 2. Although the results presented below could be analytically determined from any one of the models, all the models are involved to clarify the analyses. The SEM analyses were conducted using the AMOS 18.0 program. The models provided a good fit to the data, as indicated by the fit indexes shown in the top line of Table 2: CFI > .95 and RMSEA < .08 (RMSEA is not significantly greater than .05, $p_{\text{close}} = .332$). Standardized estimates of the parameters are presented in Fig. 2.

The relationships between the three latent variables estimated in model A were significant. Processing speed and intelligence had $-10.3\%$ of common variance. Intelligence and school achievement shared $-18.4\%$ of the variance; the corresponding estimate of the variance shared between latent processing speed and school achievement was almost equal ($-18.1\%$). A simple comparison of the correlations with school achievement suggested that processing speed and intelligence did not differ noticeably in their strength as single explanatory factors of scholastic performance.

Next, the unique individual contribution of processing speed and intelligence to the prediction of school achievement beyond the other factor was examined. The corresponding $R^2$ increments were first analyzed based on the comparison of the proportion of variability in school achievement explained in models A and B. In the model B, processing speed and
intelligence together accounted for 27.7% of the variance of school achievement. Thus, intelligence factor explained the additional 9.6% of the variance of school achievement, beyond the single processing speed explanatory factor ($\Delta R^2 = .277 - .181 = .096$). The unique contribution of the processing speed factor, beyond the intelligence factor (9.3%), was about equal to the contribution of the intelligence factor ($\Delta R^2 = .277 - .184 = .093$). Again, the results suggested that the unique contributions of processing speed and intelligence were similar in strength, with neither exceeding the other in the additional prediction of school performance.

To formally examine the significance of the observed unique impacts of these predictors on school achievement, model B was modified by constraining each of the related beta weights to zero and the corresponding $\chi^2$ changes were evaluated. If the unique contribution of processing speed beyond intelligence in predicting school achievement was not significant, constraining $\beta_{\text{speed}}$ to zero would not result in significant decrease in $\chi^2$, and vice versa. The fit indexes for the modified models are presented in Table 2. In both model B-1 ($\beta_{\text{speed}} = 0$) and model B-2 ($\beta_{\text{intelligence}} = 0$), zero constraints resulted in significant chi-square changes: $\Delta \chi^2(1) = 5.550$, $p = .018$ and $\Delta \chi^2(1) = 4.745$, $p = .029$, respectively. The results indicated that the unique impact of each of the factors (processing speed and intelligence) as predictors of school achievement was significant.

Finally, model C with the mediation effect processing speed $\rightarrow$ intelligence $\rightarrow$ school achievement was analyzed. A standardized estimate of the direct effect of processing speed on school achievement in this model was $\beta_{\text{direct}} = -.321$; an estimate of the indirect effect mediated by intelligence was $\beta_{\text{indirect}} = -.105$. In other words, the indirect effect of processing speed on school achievement was quite low (about three times lower than the direct effect). However, these values do not indicate the significance of the mediation effect. Indeed, the results presented above definitely demonstrate that mediation is not complete: processing speed influences school achievement directly, after controlling for the effect due to its impact on intelligence. However, the mediation effect itself can still be significant, providing evidence to the hypothesis that mental speed, at least to some extent, underlies the relationship between intelligence and school performance.

To obtain an estimate of the significance of the indirect effect, it was bootstrapped using Amos 18.0; Monte Carlo parametric bootstrap was performed. With 2500 bootstrap samples, the 95% bias-corrected confidence interval was $- .476$ to .008. As the confidence interval included zero, the indirect effect was regarded as non-significant (an estimate of significance was $p = .072$). In other words, an appropriate evaluation of the indirect effect processing speed $\rightarrow$ intelligence $\rightarrow$ school achievement indicated that the results are not consistent with the hypothesis that states that processing speed is a factor that affects school achievement via its impact on intelligence.$^2$

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$^2$ As suggested by the anonymous reviewer, the analyses were repeated on a dataset with listwise deletion of cases with missing outcome variable. The models that are shown in Fig. 2 were applied to the data of 171 participants for whom achievement data were available. Fit indexes were $\chi^2(6) = 10.426$, $\chi^2/df = 1.738$, CFI = .978, RMSEA = .066, $p_{\text{chisq}} = .293$. In Model A, zero-order correlations between latent variables were $r = -.335$ ($p = .015$) between processing speed and intelligence, $r = .405$ ($p < .001$) between intelligence and school achievement, $r = -.407$ ($p < .001$) between processing speed and school achievement. In Model B, effects of both latent predictors of school achievement were significant: $\beta_{\text{speed}} = -.305$ ($p = .014$) and $\beta_{\text{intelligence}} = .303$ ($p = .029$). In Model C, standardized indirect effect of processing speed on school achievement mediated by intelligence was $\beta_{\text{indirect}} = -.102$. With 2500 bootstrap samples, 95% bias-corrected confidence interval was $- .540$ to .011, estimate of significance was $p = .085$. We consider these results as comparable to those obtained on the entire sample in terms of magnitude and pattern of the effects.
were quite contradictive (Luo et al., 2003a, 2006; Rindermann each processing speed and intelligence to school achievement effects. Previous results concerning the unique contribution of the three variables (processing speed, intelligence, and school effect must be demonstrated. With the above-formulated hypothesis, a significant mediation leaves the possibility of at least a partial mediation via intelligence on school achievement still provides some evidence of the mediation). Even a significant and intelligence, after controlling for processing speed, intelligence is predicted by processing speed. An obvious theoretical model that might account for these regularities would imply causal relationships, where processing speed would be regarded as a basic factor underlying cognitive ability, which in turn influences scholastic performance. In the strict sense, only longitudinal studies with repeated measurements of all these variables would help to prove this causal-ordering hypothesis. In a cross-sectional study, core findings demonstrating that the empirical data do not contradict this hypothesis must show a significant mediation effect in the chain processing speed → intelligence → school achievement. Indeed, significant or non-significant, the direct effect of intelligence on school achievement beyond processing speed does not contradict this hypothesis (although a decrease in the magnitude of association between scholastic performance and intelligence, after controlling for processing speed, provides some evidence of the mediation). Even a significant direct effect of processing speed on school performance still leaves the possibility of at least a partial mediation via intelligence. However, to conclude that the results are consistent with the above-formulated hypothesis, a significant mediation effect must be demonstrated.

Until now, empirical studies on the relationships between all the three variables (processing speed, intelligence, and school achievement) have been too rare to summarize any definite effects. Previous results concerning the unique contribution of each processing speed and intelligence to school achievement were quite contradictory (Luo et al., 2003a, 2006; Rindermann & Neubauer, 2004; Rohde & Thompson, 2007). The present study more likely adds another piece to the puzzle rather than give any definite answer, as it doubts the significance of the mediating role of intelligence in the relationship between processing speed and school achievement.

Two processing speed tasks were used in this study. The first task required simple speeded discrimination between the shapes of the stimuli (the requirement for a long-term memory access that is caused by the necessity to actualize the known shape of a triangle can in fact be disregarded). The second task implied some non-zero loading on short-term memory, as the test was designed as a recognition task; however, this loading was quite low because each trial included only a single stimulus. Interestingly, although the second task was assumed to be more complex and in fact required more time for processing, its correlations with both intelligence scales were lower than those observed in the first task.

Of the two intelligence scales used in this study, Raven’s APM are commonly referred to as a measure of fluid intelligence, while the verbal scale of the IST heavily requires crystallized knowledge in the verbal domain. At the manifest level, the APM scores were more related to the measures of processing speed than the verbal IST scale was, which is consistent with previous studies on the relationships between processing speed, fluid and crystallized intelligence (e.g., Roberts & Stankov, 1999). On the other hand, the degree of association with school achievement was slightly higher for the v-IST than for the APM, which is also predictable (e.g., Luo et al., 2006).

The school grades that were collected in this study represented achievement in a quite diverse range of subjects: algebra, geometry, physics, Russian language, literature, and foreign language. However, two aggregate scores (math and language) that were calculated based on the initial grades were highly correlated and well explained by the single factor of school achievement.

Processing speed and intelligence individually explained about 18% of the variance of school achievement. The proportion of variability in scholastic performance that was explained by each of the predictors (especially, by intelligence) is somewhat lower than is normally reported for achievement tests, but looks reasonable for the teacher-assigned grades. It might also represent, at least to some extent, the national specificity of grading in Russian schools, as the latter in fact does not strongly depend on performance in any standardized educational tests. However, the problem of possible differences in national school grading systems, with regard to the representativeness of educational achievement, lies outside the scope of this study.

Besides estimating a model of processing speed and intelligence as two correlated predictors of scholastic performance, a model with the aforementioned mediation effect of intelligence on the relationship between processing speed and school achievement was analyzed. It must be noted that only one model with a mediation effect was tested in the present study. It seems that this is the only model that has a strong theoretical basis to allow to hypothesize causal relationships. Mathematically, any other model could be constructed with either factor (processing speed, intelligence, or school achievement) playing a role of any variable (primary independent, mediating, and dependent). A simple visual inspection of the observed correlations even suggests that a model with school achievement as a mediator of the relationships between processing speed and intelligence would result in the highest possible indirect effect. However, these models would be rather senseless theoretically and methodologically and thus were not regarded in this study.

The mediation effect processing speed → intelligence → school achievement was analyzed in terms of its statistical significance, a step that is allowed by contemporary bootstrapping procedures. Unexpectedly, the observed indirect effect of processing speed on school achievement mediated by intelligence was statistically not distinguishable from zero.

In other words, processing speed and intelligence shared some portion of the variance and both contributed significantly to the explanation of the variability in scholastic performance. Their relative strengths as predictors of school achievement were about equal, but this equality by no way meant that their impact on school achievement was due to their common variance. Instead, the unique contribution of

<table>
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<th>Model</th>
<th>$\chi^2$</th>
<th>df</th>
<th>$\chi^2$/df</th>
<th>CFI</th>
<th>RMSEA</th>
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<tr>
<td>Model B-2, $\beta_{int} = 0$</td>
<td>14.814</td>
<td>7</td>
<td>2.116</td>
<td>.961</td>
<td>.078</td>
<td>42.814</td>
</tr>
</tbody>
</table>

4. Discussion

In the literature on intelligence, the following are well-established facts: (1) intelligence explains a significant portion of variability in school achievement; and (2) to some extent, intelligence is predicted by processing speed. An obvious theoretical model that might account for these regularities would imply causal relationships, where processing speed would be regarded as a basic factor underlying cognitive ability, which in turn influences scholastic performance. In the strict sense, only longitudinal studies with repeated measurements of all these variables would help to prove this causal-ordering hypothesis. In a cross-sectional study, core findings demonstrating that the empirical data do not contradict this hypothesis must show a significant mediation effect in the chain processing speed → intelligence → school achievement. Indeed, significant or non-significant, the direct effect of intelligence on school achievement beyond processing speed does not contradict this hypothesis (although a decrease in the magnitude of association between scholastic performance and intelligence, after controlling for processing speed, provides some evidence of the mediation). Even a significant direct effect of processing speed on school performance still leaves the possibility of at least a partial mediation via intelligence. However, to conclude that the results are consistent with the above-formulated hypothesis, a significant mediation effect must be demonstrated.

Until now, empirical studies on the relationships between all the three variables (processing speed, intelligence, and school achievement) have been too rare to summarize any definite effects. Previous results concerning the unique contribution of each processing speed and intelligence to school achievement were quite contradictory (Luo et al., 2003a, 2006; Rindermann & Neubauer, 2004; Rohde & Thompson, 2007). The present study more likely adds another piece to the puzzle rather than give any definite answer, as it doubts the significance of the mediating role of intelligence in the relationship between processing speed and school achievement.

Two processing speed tasks were used in this study. The first task required simple speeded discrimination between the shapes of the stimuli (the requirement for a long-term memory access that is caused by the necessity to actualize the known shape of a triangle can in fact be disregarded). The second task implied some non-zero loading on short-term memory, as the test was designed as a recognition task; however, this loading was quite low because each trial included only a single stimulus. Interestingly, although the second task was assumed to be more complex and in fact required more time for processing, its correlations with both intelligence scales were lower than those observed in the first task.

Of the two intelligence scales used in this study, Raven’s APM are commonly referred to as a measure of fluid intelligence, while the verbal scale of the IST heavily requires crystallized knowledge in the verbal domain. At the manifest level, the APM scores were more related to the measures of processing speed than the verbal IST scale was, which is consistent with previous studies on the relationships between processing speed, fluid and crystallized intelligence (e.g., Roberts & Stankov, 1999). On the other hand, the degree of association with school achievement was slightly higher for the v-IST than for the APM, which is also predictable (e.g., Luo et al., 2006).

The school grades that were collected in this study represented achievement in a quite diverse range of subjects: algebra, geometry, physics, Russian language, literature, and foreign language. However, two aggregate scores (math and language) that were calculated based on the initial grades were highly correlated and well explained by the single factor of school achievement.

Processing speed and intelligence individually explained about 18% of the variance of school achievement. The proportion of variability in scholastic performance that was explained by each of the predictors (especially, by intelligence) is somewhat lower than is normally reported for achievement tests, but looks reasonable for the teacher-assigned grades. It might also represent, at least to some extent, the national specificity of grading in Russian schools, as the latter in fact does not strongly depend on performance in any standardized educational tests. However, the problem of possible differences in national school grading systems, with regard to the representativeness of educational achievement, lies outside the scope of this study.

Besides estimating a model of processing speed and intelligence as two correlated predictors of scholastic performance, a model with the aforementioned mediation effect of intelligence on the relationship between processing speed and school achievement was analyzed. It must be noted that only one model with a mediation effect was tested in the present study. It seems that this is the only model that has a strong theoretical basis to allow to hypothesize causal relationships. Mathematically, any other model could be constructed with either factor (processing speed, intelligence, or school achievement) playing a role of any variable (primary independent, mediating, and dependent). A simple visual inspection of the observed correlations even suggests that a model with school achievement as a mediator of the relationships between processing speed and intelligence would result in the highest possible indirect effect. However, these models would be rather senseless theoretically and methodologically and thus were not regarded in this study.

The mediation effect processing speed → intelligence → school achievement was analyzed in terms of its statistical significance, a step that is allowed by contemporary bootstrapping procedures. Unexpectedly, the observed indirect effect of processing speed on school achievement mediated by intelligence was statistically not distinguishable from zero.

In other words, processing speed and intelligence shared some portion of the variance and both contributed significantly to the explanation of the variability in scholastic performance. Their relative strengths as predictors of school achievement were about equal, but this equality by no way meant that their impact on school achievement was due to their common variance. Instead, the unique contribution of
each processing speed and intelligence beyond the other factor was significant. Most importantly, the impact of processing speed on school achievement mediated by intelligence was not significant. Thus, the results of this study are not consistent with the hypothesis which states that processing speed is a predictor of real-life scholastic performance because of the impact of processing speed on higher-order cognitive ability, which in turn is related to school achievement. Processing speed might still be a factor that underlies both intelligence and school performance, but it seems doubtful that its variance that is shared with intelligence and school achievement is qualitatively equivalent.

Finally, our concluding remark concerns the observed significant unique contributions of processing speed and intelligence to the explanation of the variability in school achievement. The possible sources of the unique effect of intelligence on scholastic performance are so frequently debated about that little space is left to add to the discussion. On the contrary, the sources of the unique impact of processing speed on school achievement that is not mediated by its possible effect on intelligence have not been thoroughly studied. This issue seems to be the most intriguing one: an interpretation of the relationship between processing speed and scholastic performance that is not associated with intelligence is a challenge for further studies.

References

Validität auf? [Speed of information processing and success at school: Do basal measures of intelligence have predictive validity?] Diagnostica, 46, 8–17.