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A Sequential Model of the Contribution of Preschool Fluid and Crystallized Cognitive Abilities to Later School Achievement

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Abstract

The present study documented in two distinct population-based samples the contribution of preschool fluid and crystallized cognitive abilities to later school achievement in primary school and examined the mediating role of crystallized abilities in this sequence of predictive associations. In both samples, participants were assessed on the same fluid and crystallized abilities at 63 months (sample 1) and 73 months (sample 2), and then regarding their school achievement in grade 1 to grade 6. Both preschool fluid and crystallized abilities were found to significantly predict school achievement, but only in the early school years. Through path analyses controlling for sex, maternal education and family income, preschool crystallized abilities mediated the association between early fluid abilities and later school achievement in the early grades of school. Crystallized abilities predicted early school achievement beyond fluid abilities, but not in the later grades. These results support the importance of early interventions aimed at both preschool fluid and crystallized abilities to prevent children from developing future school difficulties.

School achievement results from a cumulative process of mastering new, as well as improving existing skills (Duncan et al., 2007; Entwisle & Alexander, 1990; Pungello, Kuperschmidt, Burchinal, & Patterson, 1996). It is a prime factor underpinning a nation's gross domestic product and may be seen as an index of human capital (Meisenberg, 2012). Generally assessed through standardized tests or teacher assessments of reading, writing and/or mathematics (Garon-Carrier et al., 2017; Hammes, Bigras, & Crepaldi, 2016; Mattanah, Pratt, Cowan, & Cowan, 2005), individual differences in school achievement are established early and tend to be stable over time from school entry and onward (Garon-Carrier et al., 2018; Jordan, Kaplan, Ramineni, & Locuniak, 2009). They also predict many positive outcomes, including psychosocial adjustment, physical and mental health, perceived happiness, and access to higher education (Blanchflower & Oswald, 2011; Galobardes, Lynch, & Smith, 2008; Jimerson, Egeland, Sroufe, & Carlson, 2000). Given the high stability of school achievement and its long-term contribution to health, well-being, and economic growth, we need a clear understanding of the early determinants of school achievement, as well as the underlying developmental processes linking them to school achievement.

Both fluid and crystallized cognitive abilities are significant predictors of school achievement (e.g. Duncan et al., 2007; La Paro & Pianta, 2000; McGrew & Wendling, 2010). Fluid abilities are derived from basic cognitive processes involved in solving problems that do not require knowledge per se. For example, "fluid" cognitive visual-spatial skills (a central component of non-verbal intelligence), cognitive flexibility (a component of executive functions), and short-term memory have previously been associated with school achievement (e.g. Alloway & Alloway, 2010; Bull & Sceriff, 2001; Friso-van Den Bos, Van Der Ven, Kroesbergen, & Van Luit, 2013 ; Garon-Carrier et al., 2017, 2018; Gunderson, Ramirez,

Beilock, & Levine, 2012; Lemelin et al., 2007; Vock, Preckel, & Holling, 2011). Crystallized abilities are knowledge-based competencies, such as letter and number knowledge, presumably acquired through fluid abilities and exposure to appropriate learning environment (Blair, 2006; Forget-Dubois, Lemelin, Boivin, Dionne, Séguin, Vitaro, & Tremblay, 2007; Forget-Dubois, Dionne, Lemelin, Périus, Tremblay, & Boivin, 2009; Garon-Carrier et al., 2017, 2018; Lemelin et al., 2007).

There is a consensus that both fluid and crystallized abilities underlie school achievement. However, their relative contributions, and the timing of these contributions to school achievement over time are still debated (e.g., Ferrer & McArdle, 2004; Geary, Nicholas, Li, & Sun, 2017). Some have argued that fluid abilities are fundamental predictors of school achievement on the basis that children with learning disorders show deficits in fluid abilities, but not necessarily in general intelligence or crystallized abilities (Blair, 2006). For example, preschool visual-spatial cognitive skills and short-term memory at age 5 have been found to predict later numeracy and literacy at age 11 years (Alloway & Alloway, 2010). Likewise, a meta-analysis revealed that executive functions, including cognitive flexibility, are associated with school achievement in mathematics (Friso-van Den Bos et al., 2013).

On the other hand, early crystallized abilities, such as knowledge of letters, numbers, shapes and colors, have also been shown to predict school achievement in the early school years over and above certain fluid skills such as cognitive visual-spatial skill, cognitive flexibility and short-term memory (Forget-Dubois et al., 2007; Hess, Holloway, Dickson, & Price, 1984; Lemelin et al., 2007; Monette, Bigras, Guay, 2011). In a meta-analysis of six longitudinal studies, Duncan et al. (2007) found that early crystallized skills, such as early numeracy and

literacy, were the best predictors of school achievement when compared to emotional difficulties, behavior problems, and attentional abilities.

Yet, recent findings show that the contributions of fluid and crystallized abilities to school achievement are complex and tend to vary over time. For example, Geary et al. (2017) showed that the association between IQ tests, including both fluid and crystallized abilities, and achievement in mathematics was generally stable from grade 1 to grade 8, whereas the association between executive function and school achievement grew in force across the elementary school grades. The contribution of crystallized abilities to achievement in mathematics also increased over the same period. However, Geary et al. (2017) only considered a subset of mathematical crystallized abilities (basic number and arithmetical competencies, knowledge of fractions) in primary school, which precludes any conclusion about the possible contribution of a larger range of preschool crystallized abilities to later school achievement.

It is possible that the contribution of preschool crystallized abilities to later school achievement could be limited in time, while the contribution of preschool fluid abilities persists or even increases over time. Indeed, the increased academic requirements associated with schooling may progressively entail more complex reasoning strategies while relying less on early knowledge. In support of this view, Lee and Bull (2016) found that the association between visual-spatial cognitive skills and school achievement was stronger in grades 6 to 9 than in grades 1 to 5.

Genetically informed studies also provide indirect support for the time-varying contributions of early fluid and crystallized abilities to later achievement. For instance, twin

studies have shown that crystallized abilities tend to be more closely associated with environmental sources of influence, whereas fluid abilities are more likely to be accounted for by genetic sources of influences (Kovas, Haworth, Dale, & Plomin, 2007; Lemelin et al., 2007; Polderman, Gosso, Posthuma, Van Beijsterveldt, Heutink, Verhulst, & Boomsma, 2006). To the extent that crystallized abilities are more likely to develop through the common experience of schooling than fluid abilities, we could expect children who initially lagged in early knowledge (e.g., early numeracy and literacy), but with good fluid skills, to catch up. This would result in fluid abilities playing a more persistent role than early crystallized abilities in later school achievement.

However, simply comparing the unique contributions of fluid and crystallized skills to school achievement is not the most informative way to understand the developmental processes involved. Fluid skills likely contribute to the acquisition of crystallized abilities (Cattell, 1987; Kvist & Gustafsson, 2008), which means that the latter may play a mediating role in the contribution of early fluid abilities to later school achievement. Indeed, fluid abilities, such as executive functions, short-term memory and cognitive visual-spatial skills have been associated with crystallized abilities, such as numeracy and literacy (Verdine, Irwin, Golinkoff, & Hirsh-Pasek, 2014; Welsh, Nix, Blair, Bierman, & Nelson, 2010; Zhang, 2016). Furthermore, Passolunghi and Lanfranchi (2012) showed that numerical competence (crystallized abilities) in kindergarten partly mediated the association between fluid skills (working memory, and processing speed) and achievement in mathematics in grade 1. Ostergren and Traff (2013) found that preschool arithmetic skills partly mediated the association between early fluid abilities (executive function, non-verbal intelligence) and grade 1 mathematics achievement. Finally,

Chu, van Marle, and Geary (2016) showed that crystallized abilities, such as literacy and early arithmetic skills accounted for the predictive association between early fluid abilities (IQ and executive functions at ages 3 and 5 years) and achievement in kindergarten. Those studies converge in suggesting that crystallized abilities mediate the association between preschool fluid abilities and early school achievement. However, other studies failed to find such a mediation when considering a more extended period of time. For instance, Ferrer and McArdle (2004) found that growth in crystallized abilities across ages 5 to 24 years were independent of previous fluid abilities. The mediation hypothesis could thus be limited to the early school years; as the contribution of preschool crystallized abilities to later school achievement decreases over time, the mediational role of crystallized abilities may also diminish over the primary school years.

This time-limited mediation hypothesis has never been documented within a developmentally informed design covering the whole primary school period. It should be investigated longitudinally while considering the well-documented stability of individual differences in school achievement (Garon-Carrier et al., 2018; Jordan et al., 2009). For instance, in one study (Schneider & Niklas, 2017), the predictive contributions of fluid abilities (IQ, working memory) to later school achievement was reduced considerably, but remained significant when the stability of school achievement was taken into account. Thus, school achievement autoregressive pathways should be considered to determine how and when early fluid and crystallized abilities contribute to later school achievement. Longitudinal samples with repeated achievement measures are key to answering this question.

The present study. The present study aimed to address the question of the predictive association between early cognitive abilities and later school achievement in two longitudinal

samples with extended repeated measures of school achievement across the primary school years. The general objective was to assess the contribution of specific preschool fluids abilities (cognitive visual-spatial skill, cognitive flexibility, short-term memory) and crystallized abilities (knowledge of numbers, letters, color and shape) to school achievement across primary school. We hypothesized that these contributions would co-evolve and vary across primary school; specifically (1) that crystallized abilities would partly mediate the predictive association between early preschool fluid abilities and later achievement in the early school years, but not necessarily in the later years of primary school, (2) that school achievement would become highly stable by the end of primary school, and (3) that beyond early crystallized abilities, early fluid abilities would still uniquely contribute to school achievement in the later grades of primary school.

Method

Participants

Two distinct longitudinal samples were used in this study: The Quebec Newborn Twin Study (QNTS) and the Quebec Longitudinal Study of Child Development (QLSCD). The QLSCD was used to replicate the results obtained with the QNTS, here considered as a convenient sample. The first convenient sample, the QNTS, is a population-based longitudinal study of twins born between April 1995 and December 1998 in the Greater Montreal Area, Canada (Boivin et al., 2012). All parents living in the Greater Montreal Area were contacted either by phone or letter. A total of 989 families were contacted, but 662 families (1324 twins) agreed to be part of the study. The sample is mainly composed of European descent (84%) and the maternal language of the parents was mainly French or English (81,3%). The average household income was around CAN \$54,000, which is slightly higher than the average income of

families in the same region at that time. Most parents had graduated from high school, as only 12 % of mothers and 9.8% of fathers did not complete high school. A total of 929 (393 monozygotic, 533 dizygotic, 2 unknown; 50.9% girls) were assessed in the laboratory at 60 months (mean age = 63.17 months, $SD = 3.10$), just before school entry, on various relevant fluid and crystallized cognitive measures. School achievement was then assessed in grade 1 (567 twins), grade 3 (646 twins), grade 4 (628 twins) and grade 6 (506 twins).

The second sample, the QLSCD, is a prospective longitudinal study of children who were sampled to be representative of the population of Quebec (Jetté & Grosseillers, 2000). In 1998, all singleton infants between 59 and 60 gestational weeks of age in the Province of Quebec were targeted with the exception of infants in the Far North region, Cree and Inuit regions, and those in Aboriginal reserves. A sample of 2223 infants and their families selected through a region-based stratified sampling initially participated in the study; 80% of these infants lived in intact two-parent families, 10.8% in step-families, and 9.2% in single-parent families. The mean age of mothers was 28.8 years and the mean age of fathers was 31.9 years. Children were from Canadian origins (67.7%), European descent (48.6%), African or Haitian origins (20.5%) or other origins (20.5%; participants could declare more than one ethnic origin). The language most often spoken at home was mainly French or English (85.3%). Most parents had graduated from high school, as only 17.9% of mothers and 17.6% of fathers had no high school diploma. Children of the QLSCD were then quasi-yearly assessed longitudinally. The current study considered extensive cognitive assessments in kindergarten (1201 children, M age = 73.8 months, $SD = 3.05$; 53% girls), as well as school achievement ratings assessed in grade 1 (1010 children), grade 3 (967 children), grade 4 (756 children) and grade 6 (756 children).

Procedure. In the QNTS, twins were administered a battery of tests of fluid and crystallized abilities in a laboratory setting at 60 months, just before entering kindergarten. The order of testing was counterbalanced, with the exception of the *Block Design* test which was administered first. Twins were tested by two different interviewers, in two different rooms, to avoid inflated twin similarity. Teacher ratings of school achievement were then collected at the end of each school year, which allowed the teachers to be well acquainted with how their students were doing academically. In the QLSCD, children were administered a battery of tests of several fluid and crystallized ability measures at the end of kindergarten (i.e., 8 to 9 months later than the QNTS children), in school setting or at home. The order of the tests was counterbalanced. As in the QNTS, teachers' ratings of school achievement were collected at the end of each school year. All the instruments were the same in the two samples and administered in French or English.

Measures

School Achievement. In the spring of four different grade levels in primary school, school achievement was assessed by teachers (i.e. a different teacher at each school year) using a similar set of questions. The teachers rated each child's achievement in four school subjects: mathematics, writing, reading, and overall performance, relative to his or her classmates. Scores were on a 5-point Likert scale where 1 indicated *clearly under average*, 3 indicated *average*, and 5 indicated *clearly above average*. Given the high correlations between the ratings of the four school subjects (r s ranged from .69 to .98), these scores were averaged in a general school achievement score for a given year. Teacher ratings of school achievement are generally reliable and valid, as indicated by their correlations with other measures of academic achievement scores, including standardized measures of performance. In a recent study, Rimfeld et al., (2019)

reported that teacher assessments of achievement correlated strongly phenotypically ($r \sim .70$) and genetically (genetic correlation $\sim .80$) with school achievement; compared to standardized exam results, they were also as reliable and stable at every stage of the educational experience, but more predictive of later achievement. Finally, a meta-analysis estimated that teacher's assessments of student's school achievement is highly related (average $r = .62$) to their actual test performance (Südkamp, Kaiser, & Möller, 2012). Internal consistency of school achievement scores was excellent with Cronbach's alpha ranging from .94 to .95.

Crystallized Abilities.

Lollipop test (Chew & Morris, 1984). The *Lollipop test* consists of 52 questions divided into four subtests each assessing a component of preschool crystallized abilities: (a) Identification of Colors and Shapes; (b) Picture Description and Spatial Recognition; (c) Identification of Numbers and Counting and (d) Identification of Letters and Writing. An overall score can be obtained by combining the scores of the four subtests. The scores for subtests 1 to 3 range from 0 to 17, scores for subtest 4 range from 0 to 18, and overall scores range from 0 to 69. A French and an English versions were used according to the language of the child. The French version is also valid and stable through time (Venet, Normandeau, Letarte, & Bigras, 2003). The overall score was used. Cronbach alpha for this total score was $\alpha = .73$ in the twin study and $\alpha = .55$ in the singleton sample. The modest Cronbach alpha in the singleton sample is caused by ceiling effect in some subscales of the test. This measure has been shown to successfully predict early school achievement (Forget-Dubois et al., 2007; Lemelin et al., 2007)

Peabody Picture Vocabulary Test – Third Edition (PPVT–III ; Dunn, Thériault, Whalen, & Dunn, 1993). The PPVT-III is a standardized measure of language frequently used in research and clinical settings to assess receptive vocabulary. The version used in this study

contained 170 cards each depicting four different actions, objects or emotions. Children were asked to point at the image that corresponds to the word said by the tester. One point was awarded for each correct answer. The test ends after six errors out of eight trials. This measure has been widely used with success in predicting different outcomes like school achievement, school readiness or language delay (e.g. Dollaghan & Campbell, 2009; Forget-Dubois et al., 2007; Salla et al., 2015). The PPVT-III has good internal consistency, good concurrent validity, good test-retest reliability and has been validated with both French and English-speaking Canadian youths (Dunn, et al., 1993; Flipsen, 1998; Williams & Wang, 1997).

Number Knowledge test (NKT ; Okamoto & Case, 1996). Number knowledge was assessed using a shortened version of the NKT. The NKT measured the understanding of the base 10 system of whole numbers. The items of the NKT are divided into two levels which increase in difficulty. The first level has five items and the second level has 13 items. The child must get at least three successful items at the first level to go on to the second level. The test ends after three consecutive failures. The total score corresponds to the number of successful items. The NKT has high internal consistency, good test-retest reliability, good convergent validity with other measures of mathematics ability and has been shown to successfully predict school achievement in mathematics (Garon-Carrier et al., 2018; Gersten, Clarke, & Jordan, 2007; Gersten, Jordan, & Flojo, 2005).

Fluid Abilities.

Cognitive visual-spatial skills. Cognitive visual-spatial skills were assessed with the Block Design subtest of the *Wechsler Preschool and Primary Scale of Intelligence—Revised* (WPPSI-R; Wechsler, 1989). The Block Design subtest is composed of 14 models that the child must reproduce using bi-colored blocks. The test ends after 3 consecutive failures and bonus

points can be gained as a function of time. Raw scores vary from 0 to 42 and are standardized according to the exact age of the child. This performance Scale subtest has good internal consistency, test-retest reliability and it is highly correlated with the total score of the WPPSI-R ($r = .62$; Sattler, 2001). Cognitive visual-spatial skills, assessed by the Block Design, have been shown to be highly predictive of different outcomes, including number knowledge and school achievement (Forget-Dubois et al., 2007; Garon-Carrier et al., 2018:).

Short-term memory. Short-term memory was assessed with the *Visually Cued Recall Task* (VCR; Zelazo, Jacques, Burack, & Frye, 2002). During the VCR, children must memorize and recall items that are presented to them. In the first trial, the tester points two items among a series of items and asks the child to recall them. For each new trial, the number of items to be recalled in a new set of items is increased by one. The test ends after two consecutive errors or if the child reaches the maximum number of items to be recalled (10 items). The trials are presented in the same order for all participants and the items to be recalled are the same for all participants. The VCR score corresponds to the number of items recalled in the last trial completed by the participants (i.e., trial 10 or the test immediately preceding two consecutive incorrect tests). As a measure of short-term memory, the VCR has been associated with behavioral symptoms, and a host of related perinatal and familial risk (Huijbregts, Séguin, Zelazo, Parent, Japel, & Tremblay, 2006; Séguin, Parent, Tremblay, & Zelazo, 2009). The VCR has also been linked to other measures of short-term or working memory (Wang & Saudino, 2013), and shown to predict number knowledge trajectories (Garon-Carrier et al., 2018).

Cognitive flexibility. Cognitive flexibility was assessed only in the twin sample with the *Dimensional Change Card Sort* (DCCS; Zelazo, 2006), a widespread measure of executive functions. During the DCCS, children are shown two cards (e.g. a blue rabbit and a red boat) and

must sort the following cards according to one of the dimensions (color or form). After a while, the rule changes and the children must sort the cards according to the other dimension (Zelazo, 2006). Performance is measured by the correct number of responses following the rule change. DCCS has good test-retest reliability and good convergence validity (Beck, Schaefer, Pang, & Carlson, 2011; Hongwanishkul, Happaney, Lee, & Zelazo, 2005). A reflect and logarithm transformation was used to reduce negative skewness.

Control Variables. Maternal education, household income and sex were used as control variables. In the QNTS, maternal education (highest diploma obtained) and household income were obtained during a home interview with the mothers, when the twins were 6 months old. Maternal education was aggregated into a 4-point scales (from 1 to 4): from “high school not completed” to “university diploma obtained”, and household income was aggregated into a scale from 1 to 11: from “fewer than 5000\$” to “more than 80 000\$”. In the QLSCD, maternal education and household income were collected through questions from the National Longitudinal Survey of Children and Youth (see Willms & Shields, 1996), when the child was 5 months old. Maternal education was measured as their highest diploma obtained, as revealed by a 4-point self-report scale ranging from 1 (no high school diploma) to 4 (university degree). Household income was assessed on a scale from 1 to 10: from “fewer than 10 000\$” to “more than 80 000\$”. Sex (0 = boy, 1 = girl) was also measured and used as a control variable in both samples.

Analyses. All the analyses were conducted using the statistical software Mplus (version 8) and missing data were considered using the full information maximum likelihood (FIML) estimation. Data were mostly missing for school achievement measure due to attrition. In the

QNTS, the percentage of missing data ranged from 30% to 45%, while in the QLSCD, the percentage of missing data varied from 16% to 37%.

The general plan of analysis was as follows. First, we examined the correlations between all variables. Second, through path analysis, we tested the likelihood of the hypothesized model regarding the prediction of school achievement at different grades. We used the comparative fit index (CFI), the Tucker-Lewis index (TLI), and the small root-mean-square error of approximation (RMSEA) to test the fit of the model. Direct and indirect paths of the contribution of fluid abilities to school achievement through the mediation of crystallized abilities were examined. Also, stability of school achievement was estimated by adding autoregressive paths between all previous and subsequent school grades achievement measures. Control variables (maternal education, household income and sex) were added in the model to control for their association with cognitive abilities (fluid and crystallized) and school achievement measures. In the QNTS, we used a robust estimator to consider the non-independence of the twin measures (Muthen & Satorra, 1995; Rebollo, De Moor, Dolan, & Boomsma, 2006). Finally, we estimated the various hypothesized pathways by bootstrapping (1000 times; Hayes, 2009).

Results

Table 1 presents sample sizes, means and standard deviations for school achievement scores, crystallized abilities, fluid abilities and control variables for both the QNTS and the QLSCD. Crystallized abilities were found to be generally higher in the QLSCD due to the fact that they were assessed at a later age (kindergarten) than in the QNTS (60 months). However, fluid abilities and school achievement had similar means across samples.

Correlations

Table 2 presents the Pearson correlations between school achievement, crystallized abilities, fluid abilities and control variables in both samples. Correlations were significant, although modest among fluid abilities in both the QNTS (r s range: .16 to .22) and the QLSCD ($r = .11$). In both samples, the correlations were significant and substantial among the various crystallized abilities (r s range: .41 to .67). Accordingly, they were modeled to reflect a latent factor of crystallized abilities in the path analysis model. The correlations between the control variables and school achievement were positive, and in the expected direction (e.g., sex: in favor of girls), although modest in magnitude (range: .06 to .32). School achievement was found to be highly stable across grades (r s range: .62 to .79), which speaks to the importance of considering auto-regressive paths in the model. Finally, all predictors were significantly associated with school achievement, with the strongest correlations obtained for crystallized abilities (r s range: .34 to .58). It is interesting to note that both preschool fluid and crystallized abilities were significantly, and often substantially correlated to later (grade 4 and 6) school achievement.

Prediction of School Achievement

The mediation model provided an adequate fit to the observed data, as shown by a high comparative fit index (CFI=.98), a high Tucker-Lewis index (TLI=.95), as well as a small root-mean-square error of approximation (RMSEA=0.05, 90% CI [.04, .07]; Hu & Bentler, 1999). Figure 1 shows the full model with the standardized path coefficients estimates for the QNTS.

The overall model, which included the control variables, accounted for 49% of the variance in school achievement in grade 1, 51% in grade 3, and 67% in grades 4 and 6, with the latter grades including the autoregressive paths. Control variables made significant contributions

to school achievement in grade 1 (maternal education only, $\beta = .10, p = .05$), in grade 4 (sex only, $\beta = .06, p = .017$), and in grade 6 (maternal education, $\beta = .10, p = .014$, and sex, $\beta = .08, p = .006$). The model provided clear support for the mediation hypothesis. Indeed, the three measures of crystallized abilities clearly converged to create a reliable general latent crystallized abilities factor, which was significantly predicted ($R^2 = .45$) by the three fluid skills, and successfully predicted later school achievement. Specifically, the strongest predictors of school achievement in grade 1 ($\beta = .62, p < .001$) and grade 3 ($\beta = .22, p = .001$) were early crystallized abilities (latent factor). Preschool fluid abilities also predicted school achievement: cognitive visual-spatial skills predicted achievement in grade 3 ($\beta = .08, p = .033$) and grade 4 ($\beta = .11, p < .001$), and short-term memory predicted achievement in grade 6 ($\beta = .07, p = .008$). Interestingly, these modest direct contributions were significant beyond early crystallized abilities, and the strong auto-regressive (stability) paths characterizing school achievement in primary school. Finally, cognitive flexibility did not have a unique significant contribution to any school achievement measures beyond its contribution to early crystallized abilities.

Figure 2 shows the same full model for the QLSCD. Quite consistent with the QNTS results, the overall model explained 58% of the variance in school achievement in grade 1, 66% in grade 2, 60% in grade 4, and 61% in grade 6. Control variables significantly contributed to school achievement in grade 1 (maternal education only, $\beta = .06, p = .036$), and in grade 6 (sex only, $\beta = .09, p = .001$). Again, the model supported the mediation hypothesis, as the two fluid skills predicted the crystallized abilities factor ($R^2 = .36$), which successfully predicted later school achievement in grade 1 ($\beta = .75, p < .001$), and in grade 3 ($\beta = .25, p < .001$), but not beyond. Visual-spatial cognitive skills also predicted school achievement in grade 3 ($\beta = .05, p = .029$), again beyond early crystallized abilities, and the strong auto-regressive (stability) paths

characterizing school achievement in primary school. Short-term memory did not have a contribution to any school achievement measure beyond crystallized abilities.

Thus, the two models were quite consistent with the mediating role of crystallized abilities in the association between early fluid abilities and later school achievement. To better estimate the magnitude of both direct and mediation pathways, we used a bootstrapping method. Bootstrapping calculates probable estimates of the direct and indirect contributions by generating multiple empirical representations of the sampling distribution (Hayes, 2009). Table 3 shows these direct and indirect contributions and their confidence intervals in both QNTS and QLSCD after a thousand bootstrapping iterations (see Supplementary materials for detailed contributions). Again, the results were strikingly similar in both samples. Over and above the direct contributions already described, all fluid abilities could be seen as having extended mediated contributions to school achievement across primary school, i.e., through crystallized abilities in grade 1, and then through crystallized abilities and previous achievement in the later grades (as posited in Figures 1 and 2). Specifically, for cognitive visual-spatial skills, the total mediated estimates varied from .26 to .29 in QNTS, and from .31 to .27 in QLSCD; for cognitive flexibility, they varied from .12 to .13 in QNTS (only); and for short-term memory, from .10 to .10 in QNTS, and from .06 to .10 in QLSCD. Thus, in both samples, crystallized abilities totally mediated the contribution of fluid abilities to school achievement in grade 1, which then reverberated in successive school achievement across primary school.

Finally, because crystallized abilities' contributions to later school achievement could not be reduced to previous fluid abilities, we also documented their unique direct and indirect contributions to school achievement controlling for early fluid abilities (and other socio-

demographic controls). Table 4 shows these direct (also see figure 1 and 2) and indirect contributions in both QNTS and QLSCD, again after bootstrapping iterations (see Supplementary materials for detailed contributions). Thus, over and above the direct and indirect contributions of fluid abilities, crystallized abilities contributions to school achievement extended across primary school, but through previous achievement in the previous grades (as posited in Figures 1 and 2). Specifically, the total mediated estimates varied from .30 to .41 in QNTS, and from .43 to .48 in QLSCD.

Discussion

The goal of the present study was to document the contributions of preschool fluid and crystallized abilities to school achievement across primary school, and to examine the mediating role of crystallized abilities in this sequence of predictive association. Through path analyses controlling for sex, maternal education and family income, crystallized abilities were indeed found to mediate the association between early fluid abilities and later school achievement in the early grades of school. These results were strikingly similar in two distinct samples, and thus confirm the relevance of considering the coordinated and sequential contributions of preschool fluid and crystallized abilities to later school achievement. They extend previous research in several ways.

First, the present findings underlie the central role of preschool crystallized abilities in predicting later school achievement. Not only did crystallized abilities predicted early school achievement over and above fluid abilities, as shown in previous studies (e.g., Duncan et al., 2007), but they also accounted for a significant portion of fluid abilities' contribution to school achievement. A few studies found results pointing in that direction, but the present findings

confirmed that the mediation role of preschool crystallized abilities was substantial for general school achievement, and not just domain-specific achievement, such as for mathematics (Ostergren & Traff, 2013; Passolunghi & Lanfranchi, 2012; Krajewski, & Schneider, 2009).

These findings, although correlational, are consistent with the idea that children with higher fluid abilities are better equipped to acquire, before school entry, relevant crystallized abilities, such as knowledge of number or letter, and then more readily achieve in school. The general view that the acquisition of crystallized abilities stems partly from the “investment” of fluid abilities in the acquisition of crystallized abilities is not new (e.g. Cattell, 1963, 1987; Kvist & Gustafsson, 2008; Schweizer & Koch, 2002), but the present study was the first to longitudinally document this process from preschool to well into grade school.

This extended and detailed follow-up also allowed to uniquely qualify the longitudinal reach of preschool crystallized abilities, and thus of the mediation process. Indeed, the present study revealed that crystallized abilities did not add to the prediction of school achievement beyond grade 3. This time-limited contribution suggests that by grade 4, the benefits of early preschool crystallized abilities have been harvested and consolidated by children within the learning system. It is likely that the school curriculum had moved them toward more sophisticated learning issues (e.g., knowledge of fractions or grammar rules) for which the early crystallized abilities are less relevant. On that note, the other important piece of evidence from the present study stems for the strong auto-regressive paths of school achievement. Already from the start (i.e., school entry), school achievement was highly stable, and by grade 4 and continuing in grade 6, the main predictors of school achievement were by far prior school achievement, with some direct, but modest contributions of visuo-spatial cognitive skills (in both studies) and short-term memory (in QNTS only).

The lack of any unique contribution of early crystallized abilities to school achievement beyond grade 3 does not mean that crystallized abilities are no longer relevant, but rather that they have become embedded in school achievement, as skills and knowledge acquired in school progressively becomes the new crystallized abilities. Simply, children with strong crystallized abilities enter school with a head start, and then tend to keep this advantage over time.

Finally, despite the strong auto-regressive paths of school achievement and mediational role of crystallized abilities, there was some evidence of small, but systematic contributions of fluid abilities beyond grade 3. The direct predictive association between fluid abilities and school achievement at grade 3 and grade 4 was found mostly for cognitive visual-spatial skills. Most of the contributions of other fluid abilities to school achievement were mediated by crystallized abilities, except for a modest significant direct contribution for short-term memory on school achievement in grade 6. These findings are consistent with previous research showing the predictive association between fluid abilities and school achievement (e.g. Alloway & Alloway, 2010; Geary et al., 2017; McGrew & Wendling, 2010), but expands it by showing the extended reach of fluid abilities beyond crystallized abilities. This extended predictive reach may have to do with the increased complexity of reasoning strategies requested for school achievement in late primary school (Lee & Bull, 2016). The lack of an association between cognitive flexibility and school achievement is consistent with other studies showing no association when controlling for crystallized abilities (Espy, McDiarmid, Cwik, Stalets, & Hamby, 2004; Monette et al., 2011).

Implications for prevention and intervention

Given the strong stability of school achievement, children who start school ahead in terms of their fluid and crystallized abilities are likely to stay ahead academically during the

elementary school years and possibly beyond. The present findings thus highlight the importance of early preventive interventions aimed at both fluid and crystallized abilities in preschool. For example, the Abecedarian Project and the Head Start program are two programs that have successfully enhanced fluid and crystallized abilities in preschool children and future school achievement (Ramey, Campbell, Burchinal, Skinner, Gardner, & Ramey, 2000; Welsh et al., 2010). Clearly, most early intervention programs that were proven successful have targeted crystallized abilities, and our findings indicate that crystallized abilities should indeed be the primary target of intervention. However, to the extent that fluid abilities, such as working memory and non-verbal reasoning, can be improved early on (Bergman Nutley, Söderqvist, Bryde, Thorell, Humphreys, & Klingberg 2011; Sternberg, 2008), they should be promoted and included as targets of early intervention. The present findings indicate that two aspects should be considered in this endeavor: (1) the capacity for early intervention to enhance fluid abilities, and (2) the provision of learning opportunities (i.e., a stimulating environment) so that these fluid abilities can be “invested” in the mastering of relevant crystallized abilities. Future studies should document the extent to which the predictive association between fluid and crystallized abilities depends (i.e., is moderated by) on learning opportunities and contexts (e.g., the use of quality childcare services). Finally, in addition to early intervention, school-based interventions aimed at improving fluid abilities could also be considered.

Limitations

The present study should be interpreted in the context of its limitations. First, despite the plausible nature of the proposed sequence of associations, fluid abilities and crystallized abilities were assessed at the same time in preschool. Thus, it is not clear whether the posited sequence of

association between fluid and crystallized abilities holds. More precise longitudinal protocols, such as cross-lagged designs, or experimental (intervention) designs will be necessary to confirm the direction of this association. Second, only a subset of fluid and crystallized abilities was considered in the present study. For instance, the present study only used non-verbal fluid abilities measures. Verbal fluid abilities, such as verbal reasoning, may have a different association with crystallized abilities and school achievement, and should be investigated in future research. Furthermore, we did not measure working memory, a significant predictor of school achievement (Alloway & Alloway, 2010). However, the Block Design test, the measure of visual-spatial cognitive abilities and a good proxy of general IQ (Sattler, 2001), was likely to capture a significant portion of nonverbal fluid abilities. Third, school achievement was assessed only through teacher ratings. Recent research shows that teacher ratings are highly correlated with standardized assessment of school achievement (Garon-Carrier et al., 2018, Südkamp, et al., 2012; Rimfeld et al., 2019). However, the present findings should be replicated using standardized measures of school achievement. Fourth, the present study only covered school achievement in the primary school period, and the findings may thus be relevant only to that period. Results may differ in later grades (i.e., secondary school), as the contribution of early cognitive abilities to school achievement may be nonlinear (Geary et al., 2017). Finally, like most longitudinal studies, the present study was affected by missing data due to attrition. Detailed analyses revealed that data were not completely missing at random, with children from low socioeconomic status families more likely to dropout of the study. This differential attrition may have constrained the variance estimates (i.e., leading to more conservative estimates). However, we used a full information maximum likelihood (FIML) method, and further

controlled for socioeconomic status (maternal education, household income) in the models to attenuate this limitation.

Conclusion

In the present study, we tested in two distinct samples a comprehensive mediation model examining the sequential role of preschool fluid and crystallized abilities in the pathways to school achievement. Preschool crystallized abilities were found to account for the association between fluid abilities and school achievement, but in the early school years only. School achievement was highly stable across primary school, with fluid abilities having a small unique contribution to school achievement in the later grades. These results support the importance of early interventions aimed at improving both preschool fluid and crystallized abilities.

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Tables and Figures

Table 1

Descriptive variables in the two samples

	QNTS			QLSCD		
	M	SD	N	M	SD	N
<i>Fluid abilities</i>						
Block Design	19.70	6.56	929	19.92	9.92	1201
DCCS	-.17	.28	845			
VCR	4.89	2.22	903	5.93	2.37	1195
<i>Crystallized abilities</i>						
Lollipop	42.80	13.04	926	57.75	7.07	1194
PPVT	54.39	18.79	777	80.40	17.17	1162
NKT	7.85	4.17	925	13.29	3.27	1185
<i>School Achievement</i>						
SA1	3.29	1.06	568	3.54	1.17	1010
SA3	3.16	1.05	647	3.51	1.16	967
SA4	3.07	1.09	638	3.42	1.11	756
SA6	3.27	1.12	512	3.39	1.14	756
<i>Control Variable</i>						
Education	2.90	1.05	807	2.72	1.065	1200
Income	7.10	2.16	863	6.00	2.22	1192

Note. DCCS = Dimensional Change Card Sort, VCR = Visually Cued Recall Task, PPVT = Peabody Picture Vocabulary Test – Third Edition, NKT = Number Knowledge Test, SA= School Achievement

Table 2

Correlation between all variables in the QNTS (under the diagonal) and in the QLSCD (over the diagonal)

Variables	Block Design	DCCS	VCR	Lollipop	PPVT	NKT	SA1	SA3	SA4	SA6	Sex	Education	Income
<i>Fluid abilities</i>													
Block Design	-		.107*	.313*	.307*	.368*	.381*	.391*	.363*	.324*	-.043	.214*	.206*
DCCS	.184*	-											
VCR	.215*	.157*	-	.133*	.133*	.084*	.160*	.162*	.102*	.161*	.081*	.020	.012
<i>Crystallized abilities</i>													
Lollipop	.486*	.297*	.259*	-	.406*	.504*	.572*	.525*	.450*	.413*	.174*	.237*	.251*
PPVT	.354*	.275*	.282*	.543*	-	.417*	.435*	.418*	.395*	.344*	.010	.243*	.222*
NKT	.403*	.252*	.223*	.673*	.482*	-	.519*	.513*	.466*	.411*	.015	.248*	.272*
<i>School Achievement</i>													
SA1	.426*	.224*	.258*	.581*	.423*	.509*	-	.789*	.693*	.619*	.083*	.292*	.267*
SA3	.408*	.228*	.189*	.514*	.354*	.455*	.682*	-	.724*	.703*	.099*	.276*	.225*
SA4	.482*	.249*	.249*	.543*	.403*	.456*	.682*	.773*	-	.723*	.117*	.236*	.206*
SA6	.429*	.211*	.282*	.529*	.430*	.431*	.706*	.689*	.753*	-	.171*	.275*	.232*
<i>Control Variable</i>													
Sex	-.065*	.079*	.128*	.055	-.061	-.027	.062	.087*	.135*	.139*	-	-.019*	-.006
Education	.210*	.104*	.089*	.283*	.334*	.204*	.258*	.152*	.252*	.315*	-.010	-	.522*
Income	.208*	.177*	.133*	.248*	.340*	.230*	.192*	.123*	.212*	.257*	-.035	.452*	-

Note. DCCS = Dimensional Change Card Sort, VCR = Visually Cued Recall Task, PPVT = Peabody Picture Vocabulary Test – Third Edition, NKT = Number Knowledge Test, SA= School Achievement

Table 3

Direct and indirect effects of fluids abilities on school achievement through crystallized abilities and previous achievement in the two samples

Predictors	Outcome	Direct effect			Indirect effect through crystallized abilities and previous achievement				Indirect effect through crystallized abilities uniquely			
		Coefficient	SE	<i>P</i>	Coefficient	SE	Lower limit	Upper limit	Coefficient	SE	Lower limit	Upper limit
								.95	.95			.95
QNTS												
Cognitive visual-spatial skills	Achievement 1st	.068	.041	.093	.269*	.030	.193	.345	.269*	.030	.193	.345
	Achievement 3rd	.080*	.035	.023	.258*	.028	.185	.331	.097*	.026	.029	.164
	Achievement 4th	.112*	.030	.000	.273*	.027	.204	.343	.024	.022	-.032	.081
	Achievement 6th	.025	.034	.460	.293*	.031	.213	.374	.015	.027	-.055	.085
Cognitive flexibility	Achievement 1st	.013	.035	.710	.130*	.022	.073	.187	.130*	.022	.073	.187
	Achievement 3rd	.031	.033	.342	.115*	.022	.058	.173	.047*	.014	.010	.083
	Achievement 4th	.010	.027	.700	.119*	.025	.055	.184	.012	.011	-.016	.039
	Achievement 6th	-.016	.028	.569	.115*	.024	.052	.177	.007	.013	-.027	.042
Short-term memory	Achievement 1st	.014	.035	.678	.100*	.020	.048	.152	.100*	.020	.048	.152
	Achievement 3rd	.030	.031	.321	.090*	.022	.033	.134	.036*	.012	.006	.066
	Achievement 4th	.016	.028	.563	.097*	.025	.033	.160	.009	.008	-.012	.030
	Achievement 6th	.069*	.028	.015	.095*	.024	.033	.157	.006	.010	-.021	.032
QLSCD												
Cognitive visual-spatial skills	Achievement 1st	-.005	.032	.876	.307*	.027	.243	.381	.307*	.027	.243	.381
	Achievement 3rd	.054*	.025	.029	.274*	.023	.221	.337	.102*	.026	.043	.186
	Achievement 4th	.053	.030	.072	.269*	.024	.203	.324	.052	.028	-.033	.124
	Achievement 6th	.002	.029	.951	.269*	.024	.204	.335	.032	.026	-.035	.101
Short-term memory	Achievement 1st	.036	.025	.151	.083*	.023	.023	.140	.083*	.023	.026	.140
	Achievement 3rd	.009	.019	.641	.095*	.021	.038	.146	.028*	.010	.008	.057
	Achievement 4th	-.043	.025	.089	.088*	.020	.037	.147	.014	.009	-.006	.045
	Achievement 6th	.022	.024	.354	.061*	.021	.002	.118	.009	.008	-.010	.031

Note. * $p < .05$

Table 4

Direct and indirect effects of crystallized abilities to school achievement during primary school

Samples	Direct effect				Indirect effect			
	Outcome	Coefficient	SE	<i>p</i>	Coefficient	SE	Lower limit	Upper limit
							.95	.95
QNTS	Achievement 1st	.624*	.046	.000				
	Achievement 3rd	.224*	.058	.000	.299*	.037	.205	.393
	Achievement 4th	.057	.050	.256	.406*	.040	.303	.509
	Achievement 6th	.035	.063	.578	.410*	.043	.289	.522
QLSCD	Achievement 1st	.750*	.034	.000				
	Achievement 3rd	.250*	.062	.000	.427*	.035	.344	.522
	Achievement 4th	.127	.068	.062	.476*	.045	.373	.612
	Achievement 6th	.077	.062	.214	.470*	.045	.371	.602

Note. * $p < .05$

Figure 1. Mediation model of the contribution of crystallized abilities on the association between fluid abilities and school achievement in primary school in the QNTS. $\chi^2(21) = 75.02, p < .001$; RMSEA = 0.053, 90% CI [0.040, 0.066]; CFI = .983; TLI = .950. Nonsignificant contributions are indicated with dashed lines. Contributions of control variables (mother's education, family income and sex) are not indicated to simplify the model. PPVT = Peabody Picture Vocabulary Scale, NKT = Number Knowledge Test

Figure 2. Mediation model of the contribution of crystallized abilities on the association between fluid abilities and school achievement in primary school in the QLSCD. $\chi^2(19) = 70.79$ $p < .001$; RMSEA = 0.048, 90% CI [0.036, 0.060]; CFI = .987, TLI = .961 Nonsignificant contributions are indicated with dashed lines. Contributions of control variables (mother's education, family income and sex) are not indicated to simplify the model. PPVT = Peabody Picture Vocabulary Scale, NKT = Number Knowledge Test