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Research Article

Looking beyond enrollment rates: The long-term influence of preschool science curricula on children's science achievement

Mesut Saçkes[1], Kathy Cabe Trundle[2]

Abstract: This study provides evidence that what happens in preschool (i.e., preschool curriculum) can have long-term consequences years later. In the current study, we seek to answer the question of whether the inclusion of science in the preschool curriculum is associated with fourth- and eighth grade science achievement scores. Based on science achievement data from the Trends in International Mathematics and Science Study (TIMSS 2015 and 2019 cycles), the quality of preschool science learning opportunities showed long-term impacts on science achievement at the fourth grade level. Even after controlling for enrollment rates, the quality of the preschool curricula was a statistically significant predictor of fourth grade science scores with a high effect size (d=0.74). The observed impacts, however, appeared to diminish by eighth-grade. Results from this study suggest that science concepts and skills should be an integral part of preschool curricula and curricular frameworks, and policy makers should allocate resources to provide well-designed preschool education programs with high quality curricula.

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Introduction

The gap in cognitive and social skills among children from low and high socioeconomic (SES) groups appears to emerge prior to formal schooling and persists into adulthood (Heckman, 2006). Because preschool education has the potential for short- to long-term impacts on various economic, societal, and child related outcomes, researchers and educators have suggested expansion of preschool education as a viable option to address these disparities (Barnett, 2011; Cebolla-Boado et al., 2017; Cortázar et al., 2020; Heckman, 2006; McCoy et al., 2017). Evidence to support these claims comes from studies that evaluated the impact of preschool education at either local or national levels (Gormley et al., 2008; Melhuish et al., 2008), with few comparisons at the international level. The limited international studies solely examined the impact of preschool enrollment or public preschool expenditures on children's later academic achievement at fourth grade, and the results indicated that increased preschool enrollments did not necessarily lead to increased achievement (Cebolla-Boado et al., 2017; Richter et al., 2021; Strietholt et al., 2020; Waldfogel & Zhai, 2008).

Here we provide evidence for the importance of refocusing our efforts from simply expanding preschool enrollment rates to designing and providing high quality preschool education programs for children with diverse needs and to inform policy makers' decisions. High quality preschool education programs can act as an equalizing factor to close gaps in child related outcomes at the national and international levels (Heckman, 2006). Quality indicators of preschool education programs typically include staff qualifications and staff-child ratios (Sabol et al., 2013). However, the strongest predictors of preschool children's learning are the concepts and skills targeted in educational programs, which are identified and described in curricular documents (Anders et al., 2016; Sabol et al., 2013). Here we argue that the provision of expanding preschool education only has enduring effects on children's academic outcomes when they have high quality preschool curricula. Countries with high quality preschool curricula that target

[1] Balıkesir University, Necatibey School of Education, Balıkesir, Türkiye, e-mail: msackes@balikesir.edu.tr, ORCID: https://orcid.org/0000-0003-3673-1668
[2] Utah State University, Emma Eccles Jones College of Education and Human Services, Logan, UT, USA, e-mail: kathy.trundle@usu.edu, ORCID: https://orcid.org/0000-0003-4281-3782

developmentally appropriate concepts and skills might be more likely to demonstrate higher performance in international large-scale assessments. We test this hypothesis within the context of science achievement.

Factors contributing to the variations in children's science performances across countries in international large-scale assessments have been the focus of several studies since the inception of the Trends in International Mathematics and Science Study (TIMSS) and the Programme for International Student Assessment (PISA). International large-scale assessments, such as TIMSS, allow researchers to gather and compare data specific to children's mathematics and science performances, and the data can serve as an indicator of the quality of different countries' educational systems at the preschool, elementary, and middle school levels.

Previous studies that utilized international large-scale assessment data have examined the association between children's science achievement and various child, classroom, and school level factors (e.g., gender, type of instruction, academic climate) to explain performance differences in test scores across countries (Drent et al., 2013). Few studies have focused on the association between preschool or early education and children's later achievement on international large-scale assessments. These limited studies have solely examined the relationship between preschool enrollment or public preschool expenditures and impacts on children's later academic achievement at the fourth and eighth grade levels (Waldfogel & Zhai, 2008; Strietholt et al., 2020; Richter et al., 2021). No previous studies have examined the relationship between early learning opportunities provided in preschool and potential impacts on children's later science achievement as measured by international large-scale assessments.

Previous studies indicate that preschool education has the potential for short- to long-term impacts on various economic, societal, and child related outcomes (Barnett, 2011; Cebolla-Boado et al., 2017; Cortázar et al., 2020, Heckman, 2006; Knudsen et al., 2006; McCoy et al., 2017). However, the vast majority of these studies evaluated the impact of preschool education at a local or national level (Gormley et al., 2008; Melhuish, 2008). Except with one recent example (Richter et al., 2021), the extant literature includes few multiple country studies, and these studies included a limited number of countries and did not focus on curriculum-based learning outcomes. International, large-scale assessments, such TIMSS, have the potential to fill this void by allowing researchers to gather evidence about the performance of different countries' educational systems at the preschool, elementary, and middle school levels with regard to literacy, mathematics, and science outcomes.

Therefore, the current study seeks to answer the following research question "Is the inclusion of science in the preschool curriculum associated with fourth- and eighth grade science achievement scores?" We hypothesized that inclusion of learning outcomes specific to science concepts and skills in preschool curricula is a significant predictor of children's later science achievement. More specifically, we hypothesized that, even after controlling for preschool enrollment rates, the inclusion of science in preschool curricula will be a statistically significant predictor of children's fourth- and eighth-grade TIMSS science achievement scores.

Method

Study Countries

A total of 57 countries and 7 benchmarking entities (regional jurisdictions of countries such as states or provinces) participated in the 2015 round of TIMSS. The country-level measure of fourth-grade science achievement results was calculated and reported for 47 countries. Of these 47 countries, four countries did not have preschool curricula issued at the state or national level. Therefore, these four countries were not included in this study. The effective sample for the analysis of fourth-grade science scores included 43 countries, with the State of Florida representing the United States and the Province of Ontario representing Canada (Please see the list of countries in Appendix 1. Study data set). More than 312,000 students, which included nationally representative samples of approximately 4,000 students from each country,

participated in the fourth-grade assessments during the TIMSS 2015 cycle (see https://timss.bc.edu/timss2015/ for more information).

A total of 64 countries and 8 benchmarking entities participated in 2019 TIMSS cycle. The country-level measure of eighth-grade science achievement results were calculated and reported for 39 countries, of which 29 countries had matching fourth-grade science achievement results reported in the previous 2015 TIMSS cycle. Therefore, the effective sample for the analysis of eighth-grade science scores included 29 countries, with the Province of Ontario representing Canada (Please see the list of countries in Appendix 1. Study data set). More than 250,000 students, which included nationally representative samples of approximately 4,000 students from each country, participated in the eighth-grade TIMSS 2019 assessments (see https://timss.bc.edu/timss2019/ for more information).

Measures

Fourth- and Eighth-Grade Science Achievement Test Scores

The country-level assessment scores of fourth-grade science from TIMSS 2015 and eighth-grade science from TIMSS 2019 were used as outcome measures in the present study. The fourth- and eighth-grade science assessment frameworks were organized under two dimensions: content and cognitive. The content dimension for the fourth-grade assessment included three domains: Life science (45%), physical science (35%), and Earth science (20%). Life science was represented by five topic areas, physical science content included three topic areas, and Earth science content included three topic areas (Mullis & Martin, 2013). The content dimension for the eighth-grade assessment included four domains: Biology (35%), chemistry (20%), physics (25%), and Earth science (20%). Biology was represented by six topic areas, Chemistry was represented by three topic areas, Physics included five topic areas, and Earth science content included four topic areas (Mullis & Martin, 2013).

The cognitive dimensions for the fourth-grade science and eighth-grade science assessments included three domains: Knowing (fourth-grade: 40%, eighth-grade: 35%), applying (fourth-grade: 40%, eighth-grade: 35%), and reasoning (fourth-grade: 20%, eighth-grade: 30%). The fourth- and eighth-grade science achievement assessments contained a total of 176 and 220 items respectively in two formats including multiple-choice and constructed-response. The test-takers answered up to 28 science items for the fourth-grade assessment and 36 science items for the eighth-grade assessment in 36 to 45 minutes (Martin et al., 2016; Martin et al., 2020; Mullis & Martin, 2017). The international median Cronbach's alpha reliability was 0.78 for the science assessments. The science assessments scores were examined utilizing the item response theory framework and the country level science achievement scores were scaled with a mean set to 500 and standard deviation of 100 (Martin et al., 2016; Martin et al., 2020).

Preschool Science Curriculum Scores

The preschool science curriculum score was calculated for each country included in the analysis. The preschool science curriculum scores were obtained via a scoring instrument developed by the researchers. Curricular documents used by the included countries during the academic year of 2010-2011 were collected from the websites of ministries of education or relevant governmental institutions. The collected PreK curriculum documents were analyzed and scored based on the document and curriculum analysis methods (Bowen, 2009; van den Akker, 2003).

The scoring instrument consisted of five dimensions that assessed inclusion of: 1) Science as a standalone domain in the curriculum, 2) Science process skills, 3) Learning outcomes specific to Earth and space science concepts, 4) Learning outcomes specific to life science concepts, and 5) Learning outcomes specific to physical science concepts. Dimensions were rated 0 if there was no evidence of inclusion of science, rated 1 if there is partial inclusion of science and rated 2 is there is adequate level of inclusion of science. The possible total score for each country ranged from 0 to 10. Half of the countries curriculum documents were randomly selected and rated independently by two researchers to establish the inter-

scorer reliability. The Cohen's weighted kappa coefficient was 0.72, suggesting high inter-scorer reliability (Cohen, 1968).

Preschool Enrollment Rate

The country-level measure of the gross enrollment rate in preschool was used as a control variable in the study. The enrollment rate data represented children aged three to five who were attending center- or school-based programs aimed to meet the educational and developmental needs of children who are yet to start primary school. The preschool enrollment rate data were obtained from the Organisation for Economic Co-operation and Development (OECD) Family database (http://www.oecd.org/els/family/database.htm) .

Data Analysis

We used bootstrapping linear regression models (Stine, 1985) to test the hypothesized association of preschool science curricula with fourth- and eighth-grade science achievement scores. This nonparametric analytical approach was selected for the analysis of the study data because this approach does not require strict distributional assumptions, and it works well with limited sample sizes (Fox, 2016). Bivariate correlation coefficients and unstandardized β coefficients, with their corresponding confidence intervals for simple and multiple regression models, were calculated using a bootstrap procedure where a large number of random samples (n=1000) with replacements were drawn from the actual data. Coefficients were estimated for each sample.

We first tested a simple regression model, with fourth-grade science scores as a dependent variable and science curriculum scores as an independent variable. Next, we tested a multiple regression model with fourth- and eighth-grade science scores as dependent variables, science curriculum scores as independent variables, and preschool enrollment rates as control variables. Model assumptions were examined using graphical methods and formal tests. No violation of assumptions or outliers were detected. Also, the mean science achievement scores of countries with low and high science oriented preschool curriculum (countries with science as a standalone domain in their preschool curriculum versus countries who did not have science as a standalone domain in their preschool curriculum) were compared using independent samples t-tests. All analyses were performed using SPSS version 26.

The dependent variables (outcome) were fourth- and eighth-grade science scores collected in the 2015 and 2019 TIMSS cycles respectively. The mean of fourth-grade science scores (n=43 countries) was 512.18, with a standard deviation of 52.71, and the scores ranged from 352 to 590. The mean of eighth-grade science scores (n=29 countries) was 505.93, with a standard deviation of 46.23, and the scores ranged from 394 to 608. The independent variable (predictor) was the preschool science curriculum score of participating countries in the 2015 TIMSS cycle. The mean science curriculum score (n=43 countries) was 4.67 with a standard deviation of 2.331, and the scores ranged from 0 to 9. The 2010-2011 preschool enrollment rates of countries were used as a control variable. The mean preschool enrollment rate (n=43 countries) was 73.03% with a standard deviation of 21.39%, and the rates ranged from 11.13% to 100%.

Results

We found partial support for the hypothesis that inclusion of learning outcomes specific to science concepts and skills in preschool curricula have a positive impact on children's later science achievement (see Fig. 1). Initially, we calculated bootstrapped bivariate correlation coefficients for the outcome, predictor, and control variables. The relationship between countries' fourth grade science scores and science curricula scores was moderate and statistically significant (r=.44, p=0.003, BCa 95% CI for r=0.15-0.66). The relationship between countries' fourth grade science scores and preschool enrollment rates was high and statistically significant (r=.55, p=0.001, BCa 95% CI for r=0.30-0.71).

The researchers calculated a bootstrapped partial correlation coefficient for countries' fourth grade science scores and science curricula scores, using preschool enrollment rates as a control variable. The relationship between countries' fourth grade science scores and science curriculum scores remained

significant (r=0.33, p=0.036, BCa 95% CI for r=0.04-0.54).

The results of the bootstrapped simple regression analysis indicated that the preschool science curricula scores explained 19.6% of variance in countries' fourth grade science scores (F1,41=10.01, p=0.003), and were significant predictors of countries' fourth grade science scores (B=10.032, p=.013, BCa 95% CI for B=3.27-16.53). A one-point increase in science curricula scores corresponded to about a 10-point increase in countries' fourth grade science scores.

The results of the multiple regression analysis of science curricula scores on fourth grade science scores, accounting for preschool enrollment rates, indicated that the preschool enrollment rates of countries alone explained 30% of variance in countries fourth grade science scores (F1,41=17.57, p=0.001). The inclusion of the science curriculum scores into the regression model explained an additional 3.7% of variance in countries' fourth grade science scores (F1,40=4.71, p=0.036). The whole regression model explained 24.1% of the variance (F2,40=4.13, p=0.001). In the regression model, both the countries' preschool enrollment rates (B=1.11, p=0.004, BCa 95% CI for B=0.49-1.63) and the science curricula scores (B=6.55, p=0.044, BCa 95% CI for B=1.21-12.08) were statistically significant predictors of countries' fourth grade science scores. While a one-percentage increase in countries' preschool enrollment rates, on average, corresponded to about a one-point increase in countries' fourth grade science scores, a one-point increase in science curricula scores, on average, corresponded to about a seven-point increase in countries' fourth grade science scores.

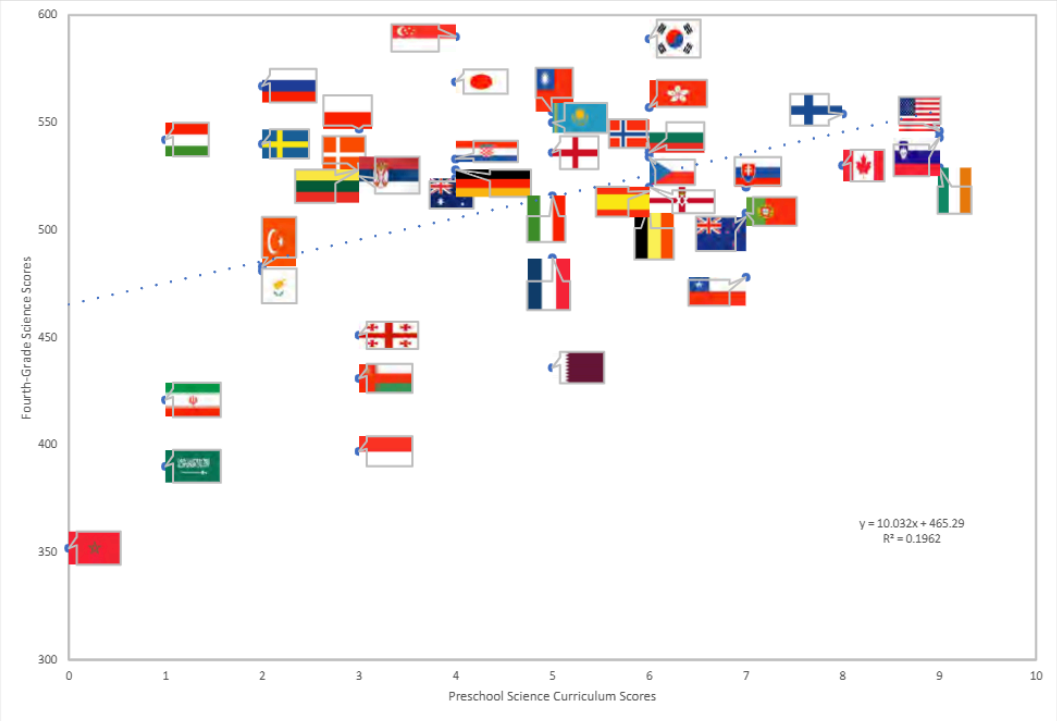

Figure 1. Preschool science curriculum scores predict fourth-grade science achievement scores

A final bootstrapped multiple regression analysis was performed to examine whether science curricula scores predicted countries' eighth-grade science scores observed in 2019 after controlling for the preschool enrollment rate of countries. The results indicated that countries' preschool enrollment rates alone explained 20% of variance in countries' eighth-grade science scores (F1,27=6.91, p=0.014). The inclusion of the science curricula scores into the regression model explained an additional 3.7% of variance in countries' eighth-grade science scores, but this effect was not statistically significant (F1,26=1.27, p=0.27).

In the whole regression model, neither the countries' preschool enrollment rates (B=0.77, p=0.053, BCa 95% CI for B=-0.01-1.51) nor the science curricula scores (B=3.96, p=0.27, BCa 95% CI for B=-3.27-10.43) were statistically significant predictors of countries' eighth-grade science scores.

The comparison of the mean science achievement test scores of countries with science as a standalone domain in their preschool curriculum (high science focus, n4th grade= 11, n8th grade=7) and countries who did not have science as a standalone domain in their preschool curriculum (low science focus, n4th grade= 32, n8th grade=22) demonstrated that countries with high science focus tend to obtain higher mean science achievement test scores at fourth-grade assessment (see Fig. 2). The difference was statistically significant for the fourth-grade assessment (p=0.042) with high effect size (d=0.74).

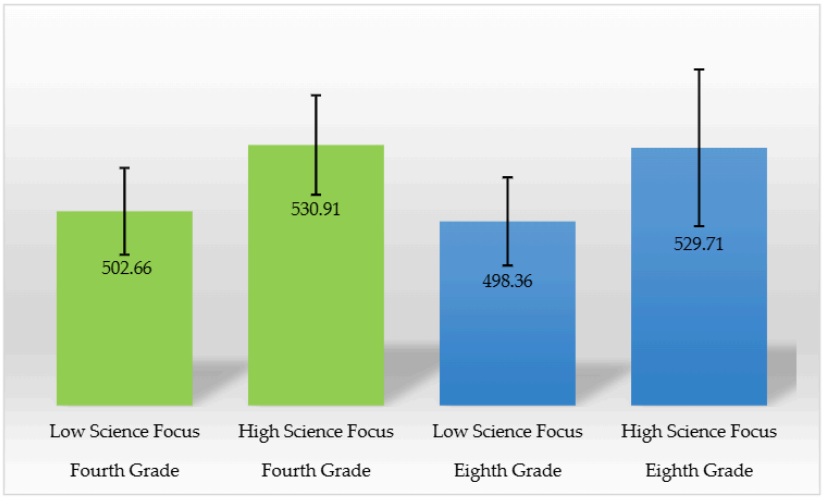

Figure 2. Mean science achievement scores of countries with low and high science oriented preschool curriculum

Discussion

In the current study, we utilized the TIMSS data set, and the findings provided partial support for the hypothesis that the inclusion of learning outcomes specific to science concepts and skills in preschool curricula have a positive impact on children's later science achievement. Even after controlling for preschool enrollment rates, the inclusion of science in preschool curricula was a statistically significant predictor of children's fourth-grade science achievement scores but not their eighth-grade science achievement scores. Countries that included science concepts and skills in their preschool curricula were more likely to obtain higher scores on fourth grade science achievement tests than countries with limited science focus in their preschool curricula. However, the observed impact of the preschool science curricula on science achievement was not durable beyond fourth-grade and appeared to diminish by eighth-grade.

There are at least two possible explanations for this observed trend in the eighth-grade data. First, the initial gains in science concept learning and skill development may have faded-out by the end of middle school. Many preschool education programs or early interventions often do not produce enduring effects on children's academic and socio-emotional outcomes (Bailey et al., 2017; Lipsey et al., 2018). The fade-out of these initial gains might be observed over the next several years, during adolescence or up to young adulthood (Bailey et al., 2017; Hogrebe & Strietholt, 2016). Decrease in the quality of science learning opportunities provided at middle grades might be responsible for the weakened preschool effect observed in our study (Cortázar et al., 2020). The second explanation comes from the loss of statistical power due to the reduced sample size in the TIMSS eighth-grade science assessment data. While the effective sample for the analysis of fourth-grade science scores included 43 countries, the effective sample for the analysis of eighth-grade science scores included 29 countries.

Nevertheless, our study suggests that preschool curricular frameworks that explicitly target science concepts and skills improve later science achievement. The findings of the current study contrast with the previous research where early science learning opportunities reported to have no short to long term impact on young children's science achievement (Kinzie et al., 2014; Saçkes et al., 2011; Saçkes et al., 2013). The findings also corroborate the results from a recent study where children who enrolled in preschool programs had higher science test scores at age 15 than their peers who did not attend preschool (Richter et al., 2021).

There are some limitations of the current study that requires caution in the interpretation of the findings. In the present study PreK curricular documents were examined in the extent to which they included science concepts and skills as a learning area. The extent to which teachers effectively implemented the curricula in preschool classrooms was not examined. There is a great degree of variability in science teaching practices in preschool classrooms which might increase or decrease the association between the quality of curricular documents and children's science achievement. In addition, some countries use a national-level preschool curriculum, such as Türkiye, while others, such as Germany, only have general guidelines or frameworks, and the extent to which federal level guidelines or curricula frameworks are adopted in local practices is not clear (Kluczniok et al., 2016). Consequently, the findings of this study should be carefully interpreted for countries with no nationwide preschool curriculum.

Conclusion

Development of cognitive and non-cognitive skills follow a hierarchical process where higher-level functions build on lower, preceding skills (Knudsen et al., 2006). Thus, high-quality preschool education programs support the development of fundamental knowledge and skills, which provide a solid foundation for the development of subsequent concepts and skills encountered in elementary grades through college. Increasing preschool enrollment rates alone, though significant, does not appear to be an effective strategy to improve educational and societal outcomes. Expanding the coverage of preschool education at the expense of quality may not return the investment costs and may result in limited or no long-term benefits (Barnett, 2011; Heckman, 2006). Policy makers should allocate resources to provide well-designed preschool education programs with high quality curricula that target developmentally appropriate concepts and skills for long-term gains.

International, large-scale assessments provide opportunities for researchers and policy makers to understand how well countries' educational systems perform in producing child outcomes specific to reading, mathematics, and science. The results of this study suggest that science concepts and skills should be an integral part of preschool curricula. Learning outcomes that are specific to science concepts and skills should be formally specified in countries' preschool curricular frameworks.

Declarations

Authors' Declarations

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