A systematic review and meta-analysis of the impact of the COVID-19 pandemic on learning

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A systematic review and meta-analysis of the impact of the COVID-19 pandemic on learning

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How has the COVID-19 pandemic affected learning progress among school-age children? A growing number of studies address this question, but findings vary depending on context. We conduct a pre-registered systematic review, quality appraisal and meta-analysis of 42 studies across 15 countries to assess the magnitude of the effect of the pandemic on learning. We find a substantial overall learning deficit (Cohen's $d = -0.14$, 95% c.i. −0.17, −0.10), which arose early in the pandemic and persists over time. Forgone learning is particularly large among children from low socio-economic backgrounds. It is also larger in math than in reading, and in middle-income countries, relative to high-income countries. There is a lack of evidence on learning progress during the pandemic in low-income countries. Future research should address this evidence gap and avoid the common risks of bias that we identify.

The COVID-19 pandemic has led to one of the largest disruptions to learning in history. To a large extent this is due to school closures, which are estimated to have affected 95 percent of the world's student population.[1] But even when face-to-face teaching resumed, instruction has often been compromised by hybrid teaching, and by children or teachers having to quarantine and miss classes. The effect of limited face-to-face instruction is likely compounded by the pandemic's consequences for children's out-of-school learning environment, as well as their mental and physical health. Lockdowns have restricted children's movement and their ability to play, meet other children, and engage in extra-curricular activities. Children's well-being and family relationships have also suffered due to economic uncertainties and conflicting demands of work, care and learning. These negative consequences can be expected to be most pronounced for children from low socio-economic family backgrounds, exacerbating pre-existing educational inequalities.

It is critical to understand how the COVID-19 pandemic has affected children's learning progress. We use the term 'learning deficit' to encompass both a delay in expected learning progress, as well as a loss of skills and knowledge already gained. The COVID-19 learning deficit is likely to affect children's life chances through their education and labor market prospects. At the societal level, it can have important implications for growth, prosperity, and social cohesion. As policy-makers across the world are seeking to limit further learning deficits and to devise policies to recover learning deficits that have already been incurred, assessing the current state of learning is crucial. A careful assessment of the COVID-19 learning deficit is also necessary to weigh the true costs and benefits of school closures.

A number of narrative reviews have sought to summarize the emerging research on COVID-19 and learning, mostly focusing on learning progress relatively early in the pandemic.[2,3,4,5,6] Moreover, two reviews harmonized and synthesized existing estimates of the effect of the pandemic on learning progress.[7,8] In line with the narrative reviews, these two systematic reviews find a statistically significant negative effect of the pandemic on learning. However, this finding is based on a relatively small number of studies (18 and 10 studies respectively). The limited evidence that was available at the time these reviews were conducted also precluded them from meta-analyzing variation in the magnitude of learning deficits over-time and across subjects, different groups of students, or country contexts.

In this paper, we conduct a comprehensive systematic review and meta-analysis of the evidence on COVID-19 learning deficits two and a half years into the pandemic. Our meta-analysis contributes to the existing research in two ways. First, we present a rigorous description and appraisal of the up-to-date body of evidence and its geographic reach and quality. More specifically, we ask (a) What is the state of the evidence, in terms of the available peer-reviewed research and gray-literature, on the effect of the COVID-19 pandemic on learning?, (b) Which countries are represented in the available evidence?, and (c) What is the quality of the existing evidence?

Our second contribution is to harmonize, synthesize and meta-analyze the existing evidence, with special attention to variation across different sub-populations and country contexts. Based on the identified studies, we ask (d) What is the magnitude of the overall effect of the COVID-19 pandemic on learning?, (e) How has the magnitude of the learning deficit evolved since the beginning of the pandemic?, (f) To what extent has the pandemic reinforced inequalities between children from different socio-economic backgrounds? (g) Are there differences in the magnitude of the learning deficit between subject domains (math and reading) and between grade levels (primary and secondary)?, and (h) To what extent does the effect of the pandemic on learning progress vary across countries with different income levels? Below, we report our answers to each of these questions in turn.

The state of the evidence

Our systematic review identified 42 studies on the effect of the COVID-19 pandemic on learning. As shown in Fig. 1,

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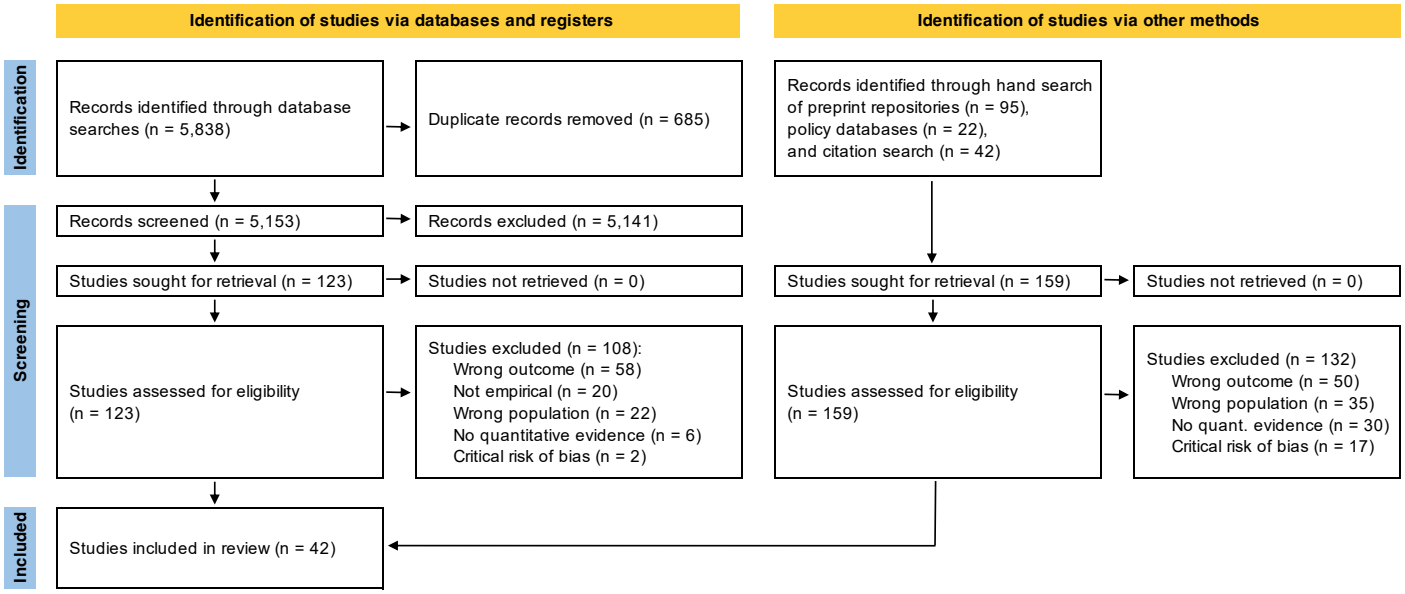

Figure 1: Study identification and selection process (PRISMA flow diagram)

the initial literature search resulted in 5,153 hits after removal of duplicates. All studies were double-screened by the first two authors. Studies had to use a measure of learning that can be standardized (using Cohen's d) and base their estimates on empirical data collected since the onset of the COVID-19 pandemic (rather than making projections based on pre-COVID-19 data). The formal database search process identified 15 eligible studies. We also hand-searched relevant preprint repositories ($n = 95$) and policy databases ($n = 22$). Further, to ensure that our study selection was as up-to-date as possible, we conducted two full forward and backward citation searches of all included studies on February 15, 2022, and on August 8, 2022 ($n = 42$).The citation and preprint hand-searches allowed us to identify 27 additional eligible studies, resulting in a total of 42 studies. Most of these studies were published after the initial database search, which illustrates that the body of evidence continues to expand. Most studies provide multiple estimates of COVID-19 learning deficits, separately for math and reading and for different school grades. The number of estimates ($n = 192$) is therefore larger than the number of included studies ($n = 42$).

The geographic reach of the evidence is limited. Table 1 shows all included studies and estimates of COVID-19 learning deficits (in brackets), grouped by country. 15 countries are represented: Australia, Belgium, Brazil, Colombia, Denmark, Germany, Italy, Mexico, the Netherlands, South Africa, Spain, Sweden, Switzerland, the United Kingdom and the United States. About half of the estimates ($n = 149$) are from the United States, 58 are from the United Kingdom, a further 70 are from other European countries, and the remaining 14 estimates are from Australia, Brazil, Colombia, Mexico, and South Africa. As this list shows, there is a strong over-representation of studies from high-income countries, a dearth of studies from middle-income countries, and no studies from low-income countries. This skewed representation should be kept in mind when interpreting our synthesis of the existing evidence on COVID-19 learning deficits.

The quality of evidence is mixed. We assessed the quality of the evidence using an adapted version of the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool.[50] More specifically, we analyzed the risk of bias of each estimate from confounding, sample selection, classification of treatments, missing data, the measurement of outcomes, and the selection of reported results. The second author performed the risk of bias assessments, which were independently checked by the first and third author. We then assigned each estimate an overall risk of bias rating (low, moderate, serious, or critical) based on the estimate and domain with the highest risk of bias. In line with ROBINS-I guidance, we excluded all studies rated 'critical' (n=19) from our meta-analysis.[50] Table S2 provides an overview of these studies as well as the main potential sources of risk of bias.

Fig. 2A shows the distribution of all studies of COVID-19 learning deficits according to their risk of bias rating separately for each domain (top six rows), as well as the distribution of studies according to their overall risk of bias rating (bottom row). The overall risk of bias was considered 'low' for 15% of studies, 'moderate' for 30% of studies, 'serious' for 25% of studies, and 'critical' for 30% of studies. As shown in Fig. 2A, common sources of potential bias were confounding, sample selection, and missing data. The likely consequence of these sources of bias is an underestimation of COVID-19 learning deficits. Studies rated at risk of confounding typically compared only two time points, without accounting for longer time trends in learning progress. The main causes of selection bias were the use of convenience samples and/or insufficient consideration of self-selection by schools or students. Several studies found evidence of selection bias, often with students from a low socio-economic

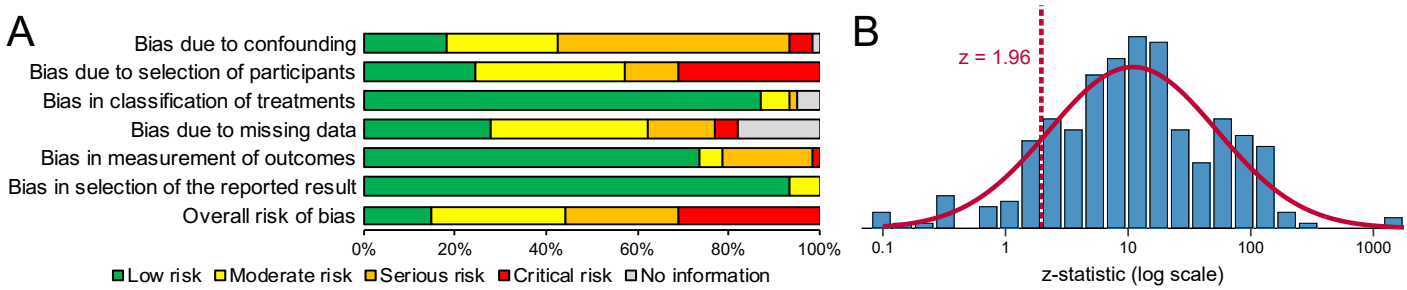

Figure 2: Risk of bias and publication bias. (A) Domain-specific and overall distribution of studies of COVID-19 learning deficits by risk of bias rating using ROBINS-I; includes studies rated to be at critical risk of bias ($n = 19$), which were excluded from the meta-analysis in line with ROBINS-I guidance; (B) z-curve: Distribution of the z-scores of all estimates included in the meta-analysis (n=291) to test for publication bias. The dotted line indicates $z = 1.96$ ($p = 0.05$), the conventional threshold for statistical significance. The overlaid curve shows a normal distribution. The absence of a spike in the distribution of the z-scores just above the threshold for statistical significance and the absence of a slump just below it indicate an absence of evidence for publication bias.

Table 1: Studies and estimates by country

Country	Studies
Australia [4]	Gore et al. 2021 [4][9]
Belgium [4]	Gambi and De Witte 2021 [2],[10] Maldonado and De Witte 2021 [2][11]
Brazil [2]	Lichand et al. 2022 [2][12]
Colombia [2]	Vegas 2022 [2][13]
Denmark [7]	Birkelund et al. 2021 [7][14]
Germany [9]	Depping et al. 2021 [4],[15] Ludewig et al. 2022 [1],[16] Schult et al. 2022a [2],[17] Schult et al. 2022b [2][18]
Italy [11]	Bazoli et al. 2022 [6],[19] Borgonovi and Ferrara 2022 [4],[20] Contini et al. 2022 [1][21]
Mexico [2]	Hevia et al. 2022 [2][22]
Netherlands [27]	Engzell et al. 2021 [8],[23] Haelermans 2021 [2],[24] Haelermans et al. 2021 [2],[25] Haelermans et al. 2022 [9],[26] Schuurman et al. 2021 [6][27]
South Africa [2]	Ardington et al. 2021 [2][28]
Spain [3]	Arenas and Gortazar 2022 [3][29]
Sweden [9]	Hallin et al. 2022 [9][30]
Switzerland [2]	Tomasik et al. 2020 [2][31]
United Kingdom [58]	Blainey et al. 2021a [12],[32] Blainey et al. 2021b [12],[33] Blainey et al. 2021c [12],[34] Department for Education 2021a [6],[35] Department for Education 2021b [2],[36] GL Assessment 2021 [4],[37] Rose et al. 2021a [2],[38] Rose et al. 2021b [4][39] Weidman et al. 2021 [4][40]
United States [149]	Domingue et al. 2021a [8],[41] Domingue et al. 2021b [4],[42] Kogan and Lavertu 2021a [1],[43] Kogan and Lavertu 2021b [9],[44] Kozakowski et al. 2021 [12],[45] Kuhfeld and Lewis 2022 [48],[46] Lewis et al. 2021 [12],[47] Locke et al. 2021 [14],[48] Pier et al. 2021 [25],[49]

Note: Countries and corresponding studies on COVID-19 learning deficits. The number of estimates are shown in brackets, by country (left) and study (right). Full references are indicated by superscript and listed in the bibliography.

background or schools in deprived areas being underrepresented after (as compared to before) the pandemic, but this was not always adjusted for. Some studies also reported a higher amount of missing data post-pandemic, again generally without adjustment, and several studies did not report any information on missing data. For an overview of the risk of bias ratings for each domain of each study see see Fig. S2, Table S1 and Table S2.

No evidence of publication bias. Publication bias can occur if authors self-censor to conform to theoretical expectations, or if journals favor statistically significant results. To mitigate this concern, we include not only published papers, but also unpublished working papers and 'gray literature', such as policy reports. Moreover, Fig. 2B tests for publication bias by showing the distribution of z-statistics for the effect size estimates of all identified studies. The dotted line indicates $z = 1.96$ ($p = 0.05$), the conventional threshold for statistical significance. The overlaid curve shows a normal distribution. If there was publication bias, we would expect a spike just above the threshold, and a slump just below it. There is no indication of this. Moreover, we do not find a left-skewed distribution of p-values (see p-curve in Fig. S3A), or an association between estimates of learning deficits and their standard errors (see funnel plot in Fig. S3B) that would suggest publication bias. Publication bias does thus not appear to be a major concern.

Results

Having assessed the quality of the existing evidence, we now present the substantive results of our meta-analysis, focusing on the magnitude of COVID-19 learning deficits and on the variation in learning deficits over time, across different groups of students, and across different country contexts.

The COVID-19 pandemic led to substantial learning deficits. Fig. 3 shows the effect sizes that we extracted from each study (averaged across grades and learning subject) as well as the pooled effect size (red diamond). Effects are expressed in standard deviations, using Cohen's d. Estimates are pooled using inverse variance weights. The pooled effect size across all studies is $d = -0.14$. Under normal circumstances, students generally improve their performance

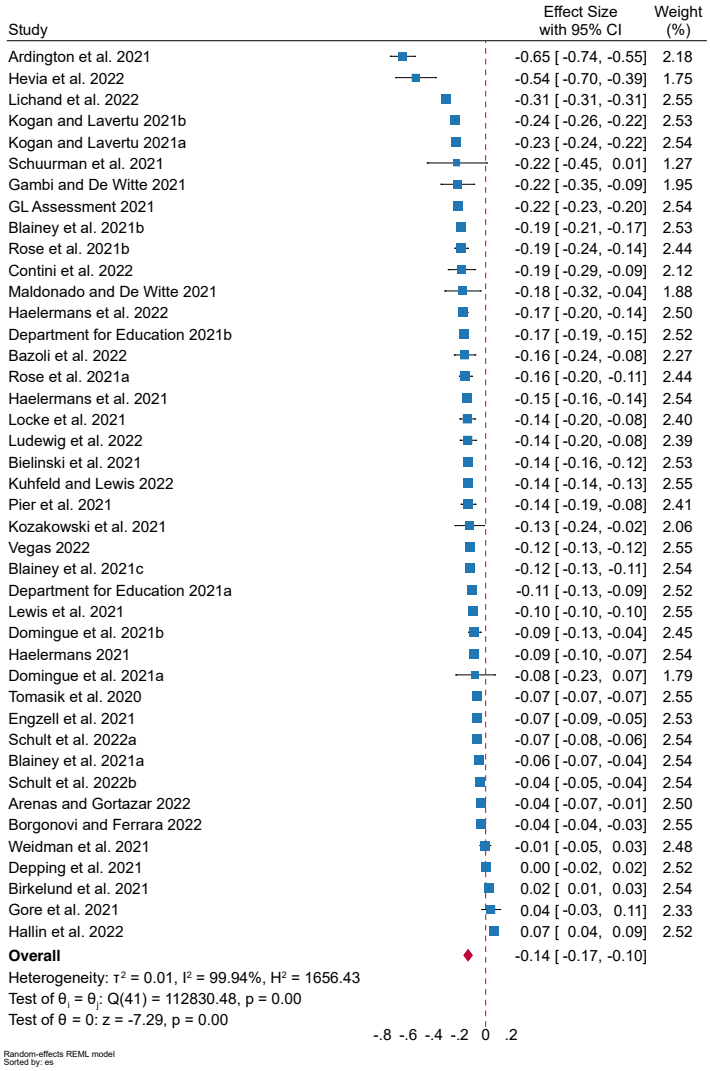

Figure 3: Forest plot showing individual estimates by study (n=42, averaged across subjects and grade levels), and the overall effect size estimate, pooled using inverse variance weights and a random-effects model. Effect sizes are expressed in standard deviations, using Cohen's d, with 95% confidence intervals, and are sorted by magnitude.

by around 0.4 standard deviations per school year.[51,52,53] Thus, the overall effect of $d = -0.14$ suggests that students lost out on 0.14/0.4, or about 35%, of a school year's worth of learning. On average, the pandemic has led to a substantial learning deficit.

Learning deficits arise early in the pandemic and persist over time. One may expect that children were able to recover learning that was lost early in the pandemic, after teachers and families had time to adjust to the new learning conditions, and structures for online learning and for recovering early learning deficits were set up. However, existing research on teacher strikes in Belgium[54] and Argentina,[55] shortened school years in Germany,[56] and disruptions to education during World War II[57] suggests that learning deficits are difficult to compensate and tend to persist in the long run.

Fig. 4 plots the magnitude of estimated learning deficits (on the vertical axis) by the date of measurement (on the horizontal axis). The color of the circles reflects the relevant country, the size of the circles indicates the sample size for a given estimate, and the line displays a linear trend. The figure suggests that learning deficits opened up early in the pandemic and have neither closed nor substantially widened since then. This would mean that efforts by children, parents, teachers, and policy-makers to adjust to the changed circumstance have been successful in preventing further learning deficits, but so far have been unable to reverse them. As shown in Fig. S6, the pattern of persistent learning deficits also emerges when we restrict our analysis to the three countries for which we have a relatively large number of estimates at different time points: The United States, the United Kingdom and the Netherlands. However, it is important to note that estimates of learning deficits are based on distinct samples of students and future research should continue to follow the learning progress of cohorts of students affected by the COVID-19 pandemic to reveal how learning deficits of these cohorts develop in different countries.

Socio-economic inequality in education increased during the pandemic. Existing research on the development of learning gaps during summer vacations,[58,59] disruptions to schooling during the Ebola outbreak in Sierra Leone and Guinea,[60] and the 2005 earthquake in Pakistan,[61] shows that the suspension of face-to-face teaching can increase educational inequality between children from different socio-economic backgrounds. The effect of the COVID-19 pandemic on learning progress is likely to have been particularly pronounced for children from low socio-economic backgrounds. These children have been more affected by school closures than children from more advantaged backgrounds.[62] Moreover, they are likely to be disadvantaged with respect to their access and ability to use digital learning technology, the quality of their home learning environment, the learning support they receive from teachers and parents, and their ability to study autonomously.[63,64,65]

Most studies we identify examine the effect of the pandemic on socio-economic inequality, attesting to the importance of the issue. Because studies use different measures of socio-economic background (e.g., parental income, parental education, free school meal eligibility, neighborhood disadvantage), pooling the estimates is not possible. Instead, we code all estimates according to whether they indicate a positive, negative, or no effect of the pandemic on learning inequality. Fig. 5 displays this information. Estimates that indicate an increase in inequality are shown on the right, those that indicate a decrease on the left, and those that suggest no change in the middle. Squares represent estimates on the effect of the pandemic on inequality in reading performance, and circles represent estimates on the effect of the pandemic on inequality in math performance. The shading represents when in the pandemic educational inequality was measured, differentiating between the first, second and third year of the pandemic. Estimates are also arranged horizontally by grade level. A large majority of estimates indicate an increase in educational inequality between children from different socio-economic backgrounds. This holds for both math and reading, across primary and secondary

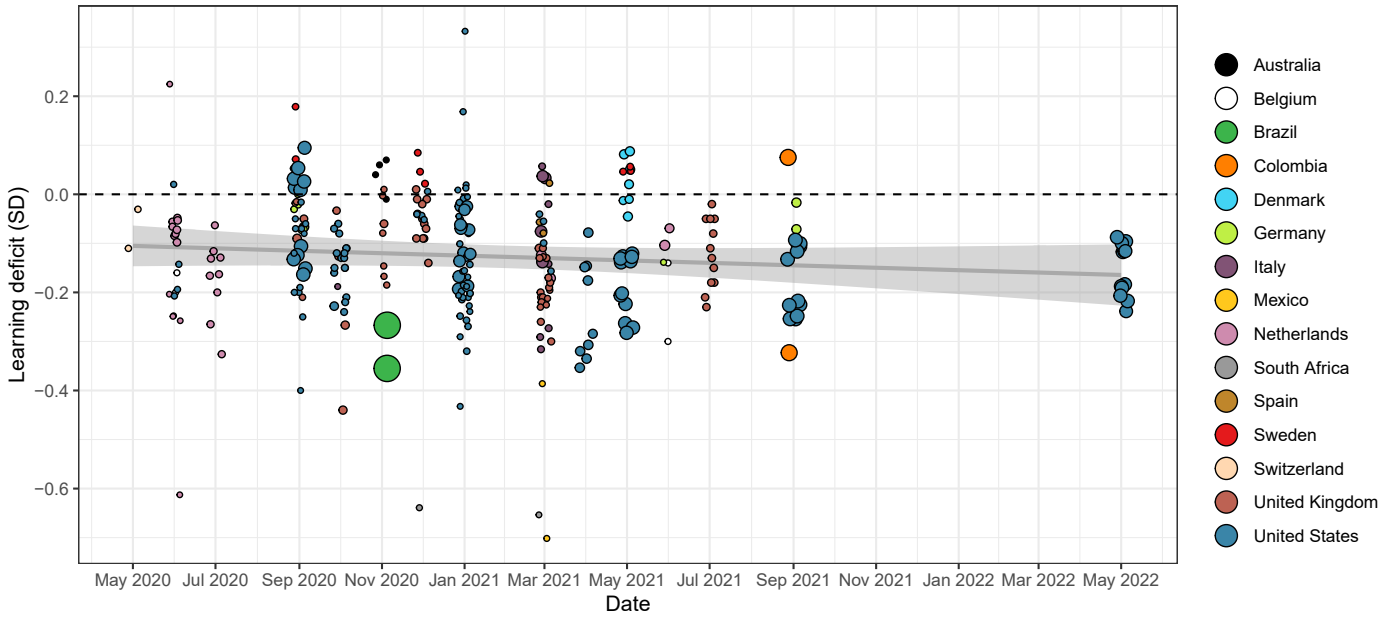

Figure 4: Estimates of COVID-19 learning deficits (n=291), by date of measurement. The horizontal axis displays the date on which learning progress was measured. The vertical axis displays estimated learning deficits, expressed in standard deviations using Cohen's d. The color of the circles reflects the respective country, the size of the circles indicates the sample size for a given estimate, and the line displays a linear trend with a 95% confidence interval.

education, at each stage of the pandemic, and independently of how socio-economic background is measured.

Learning deficits are larger in math than in reading. Available research on summer learning deficits,[58,66] student absenteeism,[67,68] and extreme weather events,[69] suggests that learning progress in mathematics is more dependent on formal instruction than in reading. This might be due to parents being better equipped to help their children with reading, and children advancing their reading skills (but not their math skills) when reading for enjoyment outside of school. Fig. 6A shows that similar to earlier disruptions to learning, the estimated COVID-19 learning deficits are larger for math than for reading (mean difference $\delta = -0.07$, $t = -4.03$, $p = 0.000$). This difference is statistically significant and robust to dropping estimates from individual countries (see Fig. S9).

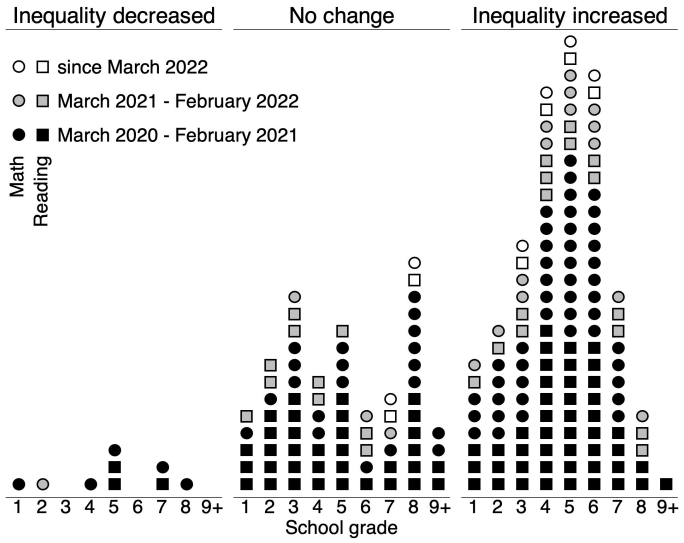

Figure 5: Harvest plot summarizing the evidence on the effect of the pandemic on educational inequality between students from different socio-economic backgrounds. Each circle/square refers to one estimate of over-time change in inequality in math/reading performance (n=211). Estimates that find a decrease/no change/increase in inequality are grouped on the left/middle/right. Within these categories, estimates are ordered horizontally by school grade. The shading indicates when in the pandemic a given measure was taken.

No evidence that learning deficits vary across grade levels. One may expect learning deficits to be smaller for older than for younger children, as older children may be more autonomous in their learning and better able to cope with a sudden change in their learning environment. Fig. 6B shows that, contrary to expectation, we find no evidence of a marked difference in the learning deficits between younger and older students (mean difference $\delta = 0.01$, $t = 0.58$, $p = 0.565$). Note, however, that secondary students were subject to longer school closures in some countries, such as Denmark,[14] based partly on the assumption that they would be better able to learn from home. This may have offset any advantage that older children would otherwise have had in learning from home.

Learning deficits are larger in poorer countries. Low and middle-income countries were already struggling with a learning crisis before the pandemic. Despite large expansions of the proportion of children in school, children in low and middle-income countries still perform poorly by international standards, and inequality in learning remains high.[70,71,72] The pandemic is likely to deepen this learning crisis and to undo past progress. Schools in low- and middle-income countries have not only been closed for longer, but

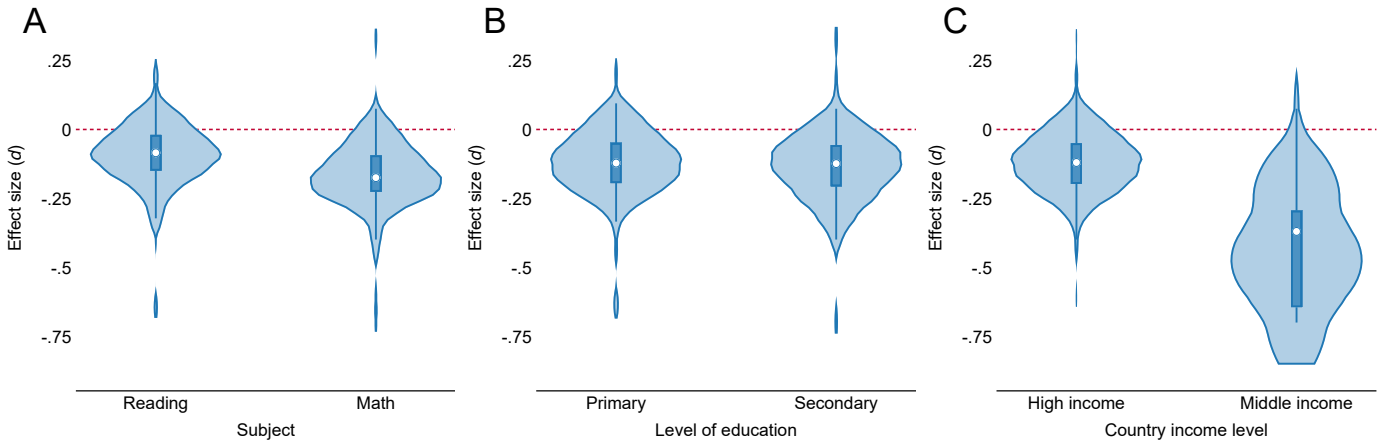

Figure 6: Variation in estimates of COVID-19 learning deficits (n=291) across individual- and country-level characteristics: (A) Learning subject (reading vs. math), (B) Level of education (primary vs. secondary), and (C) Country income level (high vs. middle). Each violin plot shows the distribution of COVID-19 learning deficit estimates for the respective subgroup, with the box marking the interquartile range and the white circle denoting the median.

have also had fewer resources to facilitate remote learning.[73,74] Moreover, the economic resources, ICT equipment and ability of children, parents, teachers, and governments to support learning from home are likely to be lower in low- and middle-income countries.[75]

As discussed above, most evidence on COVID-19 learning deficits comes from high-income countries. We found no studies on low-income countries that met our inclusion criteria, and evidence from middle-income countries is limited to Brazil, Colombia, Mexico, and South Africa. Fig. 6C groups the estimates of COVID-19 learning deficits in these four middle-income countries together (on the right) and compares them to estimates from high-income countries (on the left). The learning deficit is appreciably larger in middle-income countries than in high-income countries (mean difference $\delta = -0.29,\ t = -2.78,\ p = 0.008$). In fact, the three largest estimates of learning deficits in our sample are from middle-income countries[28,22,12] (see Fig. 3).

Discussion

Two years into the COVID-19 pandemic, there is still insufficient knowledge about its consequences for the learning progress of school-age children. This paper makes two main contributions to better understand the state of the evidence. First, it systematically reviews the existing literature on the effect of the pandemic on learning among school-age children and appraises its geographic reach and quality. Second, it harmonizes, synthesizes and meta-analyzes the existing evidence in order to examine the extent to which the pandemic has affected learning, and how this varies across different groups of students and country contexts.

We identify a sizable and growing body of evidence on the effects of the pandemic on learning. However, existing studies primarily focus on high-income countries, while there is a dearth of evidence from low- and middle-income countries. This is particularly concerning because the small number of existing studies from middle-income countries suggest that learning deficits have been particularly severe in these countries. Learning deficits are likely to be even larger in low-income countries, considering that they already faced a learning crisis before the pandemic, generally implemented longer school closures, and were under-resourced and ill-equipped to facilitate remote learning.[76,75,72,73,74] It is critical that this evidence gap on low- and middle-income countries is addressed swiftly, and that the infrastructure to collect and share data on educational performance in middle- and low-income countries is strengthened. Collecting and making available this data is a key prerequisite for fully understanding the effect of the pandemic on learning and related outcomes.[77]

About half of the studies that we identify are rated as having a serious or critical risk of bias. Future studies should minimize risk of bias in estimating learning deficits by employing research designs that appropriately account for common sources of bias. These include a lack of accounting for secular time trends, non-representative samples, and imbalances between treatment and comparison groups. These potential sources of bias may lead existing studies to underestimate of learning deficits.

Our meta-analysis suggests that the COVID-19 pandemic has led to substantial learning deficits. The pooled effect size of $d = -0.14$, implies that students lost out on about 35%, of a school year's worth of learning. This confirms initial concerns that the pandemic would cause substantial harm to student learning.[51,78,79] But our results also suggest that fears of an accumulation of learning deficits as the pandemic continues have not materialized.[80,81] On average, learning deficits emerged early in the pandemic and have neither closed nor widened. Future research should continue to follow the learning progress of cohorts of students affected by the COVID-19 pandemic to reveal how learning deficits of these cohorts develop in different countries.

The persistence of learning deficits two and a half years into the pandemic highlights the need for well-designed, well-resourced and decisive policy initiatives to recover

learning deficits. Policy-makers, schools, and families will need to identify and realize opportunities to complement and expand on regular school-based learning. Experimental evidence from low- and middle-income countries suggests that even relatively low-tech and low-cost learning interventions can have substantial, positive effects on students' learning progress in the context of remote learning. For example, sending SMS messages with numeracy problems accompanied by a short phone call was found to lead to substantial learning gains in numeracy in Botswana.[82] Sending motivational text messages successfully limited learning losses in math and Portuguese in Brazil.[83]

More evidence is needed to assess the effectiveness of other interventions for limiting or recovering learning deficits. Potential avenues include the use of the often extensive summer holidays to offer summer schools and learning camps, extending school days and school weeks, and organizing and scaling up tutoring programs. Further potential lies in developing, improving, advertising and providing access to learning apps, online learning platforms, or educational TV programs that are free at the point of use. Many countries have already begun investing significant resources to capitalize on some of these opportunities. If these implemented interventions prove effective, and if the momentum of existing policy efforts is maintained and expanded, the disruptions to learning during the pandemic may be a window of opportunity to improve and extend the education afforded to children.

Most studies that we identify find that learning deficits have been largest for children from disadvantaged socio-economic backgrounds. This holds across different time points during the pandemic, countries, grade levels, and learning subjects, and independently of how socio-economic background is measured. This suggests that the pandemic has exacerbated educational inequalities between children from different socio-economic backgrounds, which were already large before the pandemic.[84,85] Policy initiatives to compensate learning deficits need to prioritize support for children from low socio-economic backgrounds in order to allow them to recover the learning they lost during the pandemic.

There is a need for future research to assess how the COVID-19 pandemic has affected gender inequality in education. To date, there is very little evidence on this issue, and the large majority of the studies that we identified do not empirically examine learning deficits separately by gender.

Comparing estimates of learning deficits across subjects, we find that learning deficits tend to be larger in math than in reading. As noted above, this may be due to the fact that parents and children have been in a better position to compensate school-based learning in reading by reading at home. Accordingly, there are grounds for policy initiatives to prioritize the compensation of learning deficits in math and other science subjects.

Our analysis provides important evidence of how the COVID-19 learning deficit has varied between different groups of students and across country contexts. Given the limited reach of the existing evidence, we do not seek to identify the causal role of specific factors. A fruitful avenue for future research will be to use quasi-experimental designs to reveal how specific factors can account for individual and society-level variation in the extent of COVID-19 learning deficits. The considerable variation in learning deficits across sub-populations and country contexts that we find highlights the need to better understand this variation, and identify mechanisms that can guide policy measures for limiting and counteracting learning deficits.

Methods

Eligibility criteria. We consider all types of primary research, including peer-reviewed publications, preprints, working papers, and reports for inclusion. To be eligible for inclusion, studies have to measure learning progress using test scores that can be standardized across studies using Cohen's *d*. Moreover, studies have to be in English, Danish, Dutch, French, German, Norwegian, Spanish or Swedish.

Search strategy and study identification. We identify eligible studies using the following steps. First, we developed a Boolean search string defining our population (school-aged children), exposure (the COVID-19 pandemic), and outcomes of interest (e.g., math and reading). The full search string can be found in Section 1 of the Supplementary Information. We used this string to search the following academic databases: Coronavirus Research Database, Education Database, ERIC, International Bibliography of the Social Sciences (IBSS), Politics Collection (PAIS index, policy file index, political science database, and worldwide political science abstracts), Social Science Database, Sociology Collection (applied social science index [ASSIA] and abstracts, sociological abstracts, and sociology database), CINAHL, and Web of Science. Our initial search was conducted on April 27, 2021. Second, we hand-searched multiple preprint, working paper, and policy document repositories (SSRN, MPRA, IZA, NBER, OSF Preprints, PsyArXiv, SocArXiv, and EdArXiv) and relevant policy websites, including, but not limited to, the websites of the Organisation for Economic Co-operation and Development, the United Nations, the World Bank, and the Education Endowment Foundation. Third, we periodically posted our protocol via Twitter in order to crowdsource additional relevant studies not identified through the search. Last, to ensure that our analysis is comprehensive in terms of recent and relevant research, on February 14, 2022, and on August 8, 2022, we conducted two comprehensive forward and backward citation searches of all eligible studies identified in the above steps.

Data extraction. From the studies that meet our inclusion criteria we extract all estimates of the effect of the pandemic on learning progress, separately for math and reading and for different school grades. We also extract the corresponding sample size, standard error, date(s) of measurement, author name(s), and country. Last, we record whether studies differentiate between children's socio-economic background, which measure is used to this end, and whether studies find an increase, decrease or no change in learning inequality. We contacted study authors, if any of the above information was missing in the study. Data extraction was

performed by the first author and validated independently by the second author, with discrepancies resolved through discussion and by conferring with the third author.

Measurement and standardization. We standardize all estimates of the effect of the pandemic on learning using Cohen's d, which expresses effect sizes in terms of standard deviations. Cohen's d is calculated as the difference in the mean learning gain in a given subject (math or reading) over two comparable periods before and after the onset of the pandemic, divided by the pooled standard deviation of learning progress in this subject:

$$d = \frac{\bar{x}_1 - \bar{x}_2}{s},$$

where

$$s = \sqrt{\frac{(s_1^2 + s_2^2)}{2}}.$$

Effect sizes expressed as β coefficients are converted to Cohen's d:

$$d = \frac{\beta}{se} \times \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}.$$

Subject. We use a binary indicator for whether the study outcome is math or reading. One study does not differentiate the outcome but includes a composite of math and reading scores.[31]

Level of education. We distinguish between primary and secondary education. We first consulted the original studies for this information. In cases where it was not stated in a given study, students' age was used in conjunction with information about education systems from external sources to determine the level of education.[86]

Country income level. We follow the World Bank's classification of countries into four income groups: low, lower-middle, upper-middle, and high-income. Four countries in our sample place are in the upper-middle group: Brazil, Colombia, Mexico and South Africa. Remaining countries are high-income.

Data synthesis. We synthesize our data using three synthesis techniques. First, we generate a forest plot, based on all available estimates of the effect of the pandemic on learning. We pool estimates using a random-effects REML model and inverse variance weights to calculate an overall effect size (see Fig. 3).[87] Second, we code all estimates of the effect of the pandemic on educational inequality between children from different socio-economic backgrounds, according to whether they indicate a positive, negative, or no effect. We visualize the resulting distribution using a harvest plot (see Fig. 5).[88] Third, given that the limited amount of available evidence precludes multivariate or causal analyses, we examine the bivariate association between COVID-19 learning deficits and the months in which learning was measured (see Fig. 4) learning subject, grade, and countries' income level, using a series of violin plots (see Fig. 6). The reported estimates, confidence intervals and statistical significance tests of these bivariate associations are based on common-effects models with standard errors clustered by study, and two-sided tests.

Pre-registration. We prospectively registered a protocol of our systematic review and meta-analysis in the International Prospective Register of Systematic Reviews (CRD42021249944) on 19 April 2021.

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