Computers and Education Open 2 (2021) 100047

Contents lists available at ScienceDirect

Computers and Education Open

journal homepage: www.sciencedirect.com/journal/computers-and-education-open

The evolution of the association between ICT use and reading achievement in 28 countries

Francesca Borgonovi [a,*], Magdalena Pokropek [b]

[a] Social Research Institute, Institute of Education, University College London, 55-59 Gordon Square, London WC1H 0NU, United Kingdom
[b] Educational Research Institute (IBE), ul. Górczewska 8, 01-180 Warszawa, Poland

ARTICLE INFO

Keywords:
ICT use
Reading achievement
Trends
Cross-country
PISA

ABSTRACT

This paper examines the evolution of 15-year-old students' use of information and communication technologies (ICT) for fun and for learning at school and at home between 2009 and 2018. It also considers how the association between ICT use and reading achievement evolved over the same period. Results indicate that ICT use increased and that the increase was especially marked when considering ICT used for learning (both at school and at home). Boys increased their use of ICT for fun and for learning at school more than girls. Trends in ICT use did not differ by parental educational attainment. Over the same period, no quantitatively meaningful changes in reading achievement were observed. In line with the previous literature, we find that the association between different forms of ICT use and reading achievement takes an inverted U shape, with students engaging in low and high levels of use having lower levels of reading achievement than students engaged in medium levels of use. Over time, the association between different uses of ICT and reading achievement changed and became more positive at low levels and less negative at high levels of use. However, the large and rapid increases in levels of use observed between 2009 and 2018 led to more students being located in the 'high levels of use' category. The cumulative, contrasting effects of changes in levels of use and changes in the association between ICT use and reading achievement led to stable levels of achievement at the population level.

1. Introduction

Past research has considered the effects of information and communication technology (ICT) use on children's academic skills, non-cognitive skills, and social and emotional well-being [2, 12, 36, 44, 61, 75, 81]. Findings from such literature generally paint a mixed picture with some studies detailing worse outcome among children who use ICT for fun or for academic activities, and others detailing no differences in outcomes between those who use ICT and those who do not. Such differences have been considered to arise because of differences in associations depending on user characteristics, intensity of use and content of use [81].

In this work we exploit unique repeated cross-sectional data from the Programme for International Student Assessment (PISA) on reading achievement and ICT use, to derive indicators of ICT use that are comparable over time and explore variations in the evolution of the association between different forms of ICT use as well as the changing association between ICT use and reading achievement. The contribution of our work is twofold. First, we map changes between 2009 and 2018 in the use of ICT among large-representative samples of 15-year-old students in 28 countries worldwide. We consider changes in three forms of ICT use: ICT use for fun, ICT use for learning at school, and ICT use for learning at home. We highlight changes in patterns of use across key demographic groups: boys and girls and students with and without at least one parent educated at the tertiary level. Second, we identify changes in the contemporaneous association between different forms of ICT use and the reading achievement of 15-year-old students and if such association changed between 2009 and 2018.

We consider the association between ICT use and reading achievement because reading proficiency is necessary to acquire knowledge, and as such, is a precondition for individuals' success in other academic subjects, education and beyond [19,72]. Moreover, the development of reading proficiency is especially dependent on the activities children engage in outside of school, such as, for example, if they read in their free time [16]. There is evidence that patterns of engagement with reading activities changed markedly in the past decade, at least in part as a result of widespread use of technologies [32,50,71]. Teenagers report lower overall levels of reading for enjoyment and increases in the

* Corresponding author.
E-mail address: F.borgonovi@ucl.ac.uk (F. Borgonovi).

https://doi.org/10.1016/j.caeo.2021.100047
Received 21 April 2021; Received in revised form 9 July 2021; Accepted 15 August 2021
Available online 18 August 2021

amount of reading they conduct using digital devices [16, 71, 76].

2. Past Literature

2.1. Disparities in ICT use

Digital technologies are becoming increasingly widespread in societies, and new devices such as smartphones and smartwatches allow individuals to access information anytime, anywhere. As a result, there has been a sustained growth in the use of ICT devices by children in everyday life and at school [58], although there is no robust cross-country evidence on trends in patterns of use of different forms of ICT, i.e. ICT for fun, ICT for learning at school and at home. The increasing availability of ICT in many countries has reduced socio-economic differentials in overall access to digital technologies, but disparities in ICT use whether for fun or for learning still exist [8,34,80]. Disparities among children in ICT use can be due to disparities in access to ICT devices and hardware related to socio-economic status as well as disparities in ICT skills and familiarity among children and parents as well as attitudes towards ICT [80]. As a result, disparities by socio-economic status and by gender may have widened over time when considering frequency of use and in what ICT is used for [6, 81]. Evidence indicates that children with a socio-economically advantaged background use the internet more often for informational purposes and are more likely to engage in what have been described as "capital--enhancing" ICT activities compared to their socio-economically disadvantaged counterparts [85–87] . Similarly, the gender gap in videogaming in favour of boys appears to have widened over time, despite increasing use among both genders [6]. The review of the past literature leads us to expect that ICT use both for fun and for learning at home and at school increased between 2009 and 2018 among all groups. Furthermore, based on past cross-sectional empirical research we do not expect to observe large differences in different forms of ICT use across children with a different socio-economic condition. By contrast, we expect to observe growing gender gaps in ICT use for fun while we do not have strong a priori expectations on the evolution of gender gaps in the use of ICT for learning at school and at home.

2.2. The association between ICT use and reading achievement

The increase in the availability of digital technologies and diversification of devices and applications, coupled with the recognition that mastering such technologies is important in the labor market [15], has prompted many educators to promote the use of ICT in schools [65]. The aim of such efforts is to exploit potential benefits of ICT to promote students' learning but also to equip students with digital literacy, a key competence for successful participation in society and the labor market [13, 31].

Although in recent years considerable investments in ICT resources have been made in many education systems, there is little evidence about how much they changed the practice of use of ICT for learning [58]. Moreover, although there is evidence on the contemporaneous association between ICT use and academic achievement among specific cohorts of students, it remains unclear how this association evolved over time following changes in patterns of use at the individual and collective level, and development in technologies. This is especially relevant because empirical analyses indicate that the association between ICT use and achievement follows an inverted U shape. For example, the literature indicates that students who use ICT for fun and for learning activities in moderation achieve at a higher level than those who use ICT rarely or intensively [88];[58,75,88]. Changing patterns of use and changes in the intensity of use over time could therefore lead to changes in the association between ICT use and reading achievement as increasing numbers of children move from low to moderate use but also from moderate to high levels of use. However, the very shape of the association could change because effects could be relative, rather than absolute. This could occur if, for example, children who use ICT extensively have the tendency to develop behaviors that are associated with low achievement (such as multitasking, not reading instructions) [81] and only when large numbers of children engage in such practices educators recognize the problem and put in place strategies to remedy the situation.

Becoming a proficient reader requires the mastery of progressively more difficult tasks [40]. In particular, when students move from primary into secondary school, the knowledge demands they experience and the tasks they have to master become harder, while the level of support they receive typically decreases [3, 28]. At higher grade levels being a skilled reader involves being an independent reader who is able to deploy effective reading strategies to access texts of increasing complexity and variety [60]. As such, ICT use could be useful to ensure that students put the effort and energy that are necessary to persist in their studies by promoting their engagement and motivation, especially when ICT plays a large part in young people's non-academic lives [64].

It has been argued that in a world with a high degree of ICT penetration, young people's interest in and engagement with ICT stands in marked contrast to their perception of curricular content and that ICT should be embedded in teaching as a way to satisfy the intellectual, emotional and motivational needs of students [70]. The adoption of features typical of video-games or other ICT applications for learning both in classrooms and for self-study has therefore been considered as a way to increase interest, making learning more enjoyable for students [64]. Interestingly, many youngsters prefer to use paper rather than digital devices to learn. This might indicate that although they may feel motivated by ICT in the abstract, they may also experience greater cognitive strain and fatigue being associated with using ICT for learning [101]. Moreover, there may be a disparity between the sophisticated technological opportunities available in day to day settings and the unsophisticated technology use for learning promoted by schools and educators. This disparity could lead to alienation and disaffection among students [66].

Furthermore, because ICT allows individuals to perform multiple tasks using the same medium, using ICT for learning could lead to distraction, either because students might try to multitask, or because they might switch their attention across several tasks. Multitasking is defined as the simultaneous processing or execution of two or more tasks, although from a behavioral and neurocognitive perspective multitasking can be assimilated with rapid task-switching [81]. When individuals engage in different tasks in rapid succession, their attention is inevitably shared across tasks [18,29] leading to poorer academic result, attitudes, and perceived learning [79]. ICT multitasking may limit the amount of attention available for the simultaneous processing of academic content [38] and displace the amount of time dedicated to academic activities [30].

2.3. Describing the association between different forms of ICT use and reading achievement: theoretical considerations

The association between different forms of ICT and reading achievement could differ depending on the form of ICT use being considered – whether ICT is used for fun, for learning at home or for learning at school and over time. This is because different forms of ICT use could displace different activities and because different forms of ICT use could promote the development of different skills.

2.3.1. Displacement effects

Proponents of the displacement hypothesis predict that ICT use will have negative effects on reading achievement if time spent on ICT devices is time not spent on activities that are strongly and positively associated with improved reading abilities such as, for example, reading for enjoyment [82] and sleep [41]. As such, they indicate that the observed association between specific forms of ICT use and reading achievement will be the result of the type of activities that each form of

ICT use displaces. This means that what matters when considering the effect of using ICT for reading achievement is the relative productivity of time investments in the use of specific forms of ICT compared to other time investments.

The displacement hypothesis could explain the finding in the literature detailing a strong negative association between the use of ICT for learning at home and academic achievement but no association or even a positive association between the use of ICT for fun and academic achievement [58]. This could occur if the use of ICT for learning at home displaced engagement in self-study but the use of ICT for fun did not, because it substituted other types of leisure activities, and learning through ICT at home was less positively associated with reading achievement than learning that occurs without the aid of ICT. It could also explain the inverted U shape identified in the literature between ICT use for fun, for learning at home and at school and achievement, indicating that individuals with no or extensive use of ICT have lower achievement than those with moderate levels of ICT use. High levels of ICT use are in fact most likely to displace other activities and, if the marginal returns to time investments in a specific activity decrease with use, it will result in lower achievement. By contrast, because the use of ICT, whether for fun or for learning at home and at school generally involves reading, medium levels of use could complement other reading activities and, as such, be associated with better reading achievement compared to no or very limited use.

The displacement hypothesis leads us to hypothesize that, other things being equal, high levels of ICT use for fun and for learning, whether at home or at school, will be associated with worse reading achievement. By contrast, we expect that individuals using ICT moderately, whether for fun and for learning at home or at school, will have higher reading achievement than individuals who do not engage with ICT. At the population level, the displacement hypothesis leads us to expect that overall increases in ICT use over time will be associated with worse overall outcomes, as more individuals are in the descending part of the inverted U shaped distribution characterizing the association between ICT use and reading achievement. By contrast, no predictions can be made on the basis of the displacement hypothesis as to whether the same level of use is associated with different achievement levels at different points in time.

2.3.1. Learning effects

There is empirical evidence pointing towards screen inferiority with respect to the use of digital environments for learning. Although some studies have found equivalence between learning processes that occur using paper aids and computerized aids [7,53,56,69], the literature generally indicates that learning from continuous texts is less effective when performed using computers rather than paper [1,21,52]. Crucially, studies examining the relative learning gain obtained through paper-based and computerized study identify screen inferiority even when learning is evaluated using tests that contain stimuli that require the use of ICT devices and ICT familiarity, such as comprehending texts containing hypertexts [24], sound, animation, and interactive reading [54]. Therefore, the use of ICT for learning whether in the classroom or for self-study could remain less effective in promoting reading achievement even as computer-based tests are used to assess reading achievement. Screen inferiority in the development of text comprehension abilities has been hypothesized to be the result of technological disadvantages inherent to some digital devices as well as physical discomfort, such as eye strain [9,45,47]. However, screen inferiority has been identified even when modern devices designed to overcome technological and physical disadvantages are used [21,35].

The literature on the use of ICT for fun, such as the literature on videogames, suggest that the use of ICT for fun can have cognitive benefits [89][89]: for example videogames promote informal exploratory learning and can enhance problem-solving skills [22]. Research has highlighted that different patterns of ICT use for fun, such as playing videogrames, could be associated with narrower gender gaps in digital reading than in print reading [14]. Proponents of the learning to learn hypothesis argue that gaming can be used to enhance broad aspects of cognition, and can lead to general improvements in attentional capacity, cognitive control, pattern recognition, problem-solving abilities, and more efficient learning strategies [90–92]. In fact, numerous studies have identified improvements on specific measures of visuospatial cognition after short periods of playing video games (see [81] for a review). Although the literature on the cognitive consequences of videogame use is by far the largest strand of the broader literature on ICT used for fun and academic achievement, there have been studies examining the association between social media use and academic results. Findings from the literature on social media are also mixed: some studies suggest that engaging in social media could improve some aspects of academic achievement and cognitive skills [4], while others point to a positive correlation with literacy but negative with average grades [48], or even a negative association [20].

The cognitive benefits of ICT for fun detailed above are likely to be especially important when reading achievement is assessed using computer-based tests [14]. Digital reading requires a unique set of skills [33, 46], comprising not only the capacity to comprehend and interpret extended pieces of continuous texts, but also the capacity to analyze, synthesize, integrate and interpret relevant information from multiple texts and information sources [67,74]. As digital technologies and their use become pervasive, teenagers are increasingly required to apply their skills to read digital material to solve problems on computers [17, 39, 84] and, as such, the cognitive benefits of ICT use may become more pronounced.

The increasing awareness of how students process written information, coupled with improvements in both teachers' familiarity with ICT and the quality of ICT applications for educational purposes lead us to expect that over time ICT use for learning at school and at home will be associated with better reading achievement. Furthermore, since 2015 when the PISA assessment became computer-based, we expect that over time learning effects will grow larger also when considering the use of ICT for fun. The review of the literature in fact suggests that some of the skills children develop while using digital applications for leisure are important for digital reading.

3. Aim and Research Questions

Informed by the rich literature on the association between ICT use and achievement, the main objective of this paper is to identify how the use of ICT for fun, ICT for learning at school and ICT for learning at home changed between 2009 and 2018 and how the association between different forms of ICT use and reading achievement changed over time. To do so, we develop comparable measures of ICT use and relate these measures to reading achievement as measured through the PISA large-scale standardized assessment. The empirical analyses answer the following questions:

1) Did the use of ICT for learning at school and at home and the use of ICT for fun among 15-year-old students increase between 2009 and 2018 and, if so, which form of use increased the most?

2) Did changes in patterns of use differ across boys and girls and across students with and without highly educated parents?

3) Did the association between different forms of ICT use and reading achievement change between 2009 and 2018?

4. Data

4.1. PISA

PISA is a low-stake international large-scale assessment that has been administered to samples of 15-year-old students every three years since 2000. PISA involves large-representative samples of students from countries that vary widely in cultural, linguistic and social background, level of economic development, technological adoption and in how the education system is organized.

4.2. Participants

Our data come from the 2009, 2012, 2015 and 2018 editions of PISA. All cases used in our analyses were extracted from the public-use files, which can be downloaded from: http://www.oecd.org/pisa/data. Weighted samples are representative of students who are enrolled in grade 7 or above and are between 15 years and 3 months and 16 years and 2 months at the time of the assessment administration (generally referred to as 15-year-olds in this work). In each cycle, PISA participants are selected from the population of 15-year-old students in each participating country according to a two-stage random sampling procedure. The PISA technical standards require that in a first stage, a stratified sample of schools is drawn and that, in a second stage, students are selected at random in each sampled school.

The number of countries participating in the PISA study widened over time: in 2009 65 education systems took part in the study and by 2018 79 did. Since our analyses aim to identify changes in the use of ICT over time and changes in the strength of the association between ICT use and reading achievement, our sample is restricted to the subset of countries that participated in each of the four PISA editions that were administered between 2009 and 2018 and that administered the optional ICT familiarity questionnaire. Furthermore, we removed from our sample all students who reported having an immigrant background. This is because PISA allows to capture the characteristics of students with an immigrant background only in part, and between 2009 and 2018 the composition of foreign-born populations changed greatly in many OECD countries. Our analytic sample includes a total of 702,023 students in 28 countries over the four cycles.

4.3. Instruments

The PISA program consists in a series of repeated cross-sectional surveys administered every three years. In each assessment cycle participating students take part in a timed, two-hour test. After they complete the test they have a short break and then complete a questionnaire. The intention of the study is to collect information that can be compared across participating countries but also over time. In order to achieve this, in each cycle, the test contains some questions that were administered in previous cycles and the remaining new questions are selected with the aim of adhering to the underlying assessment frameworks in the assessment domains (such as reading, mathematics and science). Furthermore, statistical tests are conducted to identify the psychometric properties of each question during a field trial administration. Questions not meeting standards are discarded and not used in the main study administration.

The key assessment domains in PISA are reading, mathematics and science. Each participating student is administered, at random, a test form containing a range of assessment material. In each cycle, one of the three key PISA domains is the main domain and a larger set of test questions in that domain is administered. Reading was the main assessment domain in 2009 and 2018, mathematics was the main domain in 2012 and science was the main assessment domain in 2015. Until 2012 the core assessment was delivered as paper-and-pencil while in 2015 PISA transitioned to computer-based delivery. A mode effect study was conducted to estimate if the move to computer delivery influenced results thus limiting the comparability of achievement scores over time [59]. The study indicated that assessment instruments were comparable in the two modes of administration.

In PISA, background questionnaires complement the test. The main student questionnaire is designed to capture students' demographic and socio-economic characteristics, including parental education and occupational status, their and their parents' country of birth, household possessions. Moreover, students are asked detailed questions about their attitudes towards learning, their engagement in academic activities, as well as information about their school, peers and teachers. PISA is a flexible instrument, meaning that, on top of the main student questionnaire administered to all students in all countries, countries can decide to administer additional optional questionnaires developed at the international level, as well as national options. Among the international options that have been regularly offered for administration is the ICT familiarity questionnaire. The questionnaire was designed to identify students' use of ICT for fun and for learning, as well as students' attitudes towards various technologies.

4.4. Variable Descriptions

As an indicator of academic achievement, we use the PISA reading achievement scores. PISA test scores are included in the PISA datasets as multiply imputed measures of proficiency ("plausible values"). PISA test scores are based on item-response-theory scaling procedures and are comparable across students taking different test forms and taking the test in different editions. Reading was the main assessment domain in 2009 and 2018, meaning that a large set of questions in the PISA test were reading questions. In 2012 and 2015, when mathematics and science were the main assessment domains, the amount of assessment tasks in reading was smaller but estimates remain comparable with 2009 and 2018. In 2009 and 2012, a set of five plausible values were estimated while in 2015 and 2018 a set of 10 plausible values were reported.

We consider three types of use of ICT: ICT used for fun, ICT used for learning at home and ICT used for learning at school. Students were asked to report the frequency with which they engaged in a range of activities using the following thresholds: never or hardly ever; once or twice a month; one or twice a week; every day or almost every day.

Activities considered when probing students to report their engagement with ICT For fun included: (1) playing one-player games; (2) playing collaborative online games; (3) using e-mail; (4) chatting online; (5) browsing the internet for fun; (6) downloading music, films, games or software from the Internet;

Activities considered when probing students to report their use of ICT for learning at home included: (1) browsing the Internet for schoolwork (e.g. preparing an essay or presentation); (2) using e-mail for communication with other students about schoolwork; (3) using e-mail for communication with teachers and submission of homework or other schoolwork; (4) downloading, uploading or browsing material from your school's website (e.g. time table or course materials); (5) check the school's website for announcements, e.g. absence of teachers; (6) doing homework on a computer.

Activities considered when probing students to report their use of ICT for learning at school included: (1) chatting on line at school; (2) using e-mail at school; (3) browsing the Internet for schoolwork; (4) downloading, uploading or browsing material from the school's website; (5) posting your work on the school's website; (6) playing simulations at school; (7) practicing and drilling, such as for foreign language learning or mathematics; (8) doing individual homework on a school computer; (9) using school computers for group work and communication with other students.

Gender is a key individual-level independent variable. This variable was reported by students in the background questionnaire. In all models we report differences in outcomes associated with being a female. We also introduce an indicator that takes value 1 when students report in the main questionnaire that at least one of their parents obtained tertiary qualifications and value 0 whenever students report that neither of their parents obtained tertiary qualifications.

4.5. Methods

4.5.1. Measurement Invariance and Scaling the Main Constructs

The aim of our work is to examine differences in ICT use across years combining information from 28 countries. This is possible only if measurement invariance (also referred to as measurement equivalence in the literature) is established. Meaningful comparisons of means or associations like covariances and unstandardized regression coefficients across time points from different countries can only be conducted in the presence of measurement equivalence [93–96]. In other words, measures of ICT use that are comparable across countries and over time are needed to identify trends in different forms of ICT use, if these differ across population groups, and if the association between ICT use and reading achievement changed between 2009 and 2018.

The classical approach to test measurement invariance is Confirmatory Factor Analysis (CFA) assuming full metric or full scalar invariance. However, full metric and scalar invariance are rarely achieved in practice. A solution is to adopt a partial equivalence approach. In the partial equivalence approach some item parameters are constrained to be equal across groups, whereas others are estimated freely, therefore relaxing some of the assumptions and constraints needed in the classical, full invariance analysis framework. Indicators constructed using partial equivalence have been shown to perform very well in simulation studies [98]. Furthermore, partial equivalence reflects well the situation in real life applications in which many of the items that make up an index are comparable and display full measurement invariance properties, but a selected number of items are non-invariant [95]. In recent years, the concept of approximate measurement invariance (AMI) has also gained considerable attention [97]. The AMI postulates that estimations of reliable and comparable parameters for different groups in multiple-group models is possible despite small "natural" differences between item parameters from different groups. A combination of AMI and partial invariance appears most promising when the objective is to develop comparable indicators across a large number of diverse groups: such combination allows to consider exact measurement invariance for some parameters, exact measurement non-invariance for some other parameters, and approximate measurement invariance for the remaining parameters.

As a result, we used confirmatory factor analysis (CFA) with alignment optimization [97][57,63,97] to construct measures of ICT use that satisfy partial approximate invariance. Alignment optimization replaces cross-country equality constraints with a procedure similar to rotation in Explanatory Factor Analysis (EFA). An iterative algorithm estimates a solution that minimizes overall differences between group parameters and adjusts factor means and variances. In the end the algorithm determines a solution that has a model fit that is equal to those obtained using the configural model but also guarantees the maximum level of comparability. Simulation studies show that this method can successfully recover the group parameters even in the presence of a substantial number of non-invariant items when these are accompanied by small differences for the rest of the items [97,98] [63,97,98].

Because the alignment procedure generates results that, by design, fit to the data as well as the configural model, meaningful fit indices cannot be produced. We followed the methodological recommendations to assess the reliability of indices proposed by Asparouhov & Muthén [97] and tested the performance of alignment optimization models in the construction of PISA's ICT indicators using simulation studies. Simulations were performed according to guidelines developed by Asparouhov and Muthén [97]. In the first step we randomly generated 100 datasets that reflected the data structure in the estimation sample. For data generation we used the final parameters from fixed alignment estimation. In the second step, we used these data sets as input to estimate CFA with alignment optimization and construct each index of ICT use. For each of the 100 replications, we computed correlations between true group means and variances (used for generating the data) and estimated group means and variances. We also computed the mean square error (MSE) between true and estimated parameters. Correlations and MSEs were than averaged over replications. The correlation measure was promoted by Asparouhov and Muthen [5] as a simple measure of reliability of latent means estimated using a specific method. Asparouhov and Muthen [5] suggest that correlations larger than 0.98 indicate reliable rankings of groups. MSE provides an overall measure of accuracy of the parameter estimation. Results of the simulations are presented in Table 1

Results presented in Table 1 indicate high overall correlations between the values obtained with CFA with alignment optimization and values estimated from simulations of means and variances, and relatively low MSEs. This is an indication that the measurement model used to construct the indices guided by approximate measurement invariance assumptions provides reliable measures of indices of ICT use both in terms of cross-time and cross-country comparisons. As a result, Table 1 confirms the validity of comparisons.

4.5.2. Modelling relations between ICT and Reading Achievement

In order to estimate trends over time in ICT use we standardized all ICT use variables so that in 2009 the mean of each index would be zero and the standard deviation would be one on average across the countries in our sample. To investigate differences in trends in ICT use we compared mean levels between boys and girls and between students with and students without at least one tertiary educated parent. To estimate the association between different forms of ICT and reading achievement we fitted a series of regression models on the pooled sample of 28 countries and included country fixed effects in which reading achievement, standardized to have a mean of zero and a standard deviation of one across countries in 2009 was regressed on each indicator of ICT use, gender and parental educational attainment.

Regression models considered the PISA complex sampling design through balanced Taylor linearization [23]. Furthermore, because reading achievement is expressed in terms of plausible values [99]all estimates were conducted using multiple imputation methodology. This involved fitting five sets of models, each with one plausible value, and then combining these values using the Rubin rule [100][100] as per OECD recommendations. We employed linear regression with three-degree polynomials to capture nonlinear relations and used marginal effects to depict the relations between ICT indices and reading abilities [83].

In order to quantify differences between ICT and reading competencies in an easily interpretable way, we fitted piecewise regressions [55]. Piecewise regression allowed us to specify different intercepts and different linear slopes for values of each ICT index below/above zero. For each indicator of ICT use four piecewise regressions models are presented. In model 1 estimates describe associations controlling for background characteristics (gender and parental education), country fixed effects and year fixed effects. In model 2 controls for additional forms of ICT use were added. In model 3 interactions between indicators of ICT use and the year in which the survey took place were added (but not other forms of ICT use) and in model 4 all controls were added.

5. Results and Discussion

5.1. The evolution of ICT use

Fig. 1 illustrates changes between 2009 and 2018 in levels of ICT use as well as changes in PISA reading scores over the same period among

Table 1
Correlations and Mean Square error of population and estimated values using CFA with alignment optimization

Variable		Correlations		Mean square error	
		Average	Std. Dev.	Average	Std. Dev.
ICT for fun	Mean	0.9938	0.0009	0.0361	0.005
	Variance	0.9840	0.0010	0.0959	0.007
ICT for learning at home	Mean	0.9945	0.0008	0.0657	0.017
	Variance	0.9922	0.0010	0.0603	0.014
ICT for learning at school	Mean	0.9978	0.0003	0.2183	0.017
	Variance	0.9968	0.0004	0.0860	0.025

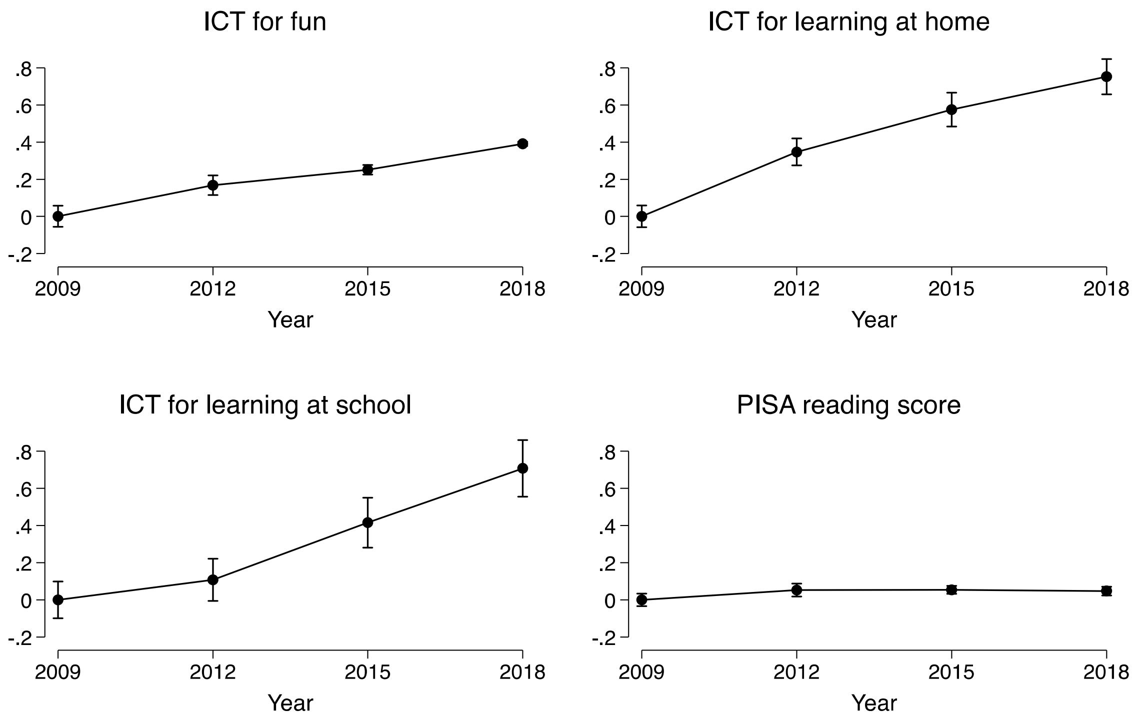

Fig. 1. Trends in levels of ICT use and reading achievement between 2009 and 2018, OECD average

15-year-old students in OECD countries. Although PISA reading scores remain flat over the period, ICT use increased markedly over time, and the rate of such increase differed depending on the type of ICT use considered. More specifically, the increase in the use of ICT for fun was small when compared to the steep increase in the use of ICT for learning occurring in the home setting and in school settings. In 2009 the value of the index of ICT use for fun was fixed to a mean of 0 points. By 2018 it had grown by 39% of a standard deviation. By contrast, the value of the ICT use for learning at home index grew by 75% of a standard deviation between 2009 and 2018, and the mean value of the ICT use for learning at school index grew by 71% of a standard deviation in the same period. The different patterns could reflect, in part, the fact that ICT was already highly used for fun in 2009 and therefore there was less room for marked increases given students' overall time availability. In any case they indicate that the use of ICT for academic purposes whether in school settings or at home was already increasing rapidly before the COVID-19 pandemic hit in 2020.

5.2. Heterogeneity in the evolution of ICT use

In line with the literature on gender differences in reading achievement and the literature on socio-economic disparities in academic achievement, Fig. S1 and 5 indicates that girls outperform boys in reading (on average by 41% of a standard deviation) and Fig. S2 indicates that children with tertiary educated parents outperform children with no parent who achieved tertiary level qualifications (on average by 43% of a standard deviation). Furthermore, results presented suggest that gender differences in favor of girls narrowed over the period and so did differences by parental educational attainment.

Fig. S1 in the Supplementary Online Annex further reveals that boys are more likely to use ICT than girls, particularly for fun and for learning at school and that gender differences in all uses of ICT widened between 2009 and 2018, although among girls between 2015 and 2018 the increase in ICT use for fun became more pronounced approaching rates of increase observed among boys. As a result, the gender gap in the use of ICT for fun increased from 16% of a standard deviation in 2009 to 28% of a standard deviation in 2012, 47% of a standard deviation in 2015 and 43% of a standard deviation in 2018. Increases in the use of ICT for learning at home was similar among boys and girls in 2009, it increased in a similar way among both boys and girls between 2009 and 2012 but after 2012 the increase among boys outpaced that observed among girls. As a result, the gender gap in ICT use for learning at home changed from 2% of a standard deviation in favor of boys in 2009, 2% of a standard deviation in favor of girls in 2012; 12% of a standard deviation in favor of boys in 2015 and 17% of a standard deviation in favor of boys in 2018. A similar pattern can be observed with respect to the use of ICT for learning at school: gender differences were small and imprecisely estimated in 2009 and 2012, but after 2012 the use of ICT for learning at school increased markedly, especially among boys. The gender gap in ICT used for learning at school changed from 17% of a standard deviation in 2009, 20% of a standard deviation in 2012, 31% of a standard deviation in 2015 and 35% of a standard deviation in 2018. By contrast, Fig. S2 in the Supplementary Online Annex suggests that differences in trends in ICT use among 15-year-old students with tertiary and without tertiary educated parents differed little.

Figs. 2, 3, 4 and S3 in the Supplementary Online Annex indicate that between 2009 and 2018 there were marked changes not just in the average levels of reading achievement and ICT use but especially in the distributions of reading achievement and ICT use in the population of 15-year-old students. On average, reading achievement changed little over the period. However, especially since 2015, the distribution became considerably flatter and the standard deviation increased as fewer students had levels of performance that were closer to the average and a larger number of students had achievement scores that were either very much below or very much above the average.

In 2009 the distribution of students' use of ICT for fun was left skewed but with a sizable number of students displaying very low and low levels of use, and many students reporting high levels of use. The increase in average levels of use of ICT for fun that occurred between 2009 and 2018 was due to a remarkable change in the distribution of use over the period: by 2018 almost no student reported very low levels of use and the vast majority of students reported levels of use that were just below or well above the average use observed in 2009.

By contrast, the distributions of use of ICT for learning either at home

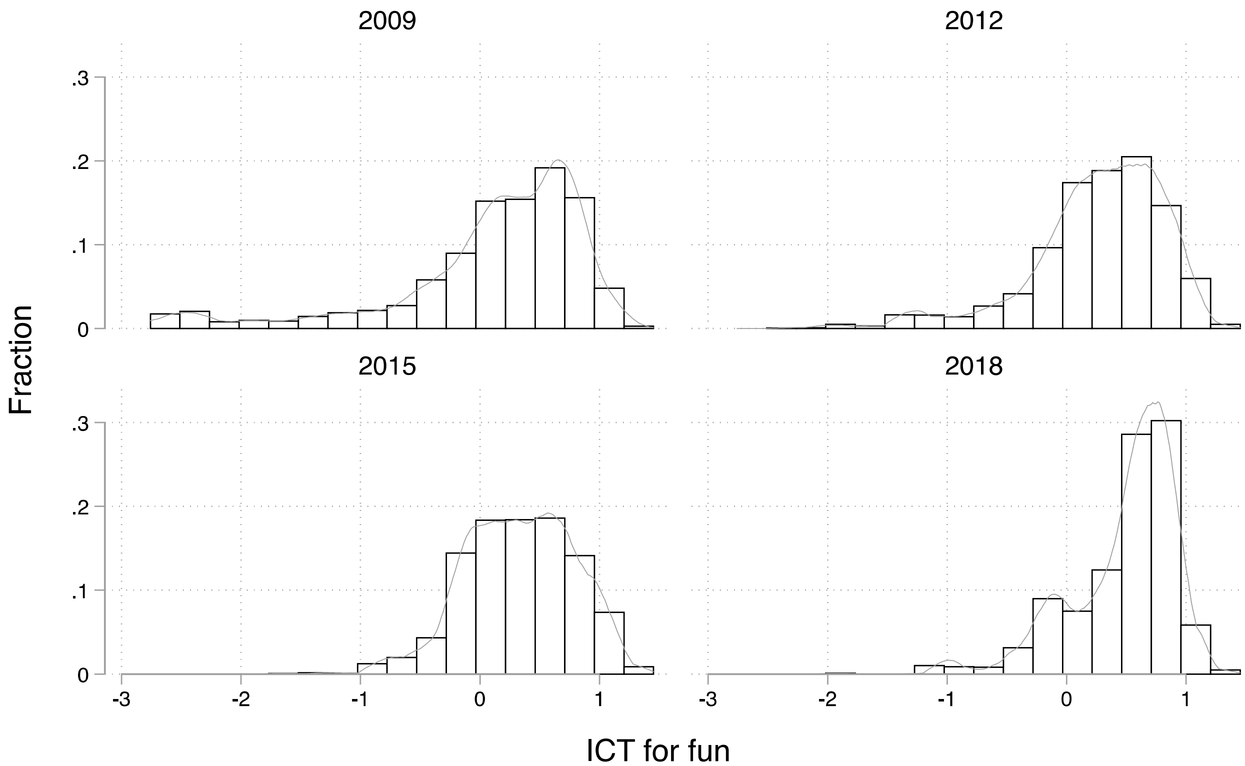

Fig. 2. Trends in the distribution of the use of ICT for leisure between 2009 and 2018

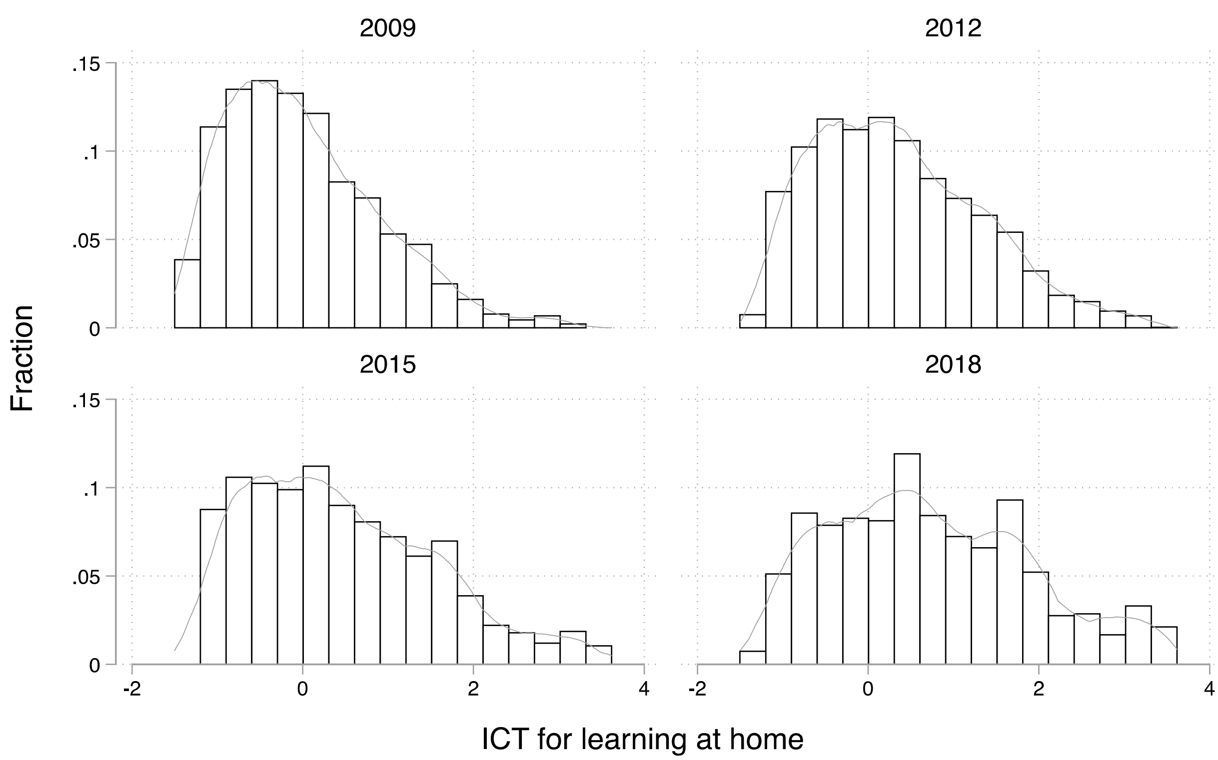

Fig. 3. Trends in the distribution of the use of ICT for learning at home between 2009 and 2018

or at school were right-skewed in 2009. The use of ICT for learning at school had an especially skewed distribution with many students reporting very low levels of use in 2009 and while it remained skewed, a larger number of students reported higher levels of use by 2018. By contrast, use of ICT for learning at home by 2018 had acquired a rather symmetric, unimodal distribution, with many children reporting average levels and some reporting either high or low levels of use.

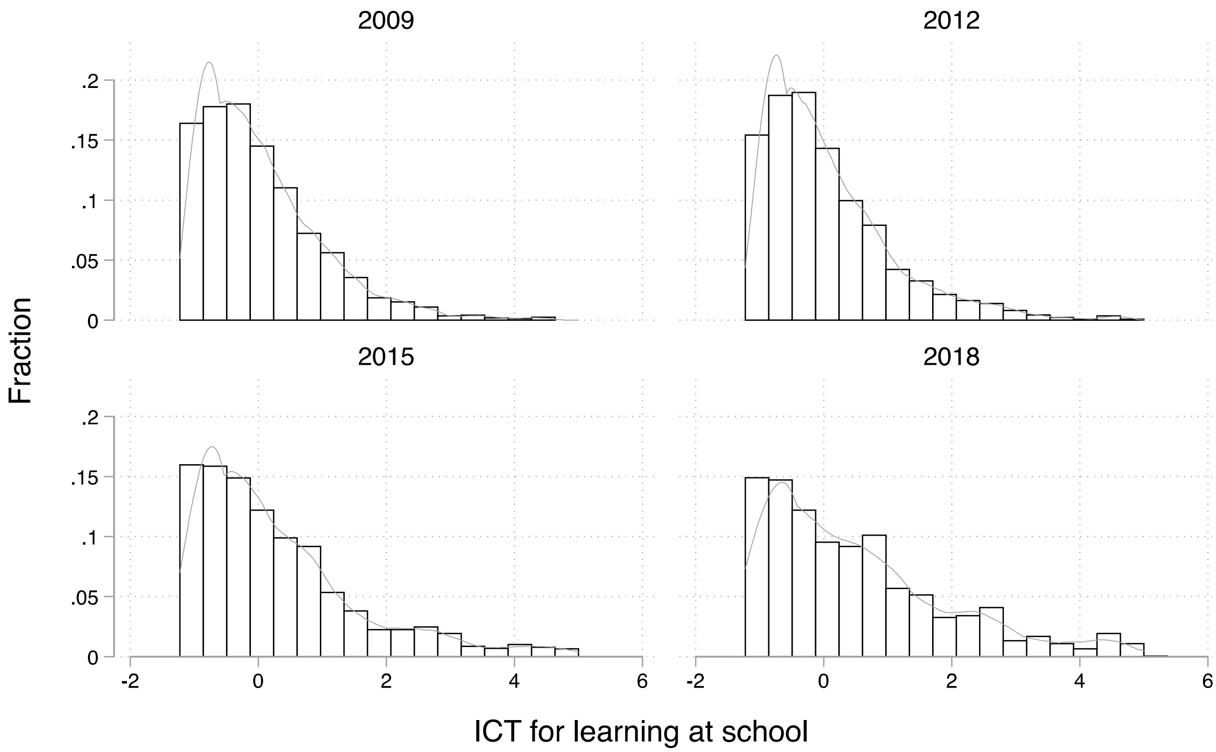

Fig. 4. Trends in the distribution of the use of ICT for learning at school between 2009 and 2018

5.3. *The evolution of the association between ICT use and reading achievement*

Table 2 details changes between 2009 and 2018 in the average association between different forms of ICT use and reading achievement. Results suggest that the association between ICT use for fun and reading achievement was low throughout the period, ranging from the small positive in 2009 to the small negative in 2018. By contrast, on average students making greater use of ICT for school purposes at home or at school generally had lower reading achievement than students making less use. The strongest negative association was between ICT use for learning purposes at school and reading achievement and the association remained relatively stable over the period ranging from $r = -.196$ in 2009 to $r=-.237$ in 2018. By contrast, the association between ICT use for school at home grew progressively more negative over time: in 2009 $r = -.013$ and in 2018 $r = -.144$. The use of ICT for fun was positively but weakly associated with the use of ICT for learning both at home and at school throughout the period. The association between the use of ICT for learning at home and using it at school was positive and grew stronger over the period: it was $r = .410$ in 2009 and $r = .569$ in 2018.

Fig. 5 considers potential non linearities in the associations between reading achievement and different forms of ICT. Fig. 5 indicates that the association between ICT use for fun and reading achievement is well represented by an inverted U shape and that the inverted U shape became steeper at low levels of ICT use over time. Moreover, relations shifted to the right over the period, reflecting increasing use. In 2009, 15-year-olds who used little ICT for fun had the lowest levels of reading achievement. Achievement was higher among students with higher levels of use, but there were only small differences in achievement between students who differed little in ICT use. Achievement was highest among students with average levels of ICT use. Beyond such threshold, increasing levels of ICT use for fun were associated with increasingly lower levels of achievements. Starting in 2012, fewer students reported low levels of use, a trend that became more pronounced over time. Moreover, students with very low levels of ICT use for fun over time had lower levels of achievement than students with comparable levels of use in 2009. From 2012 onwards, at low levels of use, achievement started to be markedly higher among students with higher levels of use. In all four PISA surveys students with the highest levels of reading achievement were students that used ICT for fun in line with the average levels of use that were observed in 2009.

The association between ICT use for learning at home can also be described by an inverted U shape: the highest achieving students are students with levels of use that are aligned with the levels of use observed on average across OECD countries in 2009. Moreover, the positive change in reading achievement that is associated with levels of use below the average is greater than the negative change in reading achievement that is associated with levels of use above the average. Between 2009 and 2018 associations became steeper at low levels of use, although there is evidence of a second inflection point at very high levels of use of ICT for learning at home. Interestingly, Fig. 5 indicates that the association between ICT use for learning at school is broadly negative

Table 2
Trends in the association between ICT use and reading achievement Pearson correlations

Year	Associations between reading and:			Association between ICT for learning at home	Association between ICT for learning at home and	Association between ICT for fun and
	ICT for fun	ICT for learning at home	ICT for learning at school	ICT for fun	at school	for learning for school
2009	0.021	-0.013	-0.196	0.345	0.410	0.127
2012	-0.007	0.010	-0.189	0.227	0.457	0.166
2015	-0.047	-0.090	-0.206	0.237	0.558	0.222
2018	-0.018	-0.144	-0.237	0.225	0.569	0.192

given levels of use observed between 2009 and 2018, although between 2009 and 2018 students with the lowest levels of use increasingly lagged behind in terms of reading achievement when compared to students with low levels of use.

5.4. Differences in the evolution of the association between ICT use and reading achievement

Results presented in Fig. 5 clearly indicate that the association between ICT use and reading achievement differs according to the level of ICT use. Such Figs. also suggest that levels of use observed on average across students in OECD countries in 2009 broadly correspond to the peak of the inverted U that describes the association between ICT use and reading achievement. Tables 3, 4 and 5 more formally describe the association between each indicator of ICT use and reading achievement while controlling for background characteristics such as gender and parental educational attainment, how associations changed over time and how results are affected by the inclusion of additional controls characterizing other forms of ICT use.

Results describing the association between ICT use for fun and reading achievement in Table 3 indicate that over the 2009-2018 period, the use of ICT for fun was positively associated with reading achievement at low levels of use and negatively associated with reading achievement at high levels of use (model 1 results). Controlling for other forms of ICT use in model 2 halved the estimated positive association at low levels of use and pointed to a lack of association over the period at high levels of use. However, models 3 and 4 indicate that associations changed markedly over the period. At levels of use lower than 0 in 2009, when controlling for all factors in model 4, increases in use of ICT for fun were associated with a positive difference of 8% of a SD in reading achievement. By 2018 this difference grew considerably and stood at 44% of a SD. At levels of use above 0 in 2009, when controlling for all factors in model 4, increases in use of ICT for fun were associated with a negative difference of 12% of a SD in reading achievement. By 2018 this difference was no longer negative and, in fact, increases at high levels of use were associated with a positive difference in reading achievement. By 2018, a change of one SD in ICT use for fun at high levels of use was associated with a positive change of around 10% of a SD in reading achievement.

Estimates presented in model 1 of Table 4 suggest that on average, over the 2009-2018 period, the use ICT for learning at school was positively associated with reading achievement at levels of use higher than 0: a change of one SD in ICT for learning at school was associated with a positive difference of 14% of a SD in reading achievement for levels of use greater than 0. However, the use ICT for learning at school was negatively associated with reading achievement at levels of use lower than 0: a change of one SD in ICT for learning at school was associated with a positive difference of 19.5% of a SD in reading achievement for levels of use lower than 0. Controlling for other forms of ICT halved the strength of the association observed for values of use of ICT for learning at school higher than 0. Models 3 and 4 indicate that also in the case of use of ICT for learning at school relations changed over time. In particular, the association between the use of ICT for learning at school and reading achievement became positive at low levels of use only starting in 2015 and the negative association observed at high levels of use became slightly less negative over time.

Finally, Table 5 reports results for the association between the use of ICT for learning at home and reading achievement. In line with results

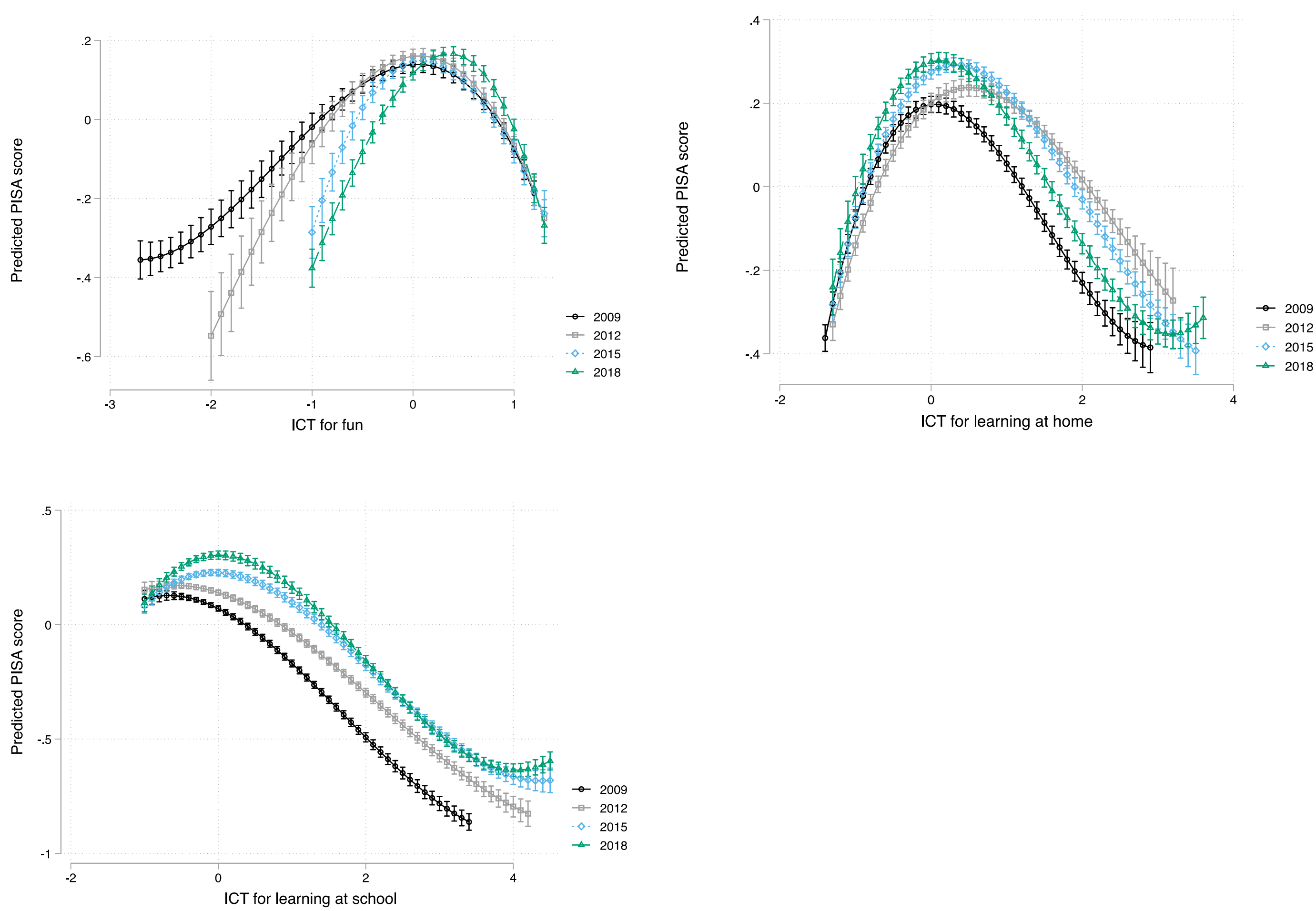

Fig. 5. . Trends in the association between reading achievement and the use of ICT

Table 3
Regression results describing changes in the association between ICT use for leisure and reading achievement between 2009 and 2018

	(1)	(2)	(3)	(4)
Intercept <0	-0.175***	0.0397*	-0.139***	0.0917***
	(0.0208)	(0.0191)	(0.0210)	(0.0191)
Intercept >=0	-0.120***	0.0946***	-0.123***	0.102***
	(0.0207)	(0.0186)	(0.0208)	(0.0186)
ICT for fun (<0)	0.161***	0.0833***	0.154***	0.0805***
	(0.0101)	(0.0108)	(0.00997)	(0.0106)
ICT for fun (>-=0)	-0.0935***	0.000766	-0.172***	-0.117***
	(0.00886)	(0.00775)	(0.0145)	(0.0135)
Female	0.349***	0.303***	0.357***	0.315***
	(0.00493)	(0.00482)	(0.00494)	(0.00485)
Parents educated at the tertiary level	0.405***	0.394***	0.404***	0.393***
(baseline no parent with tertiary qualifications)	(0.00420)	(0.00424)	(0.00419)	(0.00422)
Year 2012	0.000128	0.0157	0.00337	0.0169
	(0.0125)	(0.0121)	(0.0132)	(0.0120)
Year 2015	-0.0305**	0.0497***	-0.0501***	0.00320
	(0.0118)	(0.0104)	(0.0129)	(0.0117)
Year 2018	-0.0688***	0.0561***	-0.101***	-0.00761
	(0.0130)	(0.0130)	(0.0141)	(0.0129)
ICT for learning at home		0.107***		0.109***
		(0.00431)		(0.00414)
IC for learning at home ^2		-0.125***		-0.125***
		(0.00469)		(0.00437)
IC for learning at home ^3		0.0227***		0.0219***
		(0.00134)		(0.00124)
ICT for learning at school		-0.112***		-0.115***
		(0.00725)		(0.00706)
ICT for learning at school ^2		-0.0783***		-0.0752***
		(0.00582)		(0.00562)
ICT for learning at school^3		0.0150***		0.0143***
		(0.00113)		(0.00110)
Year 2012# ICT for fun (<0)			0.0882*	0.122**
			(0.0349)	(0.0374)
Year 2015# ICT for fun (<0)			0.239***	0.263***
			(0.0331)	(0.0359)
Year 2018# ICT for fun (<0)			0.363***	0.361***
			(0.0315)	(0.0283)
Year 2012# ICT for fun (>=0)			0.0398*	0.0594***
			(0.0188)	(0.0164)
Year 2015# ICT for fun (>=0)			0.123***	0.204***
			(0.0211)	(0.0168)
Year 2018# ICT for fun (>=0)			0.152***	0.232***
			(0.0206)	(0.0175)
Country Fixed effects	YES	YES	YES	YES
N	645410	642240	645410	642240
adj. R^2	0.1314	0.1821	0.1342	0.1863

Standard errors in parentheses. * $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

Table 4
Regression results describing changes in the association between ICT use for learning at school and reading achievement between 2009 and 2018

	(1)	(2)	(3)	(4)
Intercept <0	0.0144	0.132***	-0.00460	0.121***
	(0.0198)	(0.0196)	(0.0203)	(0.0201)
Intercept >=0	-0.0634**	0.0427*	-0.0773***	0.0404*
	(0.0193)	(0.0183)	(0.0193)	(0.0189)
ICT for school (<0)	0.140***	0.0634**	0.0405	-0.0382
	(0.0197)	(0.0198)	(0.0323)	(0.0315)
ICT for school (>-=0)	-0.195***	-0.179***	-0.234***	-0.239***
	(0.00440)	(0.00453)	(0.00640)	(0.00664)
Female	0.303***	0.302***	0.300***	0.300***
	(0.00452)	(0.00481)	(0.00452)	(0.00466)
Parents educated at the tertiary level	0.414***	0.394***	0.412***	0.391***
(baseline no parent with tertiary qualifications)	(0.00417)	(0.00423)	(0.00414)	(0.00416)
Year 2012	0.0586***	0.0154	0.0495***	-0.00168
	(0.0119)	(0.0124)	(0.0116)	(0.0119)
Year 2015	0.0866***	0.0455***	0.139***	0.0854***
	(0.0110)	(0.0105)	(0.0117)	(0.0119)
Year 2018	0.100***	0.0516***	0.184***	0.125***
	(0.0135)	(0.0131)	(0.0142)	(0.0147)
ICT for learning at home		0.0992***		0.0979***
		(0.00449)		(0.00450)
ICT for learning at home ^2		-0.133***		-0.132***
		(0.00462)		(0.00428)
ICT for learning at home ^3		0.0268***		0.0263***
		(0.00141)		(0.00129)
ICT for fun		0.114***		0.122***
		(0.0130)		(0.0112)
ICT for fun^2		-0.0536***		-0.0577***
		(0.00744)		(0.00667)
ICT for fun^3		-0.0278***		-0.0293***
		(0.00440)		(0.00394)
Year 2012# ICT for learning at school (<0)			0.00182	0.00181
			(0.0412)	(0.0423)
Year 2015# ICT for learning at school (<0)			0.196***	0.197***
			(0.0362)	(0.0341)
Year 2018# ICT for learning at school (<0)			0.277***	0.288***
			(0.0422)	(0.0438)
Year 2012# ICT for learning at school (>=0)			0.0294***	0.0477***
			(0.00809)	(0.00818)
Year 2015# ICT for learning at school (>=0)			0.0412***	0.0676***
			(0.00894)	(0.00875)
Year 2018# ICT for learning at school (>=0)			0.0298**	0.0550***
			(0.00965)	(0.00948)
Country fixed effects	YES	YES	YES	YES
N	648859	642240	648859	642240
adj. R^2	0.1678	0.1821	0.1705	0.1855

Standard errors in parentheses. * $p < 0.05$
** $p < 0.01$
*** $p < 0.001$

presented in Tables 3 and 4, findings reported in Table 5 suggests that the association between ICT use for learning at home and reading achievement became more positive at low levels of use over time, and that the association between ICT use for learning at home and reading achievement became less negative at high levels of use over time.

6. Conclusion and Implications

The ubiquitous presence of ICT in children's lives has been a growing concern amongst educators, politicians, and parents for decades [62]. Such concerns increased during the COVID-19 pandemic: face-to-face schooling was interrupted and remote learning through ICT technologies became widespread [26]. In the spring of 2020, an Internet connection and a mobile device replaced the classroom in the space of a day for hundreds of millions of students worldwide [78]. An increasing number of studies examine the effects of school closures due to COVID-19 on students' learning progress [27, 78] and the effectiveness of remote learning to substitute face-to-face learning has been questioned in this context as not being effective [68, 77, 78].

Table 5
Regression results describing changes in the association between ICT use for learning at home and reading achievement between 2009 and 2018

	(1)	(2)	(3)	(4)
Intercept <0	0.0528**	0.166***	0.0438*	0.151***
	(0.0196)	(0.0196)	(0.0199)	(0.0199)
Intercept >=0	-0.0393*	0.0800***	-0.0599**	0.0600**
	(0.0186)	(0.0184)	(0.0190)	(0.0189)
ICT home(<0)	0.387***	0.367***	0.332***	0.256***
	(0.0112)	(0.0115)	(0.0154)	(0.0168)
ICT home(>-=0)	-0.164***	-0.0510***	-0.182***	-0.0989***
	(0.00403)	(0.00402)	(0.00827)	(0.00868)
Female	0.323***	0.301***	0.321***	0.302***
	(0.00465)	(0.00478)	(0.00463)	(0.00471)
Parents educated at the tertiary level	0.407***	0.394***	0.407***	0.394***
(baseline no parent with tertiary qualifications)	(0.00425)	(0.00423)	(0.00424)	(0.00417)
Year 2012	0.0387***	0.0172	0.0229	0.0181
	(0.0116)	(0.0123)	(0.0158)	(0.0158)
Year 2015	0.0515***	0.0454***	0.0932***	0.0910***
	(0.0108)	(0.0104)	(0.0136)	(0.0127)
Year 2018	0.0316**	0.0536***	0.0926***	0.119***
	(0.0119)	(0.0131)	(0.0144)	(0.0133)
ICT for learning at home		-0.109***		-0.113***
		(0.00723)		(0.00707)
ICT for learning at home ˆ2		-0.0803***		-0.0784***
		(0.00587)		(0.00566)
ICT for learning at home ˆ3		0.0151***		0.0148***
		(0.00116)		(0.00114)
ICT for learning at school		0.115***		0.122***
		(0.0130)		(0.0117)
ICT for learning at home ˆ2		-0.0606***		-0.0648***
		(0.00739)		(0.00701)
ICT for learning at home ˆ3		-0.0299***		-0.0264***
		(0.00441)		(0.00407)
Year 2012# ICT for learning at home(<0)			0.0452	0.0923**
			(0.0295)	(0.0311)
Year 2015# ICT for learning at home (<0)			0.142***	0.224***
			(0.0208)	(0.0201)
Year 2018# ICT for learning at home (<0)			0.137***	0.255***
			(0.0256)	(0.0256)
Year 2012# ICT for learning at home (>=0)			0.0647***	0.0692***
			(0.0109)	(0.0109)
Year 2015# ICT for learning at home (>=0)			0.0137	0.0485***
			(0.0103)	(0.0102)
Year 2018# ICT for learning at home (>=0)			-0.00818	0.0321**
			(0.00971)	(0.0103)
Country fixed effects	YES	YES	YES	YES
N	643704	642240	643704	642240
adj. R^2	0.1490	0.1818	0.1501	0.1842

Standard errors in parentheses. * $p < 0.05$
** $p < 0.01$
*** $p < 0.001$.

The evidence presented suggests that already before the pandemic, whether in school or at home, students had increased their use of ICT for learning. By developing indicators of ICT use that are comparable across countries and over time, we show that the use of ICT for learning at school and at home increased by around three quarters of a standard deviation between 2009 and 2018. As a potential reflection of the greater use of ICT at school, the PISA test changed mode of administration between 2012 and 2015: until 2012 it was delivered in paper booklets while from 2015 it became computer based. Increases in the use of ICT for fun were large but not as pronounced (41% of a standard deviation), a possible reflection of the fact that teenagers already used ICT for fun to a much higher degree in 2009. Gender gaps became more pronounced over the period, with boys consuming more ICT for learning and for fun than girls, while we did not observe disparities in the use of ICT by parental educational attainment in any of the years under examination.

In line with the previous literature [75,88], we identify an inverted U-shaped association between different forms of ICT use and reading achievement and that in 2009, the association between ICT for learning at school and reading achievement was decreasing over the observed distribution of use. At the population level, the association between the use of ICT and reading achievement became more negative over time. However, this change was a reflection of the increase in ICT use among boys, who generally have lower levels of achievement. Over time, associations between different forms of ICT use and reading achievement grew more positive at low levels and less negative at high levels. Because ICT use increased markedly over the period, and therefore more students were located in the decreasing section of the association, overall levels of achievement remained relatively stable despite large increases in ICT use.

Our study suggests that as the use of ICT becomes pervasive and familiarity with ICT becomes important to be able to take part in computer-administered tests, students who have very low levels of use will be increasingly penalized and display lower reading achievement than students with moderate levels of use. At the same time, high levels of use remain associated with lower achievement than moderate levels of use, even when the use of ICT is widespread and ICT is integrated in testing. At high levels of use, any gains in reading achievement that are associated with greater familiarity with ICT are more than compensated by displacement effects of activities that would be more conducive to reading proficiency, such as, for example, practicing reading. Table S1 in the Supplementary Online Annex suggests that between 2009 and 2018, just as the use of ICT increased, there was a sizable increase in the number of students who considered reading a waste of time or who reported reading only if they had to.

Results presented indicate that ensuring that all students have access to and are familiar with a broad array of ICT devices may be increasingly important to ensure that they are able to demonstrate their skills effectively. As many activities occur through technology, the ability to effectively operate ICT moderates children's expression of what they know and can do. However, familiarity with ICT devices can be achieved through levels of use that are considerably lower than the levels of use many teenagers engage in. In particular, until 2018 ICT use for learning at home and especially at school, appear to have been associated with lower overall reading achievement beyond very low levels of use. Although our results cannot be interpreted causally, they suggest that before the pandemic, students displayed greater proficiency when their teachers only used ICT in the classroom in a limited way and for certain activities. The fact that the use of ICT for learning, whether in school or at home, increased the most among groups of students that are generally more difficult to motivate with learning, such as boys, suggests that until 2018 the use of ICT for learning was used by educators as a way to build engagement and motivation. However, despite potential motivational benefits and potential improvements in the quality of ICT resources used in classrooms and in teachers' ability to effectively use ICT in the classroom, our study suggests that when ICT is used extensively for learning, text comprehension skills tend to be lower.

The COVID-19 pandemic forced many teachers and educators to undergo rapid professional development and learn how best ICT could be used in instruction despite the rapid increases between 2009 and 2018 in the use of ICT for learning both at school and at home detailed in this work [25, 49]. Social distancing requirements in fact demanded a complete overhaul of learning activities and ICT was used as never before [42,78] At the same time, parents worldwide came to accept that their children would consume considerably more time using digital devices, since social distancing prevented children from interacting with their friends face to face [11, 43]. After the COVID-19 pandemic, children, parents and educators will have to adapt to a new normal and will have to critically evaluate when, how much and for what ICT should be used for learning and for leisure. Our work suggests that there is value in promoting a moderate use of ICT for learning both at home and at school and that the extent to which ICT can contribute to learning can evolve in line with innovations in technologies and the ability of educators to make the most of technological advanced. At the same time, high levels of ICT use can prevent children from acquiring the variety of skills that are needed to become proficient readers. School principals, teachers and educators should be supported to ensure that are able to identify and implement a range of tools and technologies in the classroom, tailoring instruction to the needs of diverse student populations. At the same time, parents should be empowered so that they can monitor their children's use of ICT in their free time and guide their children as they grow so that they engage in a range of activities [42].

6.1. Limitations

Our study suffers from a number of limitations that could be addressed in future research. First, the repeated cross-sectional dimension of the study means that results cannot be interpreted causally. Second, our indicators of ICT use identify quantitative dimensions (such as how frequently and how many different activities children engaged in) rather than qualitative dimensions (such as content of ICT use). Third, findings refer to text comprehension skills and may therefore not apply in the same way to other domains, such as mathematics and science. Finally, although our work considers relationships across a large number of countries over almost a decade, they cannot necessarily be generalized to other context, whether temporal or geographic.

Declaration of Competing Interests

None

Acknowledgements

The authors would like to thank Artur Pokropek for help with the analyses. Francesca Borgonovi recognises support from the British Academy through its Global Professorship scheme. 4JS.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.caeo.2021.100047.

References

[1] Ackerman R, Goldsmith M. Metacognitive regulation of text learning: on screen versus on paper. J Experimental Psychol: Appl 2011;17(1):18–32.
[2] Agasisti T, Gil-Izquierdo M, Han SW. ICT use at home for school-related tasks: What is the effect on a student's achievement? Empirical evidence from OECD PISA data. Education Econ 2020;28(6):601–20.
[3] Alexander PA, Jetton TL. Learning from text: A multidimensional and developmental perspective. In: Kamil ML, Pearson PD, Barr R, Mosenthal PB, editors. Handbook of reading research, Vol. 3. New York, NY: Routledge; 2000. p. 285–310.
[4] Alloway TP, Alloway RG. The impact of engagement with social networking sites (SNSs) on cognitive skills. Comput Hum Behav 2012;28(5):1748–54.
[5] Asparouhov T, Muthen B. Multiple-group factor analysis alignment. Structural Equation Modeling: A Multidisciplinary J 2014;21(4):495–508. https://doi.org/10.1080/10705511.2014.919210.
[6] Avvisati F, Borgonovi F. Young videogamers and their approach to science inquiry. DoQSS Working Papers. 21-05. London; 2021.
[7] Ball R, Hourcade JP. Rethinking reading for age from paper and computers. Int J Hum-Comput Interaction 2011;27(11):1066–82.
[8] Becker B. Educational ICT use outside school in the European Union: disparities by social origin, immigrant background, and gender. J Children and Media 2020. https://doi.org/10.1080/17482798.2021.1902359.
[9] Benedetto S, Drai-Zerbib V, Pedrotti M, Tissier G, Baccino T. E-readers and visual fatigue. PLoS One 2013;8(12):1–7.
[11] Bent EM. The role of digital media in family life during the UK lockdown 2020. J Children and Media 2021;15(1):33–6.
[12] Biagi F, Loi M. Measuring ICT use and learning outcomes: Evidence from recent econometric studies. Eur J Education 2013;48(1):28–42.
[13] Binkley M, Erstad O, Herman J, Raizen R, Ripley M, Rumble M. Defining 21st century skills. In: Griffin P, McGaw B, Care E, editors. Assessment and teaching of 21st century skills. Dordrecht: Springer; 2012. p. 17–66.
[14] Borgonovi F. Video gaming and gender differences in digital and printed reading performance among 15-year-olds students in 26 countries. J Adolesc 2016;48:45–61.
[15] Carretero, S., Vuorikari, R., & Punie, Y. (2017). DigComp 2.1: The Digital Competence Framework for Citizens with eight proficiency levels and examples of use (No. JRC106281). Joint Research Centre (Seville site).
[16] Clark C, Rumbold K. Reading for Pleasure: A Research Overview. National Literacy Trust 2006.
[17] Coiro J, Knobel M, Lankshear C, Leu DJ. The handbook of research in new literacies. New York: Taylor and Francis; 2008.
[18] Colom R, Martínez-Molina A, Shih PC, Santacreu J. Intelligence, working memory, and multitasking performance. Intelligence 2010;38(6):543–51. https://doi.org/10.1016/j.intell.2010.08.002.
[19] Cunningham AE, Stanovich KE. What reading does to the mind, 22. American Educator; 1998. p. 1–8.
[20] Cudo A, Kopiś N, Francuz P, Błachnio A, Przepiórka A, Torój M. The impact of Facebook use and Facebook intrusion on cognitive control: Effect in proactive and reactive control. Advances in Cognitive Psychol 2019;15(1):63.
[21] Daniel DB, Woody WD. E-textbooks at what cost? Performance and use of electronic v. print texts. Comput Education 2013;62:18–23.
[22] De Freitas S, Oliver M. How can exploratory learning with games and simulations within the curriculum be most effectively evaluated? Comput education 2006;46(3):249–64.
[23] Demnati A, Rao JNK. Linearization variance estimators for survey data. Survey Methodol 2004;30(1):17–26.
[24] DeStefano D, LeFevre J. Cognitive load in hypertext reading: a review. Comput Hum Behav 2007;23:1616–41.
[25] Donitsa-Schmidt S, Ramot R. Opportunities and challenges: teacher education in Israel in the Covid-19 pandemic. J Education for Teaching 2020;46(4):586–95.
[26] ... Dwivedi YK, Hughes DL, Coombs C, Constantiou I, Duan Y, Edwards JS, Upadhyay N. Impact of COVID-19 pandemic on information management research and practice: Transforming education, work and life Int J Inf Manage 2020;55:102211.
[27] Engzell P, Frey A, Verhagen MD. Learning loss due to school closures during the COVID-19 pandemic, 118. PNAS; 2021, e2022376118.
[28] Ehri L, Snowling M. Developmental variation in word recognition. In: Shulman B, Apel K, Ehren B, Silliman E, Stone C, editors. Handbook of language and literacy development and disorders. New York, NY: Guilford Press; 2004. p. 433–60.
[29] Foerde K, Knowlton BJ, Poldrack RA. Modulation of competing memory systems by distraction. Proc Natl Acad Sci 2006;103(31):11778–83.
[30] Fox, A. B., Rosen, J., & Crawford, M. (2009). Distractions, distractions: Does instant messaging affect college students' performance on a concurrent reading comprehension task? *Cyberpsychology and Behavior,* 12(1), 51–53. https://doi.org/10.1089/cpb.2008.0107.
[31] Fraillon J, Schulz W, Ainley J. International computer and information literacy study: Assessment framework. Amsterdam: IEA; 2013.
[32] Hughes-Hassell S, Rodge P. The leisure reading habits of urban adolescents. J Adolescent & Adult Literacy 2007;51(1):22–33.
[33] Goldman SR, Braasch JL, Wiley J, Graesser AC, Brodowinska K. Comprehending and learning from Internet sources: Processing patterns of better and poorer learners. Read Res Q 2012;47(4):356–81.
[34] Gracia P, Garcia-Roman J, Oinas T, Anttila T. Child and adolescent time use: A cross-national study. J Marriage and Family 2020;82(4):1304–25.
[35] Gu X, Wu B, Xu X. Design, development, and learning in e-textbooks: what we learned and where we are going. J Comput Education 2015;2(1):25–41.
[36] Gubbels J, Swart NM, Groen MA. Everything in moderation: ICT and reading performance of Dutch 15-year-olds. Large-scale Assessments in Education 2020;8(1):1.
[38] Junco R, Cotten SR. No A 4 U: The relationship between multitasking and academic performance. Comput Education 2012;59(2):505–14.
[39] Kemp N. Mobile technology and literacy: effects across cultures, abilities and the lifespan. J Comput-Assisted Learning 2011;27(1):1–3.
[40] Kieffer Michael J. Before and after third grade: Longitudinal evidence for the shifting role of socioeconomic status in reading growth. Reading and Writing 2012;25:1725–46.
[41] King DL, Gradisar M, Drummond A, Lovato N, Wessel J, Micic G, et al. The impact of prolonged violent video-gaming on adolescent sleep: an experimental study. J Sleep Res 2013;2:137–43.
[42] ... Király O, Potenza MN, Stein DJ, King DL, Hodgins DC, Saunders JB, Demetrovics Z. Preventing problematic internet use during the COVID-19 pandemic: Consensus guidance Compr Psychiatry 2020;100:152180.
[43] Koskela T, Pihlainen K, Piispa-Hakala S, Vornanen R, Hämäläinen J. Parents' views on family resiliency in sustainable remote schooling during the COVID-19 outbreak in Finland. Sustainability 2020;12(21):8844.
[44] Kunina-Habenicht O, Goldhammer F. ICT Engagement: a new construct and its assessment in PISA 2015. Large-scale Assessments in Education 2020;8:1–21.
[45] Leeson HV. The mode effect: a literature review of human and technological issues in computerized testing. Int J Testing 2006;6(1):1–24.

[46] Leu DJ, Forzani E, Rhoads C, Maykel C, Kennedy C, Timbrell N. The new literacies of online reading and comprehension: rethinking the reading achievement gap. Read Res Q 2015;50(1):37–59.
[47] Li LY, Chen GD, Yang SJ. Construction of cognitive maps to improve e-book reading and navigation. Computers & Education 2013;60(1):32–9.
[48] Liu D, Kirschner PA, Karpinski AC. A meta-analysis of the relationship of academic performance and Social Network Site use among adolescents and young adults. Comput Hum Behav 2017;77:148–57.
[49] Lockee BB. Shifting digital, shifting context:(re) considering teacher professional development for online and blended learning in the COVID-19 era. Educational Technol Res Development 2021;69(1):17–20.
[50] Loh CE, Sun B. I'd still prefer to read the hard copy: Adolescents' print and digital reading habits. J Adolescent & Adult Literacy 2019;62(6):663–72.
[52] Mangen A, Walgermo BR, Brønnick K. Reading linear texts on paper versus computer screen: effects on reading comprehension. Int J Educational Res 2013;58:61–8.
[53] Margolin SJ, Driscoll C, Toland MJ, Kegler JL. E-readers, computer screens, or paper: does reading comprehension change across media platforms? Appl Cogn Psychol 2013;27:512–9.
[54] Mayer RE, Heiser J, Lonn S. Cognitive constraints on multimedia learning: when presenting more material results in less understanding. J Educ Psychol 2001;93(1):187–98.
[55] McZgee VE, Carleton WT. Piecewise regression. J Am Statist Assoc 1970;65(331):1109–24.
[56] Murray MC, Pérez J. E-textbooks are coming: are we ready? Issues in Informing Sci Information Technol 2011;8:49–60.
[57] Muthén B, Asparouhov T. IRT studies of many groups: The alignment method. Front Psychol 2014;5:978.
[58] OECD. *Students, Computers and Learning: Making the Connection*. Paris: PISA, OECD Publishing; 2015. https://doi.org/10.1787/9789264239555-en.
[59] OECD (2016), Annex 6 in PISA 2015 Results (Volume I): Excellence and Equity in Education, PISA. OECD Publishing, Paris, https://doi.org/10.1787/9789264266490-en.
[60] OECD (2021). The State of School Education: One Year into the COVID Pandemic. https://doi.org/10.1787/201dde84-en.
[61] Orben A, Przybylski AK. The association between adolescent well-being and digital technology use. Nature Hum Behav 2019;3:173–82.
[62] Orben A. The Sisyphean Cycle of Technology Panics. Perspectives on Psychological Sci 2020;15(5):1143–57. https://doi.org/10.1177/1745691620919372.
[63] Pokropek A, Lüdtke O, Robitzsch A. An extension of the invariance alignment method for scale linking. Psychological Test and Assessment Model 2020;62(2):305–34.
[64] Prensky M. Digital game-based learning. New York: McGraw-Hill; 2001.
[65] Redecker, C. (2017). European framework for the digital competence of educators: DigCompEdu (No. JRC107466). Joint Research Centre (Seville site).
[66] Prensky M. Engage me or enrage me. EDUCASE Review 2005;40(5):61–4. September/October.
[67] Rouet J-F. The skills of document use: From text comprehension to web-based learning. Mahwah, NJ: Lawrence Erlbaum Associates; 2006.
[68] Reich J. Failure to disrupt: Why technology alone can't transform education. Harvard University Press; 2020.
[69] Salmerón L, García V. Children's reading of printed text and hypertext with navigation overviews: the role of comprehension, sustained attention, and visuo-spatial abilities. J Educational Comput Res 2012;47(1):33–50.
[70] Shapiro J. The New Childhood: Raising kids to thrive in a digitally connected world. London: Hachette; 2019.
[71] Singer LM, Alexander PA. Reading across mediums: Effects of reading digital and print texts on comprehension and calibration. The J Experimental Education 2017;85(1):155–72.
[72] Smith MC, Mikulecky L, Kibby MW, Dreher MJ, Dole JA. What will be the demands of literacy in the workplace in the next millennium? Read Res Q 2000;35(3):378–83. https://doi.org/10.1598/rrq.35.3.3.
[74] Spiro JJ, Deschryver M, Hagerman MS, Morsink P. Reading at a crossroads? In: Thompson P, editor. Disjunctures and continuities in current conceptions and practices. New York: Routledge; 2015.
[75] Steffens K. ICT Use and Achievement in Three European Countries: what does PISA tell us? Eur Educational Res J 2014;13(5):553–62.
[76] Sullivan A, Brown M. Reading for pleasure and progress in vocabulary and mathematics. Br Educational Res J 2015;41(6):971–91.
[77] Thompson C. Smarter than you think: How technology is changing our minds for the better. The Penguin Press; 2013.
[78] UNESCO. Covid-19 Impact on Education. 2021. https://en.unesco.org/covid19/educationresponse.
[79] Van Der Schuur WA, Baumgartner SE, Sumter SR, Valkenburg PM. The consequences of media multitasking for youth: A review. Comput Hum Behav 2015;53:204–15. https://doi.org/10.1016/j.chb.2015.06.035.
[80] Van Dijk JAGM. The evolution of the digital divide. The digital divide turns to inequality of skills and usage. In: Bus J, Crompton M, Hildebrandt M, Metakides G, editors. Digital enlightenment yearbook 2012. Amsterdam: IOS Press; 2012. p. 57–75. https://doi.org/10.3233/978-1-61499-057-4-57.
[81] Vedechkina M, Borgonovi F. A review of evidence on the role of digital technology in shaping attention and cognitive control in children. Front Psychol Sci 2021. https://doi.org/10.3389/fpsyg.2021.611155.
[82] Weis R, Cerankosky BC. Effects of video-game ownership on young boys' academic and behavioral functioning: A randomized, controlled study. Psychol Sci 2010;21(4):463–70. https://doi.org/10.1177/0956797610362670.
[83] Williams R. Using the Margins Command to Estimate and Interpret Adjusted Predictions and Marginal Effects. Stata J Promot Commun Stat Stata 2012;12:308–31.
[84] Wirth J, Klieme E. Computer-based assessment of problem solving competence. Assessment in Education: Principles, Policy and Practice 2004;10:329–45.
[85] Notten N, Becker B. Early home literacy and adolescents' online reading behavior in comparative perspective. International Journal of Comparative Sociology 2017;58(6):475–93. https://doi.org/10.1177/0020715217735362.
[86] Hargittai E, Hinnant A. Digital inequality: Differences in young adults' use of the internet. Communication Research 2008;35(5):602–21. https://doi.org/10.1177/0093650208321782.
[87] Notten N, Peter J, Kraaykamp G, Valkenburg PM. igital divide across borders—A cross-national study of adolescents' use of digital technologies. European Sociological Review 2009;25(5):551–60.
[88] Gubbels J, Swart NM, Groen MA. Everything in moderation: ICT and reading performance of Dutch 15-year-olds. Large-scale Assessments in Education volume 2020;8. https://doi.org/10.1186/s40536-020-0079-0.
[89] Feng J, Spence I. Playing Action Video Games Boosts Visual Attention.. Video Game Influences on Aggression, Cognition, and Attention. Springer; 2018. p. 83–104. https://doi.org/10.1007/978-3-319-95495-0_8.
[90] Bavelier D, Achtman RL, Mani M, Föcker J. Neural bases of selective attention in action video game players. Vision Research 2012;61:132–43. https://doi.org/10.1016/j.visres.2011.08.007.
[91] Green CS, Bavelier D. Learning, attentional control, and action video games. Current Biology 2012;22(6):197–206. https://doi.org/10.1016/j.cub.2012.02.012.
[92] Prensky M. *Brain Gain: Technology And The Quest For Digital Wisdom*. St. Martin's Publishing Group; 2012.
[93] Meredith W. Measurement invariance, factor analysis and factorial invariance. Psychometrika 1993;58:525–43. https://doi.org/10.1007/bf02294825.
[94] Steenkamp JBE, Baumgartner H. Assessing measurement invariance in cross-national consumer research. Journal of Consumer Research 1998;25:78–90.
[95] Davidov E, Meuleman B, Cieciuch J, Schmidt P, Billiet J. Measurement equivalence in cross-national research. Annual Review of Sociology 2014;40:55–75. https://doi.org/10.1146/annurev-soc-071913-043137.
[96] Pokropek A, Borgonovi F, McCormick C. On the cross-country comparability of indicators of socioeconomic resources in PISA. Applied Measurement in Education 2017;30:243–58. https://doi.org/10.1080/08957347.2017.1353985.
[97] Asparouhov T, Muthén B. Multiple-group factor analysis alignment. Structural Equations Modelling 2014;21:495–508. https://doi.org/10.1080/10705511.2014.919210.
[98] Pokropek A, Davidov E, Schmidt P. A monte carlo simulation study to assess the appropriateness of traditional and newer approaches to test for measurement invariance. Srtuctural Equations Modelling 2019;26:724–44. https://doi.org/10.1080/10705511.2018.1561293.
[99] Mislevy RJ, Beaton AE, Kaplan B, Sheehan KM. Estimating Population Characteristics From Sparse Matrix Samples of Item Responses. Journal of Educational Measurement 1992;29(2):133–61. https://doi.org/10.1111/j.1745-3984.1992.tb00371.x.
[100] Little RJA, Rubin DB. Statistical Analysis with Missing Data. New York: John Wiley & Sons; 1987.
[101] Woody WD, Daniel DB, Baker CA. E-books or textbooks: Students prefer textbooks. Computers & Education 2010;55:945–8. https://doi.org/10.1016/j.compedu.2010.04.005.