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Basic ICT access and reading achievement: First-level digital divide patterns among U.S. 15-year-olds in the PISA 2018

Nirmal Ghimire^{1,*}, Kouider Mokhtari²

¹ Watson College of Education, The University of North Carolina Wilmington, Wilmington, NC 28403, United States

² College of Education and Psychology, The University of Texas at Tyler, Tyler, TX 75799, United States

* Corresponding author: Nirmal Ghimire, ghimire.nirmal@yahoo.com

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Abstract: The reading performance of U.S. 15-year-old students is influenced by multiple factors, yet prior research on first-level digital divide indicators, such as access to home computers, internet connectivity, and information and communication technology (ICT) devices, has yielded mixed results. This study investigates the relationship between home technology access and reading achievement among U.S. 15-year-olds using data from the 2018 Program for International Student Assessment (PISA). After listwise deletion of missing ICT data, the analytic sample included 4565 students from 164 U.S. schools. Reading achievement was measured using ten plausible values reflecting students' ability to locate, understand, and evaluate textual information. We employed survey-weighted regression with progressive model development, conducting ten separate analyses and synthesizing results using Rubin's rules to account for measurement uncertainty. Findings revealed that basic technology access explained 10.6% of the variance in reading performance. Consistent computer access at home was associated with higher achievement. However, internet access presented nuanced effects: students with internet access but no reported use performed worse than those without access, while active users showed positive associations. ICT device quantity exhibited a curvilinear relationship with optimal reading performance linked to ownership of around 8–9 devices, declining thereafter. These results underscore that while first-level digital divide indicators are associated with reading outcomes, access alone is not sufficient. Engagement patterns and moderated device use are key to maximizing educational benefits.

Keywords: reading achievement; home computer ownership; home internet access; ICT devices; digital divide; academic outcomes; digital literacy

1. Introduction

The rise in access and usage of information and communication technologies (ICTs) has profoundly impacted how information is consumed in the 21st century. As of 2012, 72% of households participating in the Program for International Student Assessment (PISA) had at least one computer [1]. By 2019, over 83% of U.S. households had at least one computer and Internet access had risen to 47% globally and over 93% in North America [2]. This proliferation of Internet and ICT devices has reshaped reading habits and information consumption, giving rise to new digital communication genres including emails, text messages, and gaming lingo [3]. However, this widespread access raises fundamental questions about whether basic ICT access gaps, known as the first-level digital divide, continue to be associated with academic achievement.

The concept of the digital divide originally focused on inequalities in basic access to computers and internet connectivity. Early research consistently demonstrated that

students with home ICT access outperformed those without, establishing technology access as an important factor in educational equity [4]. Studies found that attitudes toward technology use were linked to achievement and influenced later educational prospects, while other showed positive associations between home computers and reading achievement in early grades [4].

As technology has become more prevalent, the nature of reading has transformed. Emerging digital tools have reshaped how young people access, interact with, and exchange information, ultimately influencing their reading abilities. Students now engage with multiple digital formats including emails, websites, e-books, and social media content [3]. This shift has led to new forms of digital reading that differ significantly from traditional print formats, requiring different skills and potentially creating new forms of educational inequality.

Despite widespread technology adoption, questions remain about whether basic access gaps still matter for academic outcomes. Recent research presents mixed findings about home ICT associations with reading performance [5], with some studies suggesting negative effects [6] while others find positive associations [7]. These conflicting results highlight the need for clear evidence about whether fundamental technology access disparities continue to be associated with reading achievement in today's more connected educational landscape.

This study addresses this question by examining associations between basic home ICT access and reading achievement among U.S. 15-year-olds using the 2018 Programme for International Student Assessment (PISA) data. By focusing on home computer availability, internet access, and the number of ICT devices, we investigate whether the foundational premise of digital divide research, that basic technology access is associated with educational outcomes, remains relevant for contemporary students. Thus, this research is guided by two main questions:

- (1) How do access to home computers and the Internet, individually and combined, relate to reading assessment scores for 15-year-old U.S. students?
- (2) What is the relationship between the number of ICT devices in the home and reading assessment scores among 15-year-old U.S. students, and does this relationship vary by access to home computers and the Internet?

2. Literature review

2.1. The evolution of digital reading and ICT access

The paradigm shift from print to digital literacy during the past 20 years is closely tied to the proliferation of ICT devices that emerged in the late 1990s. Reading today looks different than it did some two decades ago, with many new genres of digital communication (e.g., email, text messages, gaming lingo) changing how information is sent and understood [3]. This transformation has made the examination of home ICT access and its relationship to academic achievement increasingly important.

2.2. Early evidence for ICT access benefits

Early systematic studies established positive associations between home technology access and reading achievement. Espinosa et al. [4] used the Early

Childhood Longitudinal Study (ECLS) 1998–1999 to examine the impact of home technology on students' reading and math achievement in early grades. The researchers found that using computers at home, particularly with internet access, was positively correlated with K and 3rd grade students' reading achievement. The two-level hierarchical linear growth model showed statistically significant effects on both final reading achievement status and growth rates across time [4].

Similarly, Vigdor et al. [8] studied the impact of home computers and high-speed internet access among 5th-8th grade North Carolina public school students between 2000–2005. Results showed small but statistically significantly higher scores for students with home computer access, in contrast, high-speed internet access effects were non-confirmatory [8].

2.3. The importance of purposeful ICT use

Subsequent research revealed that the type and purpose of ICT use significantly influence educational outcomes. Petko et al. [7] analyzed approximately 294,991 samples from 39 countries using 2012 PISA data, examining the 15-year-old students' ICT use, ICT-related attitudes, and test scores. Results showed that the frequency of computer use for school-related purposes at home had statistically significant positive impacts on their reading test in 29 countries, with models explaining 19.5% to 42.6% of students' reading scores variability [7].

Lee and Wu [9] conducted a similar study with a sample size of 297,259 15-year-old students from 42 countries using 2009 PISA data, finding statistically significant positive but indirect impacts of ICT availability at home. The authors concluded that students need to either spontaneously use home ICT resources meaningfully or require close direction and supervision of parents or guardians. These findings were consistent with Gubbels et al. [10], who found that students' reading scores increased as ICT usage increased at school and home for school-related work but became unfavorable for those who used them excessively.

Recent large-scale analyses have further validated these findings about purposeful ICT use. Sanfo [11] examined Japanese PISA 2018 data and found that subject-related ICT use positively influenced reading, mathematics, and science outcomes, while leisure use showed negative associations across all domains. Similarly, Hu and Yu [12] analyzed longitudinal PISA data from 2009–2018 across 57 countries, revealing that the relationship between digital technology and reading varies significantly by purpose: recreational email and online news consumption were positively associated with reading achievement, while recreational social networking and gaming showed negative associations. Li and Petersen [13] extended this understanding through multilevel structural equation modeling with PISA 2015 data, demonstrating that ICT use outside school for academic purposes showed positive effects, while leisure and social use had negative direct effects but positive indirect effects through student autonomy and interest.

2.4. Contradictory and negative findings

Despite evidence of positive effects, several studies report contradictory findings. Rosen and Gustafsson [6] attempted to identify the longitudinal effect of home

computer availability on reading achievement among 4th grade students using data from the International Association for the Evaluation of Educational Achievement (IEA) 10-Year Trend Study and followed up with the 2001–2006 data from the Progress in International Reading Literacy Study (PIRLS). Regression analyses in both datasets showed statistically significant negative effects of home computers on students' reading achievement scores [6].

Likewise, Hu et al. [5] reported that student ICT availability at home was negatively associated with academic achievement after analyzing 2015 PISA data that included 305,414 students from 44 countries. These findings aligned with meta-analytical research, e.g., Delgado et al. [14] and Kong et al. [15] suggesting that traditional paper-based reading was more effective than digital reading, concluding that access to ICT devices only lowers students' academic achievement.

These mixed findings persist in recent research. Arpaci et al. [16] examine PISA 2015 data across 35 countries and found that ICT development indices, suggesting that context matters significantly. Huang et al. [17] analyzed East Asian PISA 2015 data and found that while ICT self-efficacy positively predicts ICT use, ICT use in learning showed negative associations with science achievement, a relationship mediated by students' enjoyment in learning. Agasisti et al. [18] provided evidence from Latin American contexts that ICT availability was more influential than ICT use in improving educational outcomes, highlighting the persistent importance of basic access.

2.5. Experimental and intervention studies

Conversely, an experimental study conducted by Malamud et al. [19] on 2457 out of 4847 interested samples of elementary-level students (grades 3–5) from 14 low-achieving public schools in Metropolitan Lima, Peru. The students were classified as either No Laptop, Laptop Only, or Laptop + Internet groups, and their performance on various aspects of computer and internet use, including reading and math cognitive tests were measured. In most of the measures, students having access to home internet and computers outperformed the Laptop Only groups, which in turn outperformed the control group. However, the researcher found no statistically significant difference in students' reading test scores based on group assignments. In other words, contrary to research that either reported a positive or negative impact of home ICT on reading, this study did not find a difference in test scores either way.

2.6. Contemporary U.S. and international evidence

Several recent studies have further explored the relationship between home ICT access and academic achievement. Erdogdu [20] found that while general technology use did not predict achievement, equity of access to specific home ICT resources did positively predict reading scores. Similarly, Borgonovi and Pokropek [21] found that equitable home computer and internet access led to higher reading achievement, though this relationship has weakened over time as access became more universal. Calica [22] also found positive links between home internet access and Philippine students' reading scores when accounting for parental support.

However, other studies paint a more complex picture. For example, Daoud et al. [23]

review showed benefits of home internet access and were influenced by parental monitoring and child's usage. Additionally, Delgado et al. [14] meta-analysis suggested digital reading may negatively impact comprehension relative to print, especially for those with lower prior knowledge. Recent U.S.-focused research by Ghimire and Mokhtari [24] using PISA 2018 data found patterns consistent with purposeful use importance, demonstrating that active internet engagement was crucial for positive reading outcomes, while device overabundance (beyond 9–10 devices) showed negative associations. This work was extended internationally by Ghimire and Regmi [25], who used hierarchical linear modeling across 79 countries to reveal that home technology access showed stronger positive effects in technology-poor schools suggesting compensatory mechanisms. Taken together, these studies reinforce that while home technology can support academic achievement, outcomes depend on digital equity and purposeful use of ICT for reading and learning.

2.7. The present study

The concept of the digital divide originally focused on disparities in basic access to computers and internet connectivity. Early research consistently demonstrated that students with home ICT access outperformed those without [4,8,9]. However, as technology has become more widespread, questions have emerged about whether these fundamental access gaps still influence academic achievement.

Recent studies present conflicting findings about associations between home ICT and reading performance [5–7], with some suggesting that the nature of technology use may be more important than mere access [10,23]. Contemporary research continues to show mixed results: Arpaci et al. [16] found that ICT factors explained more variance in countries with lower technology development, while Sanfo [11] demonstrated that subject-related ICT use positively associated with achievement, but leisure use showed negative associations. Agasisti et al. [18] found that ICT availability was more important than ICT use for educational outcomes in Latin American contexts. However, most recent research examines multiple countries or complex usage patterns, leaving unclear whether basic access disparities, the first level of digital divide, continue to be associated with U.S. students' reading achievement specifically.

This study addresses this question by examining whether home computer access, internet availability, and the number of ICT devices are associated with reading achievement differences among U.S. 15-year-olds. Using PISA 2018 data from 4838 students across 164 schools, we test whether the fundamental premise of digital divide research, the basic technology access is associated with educational outcomes, remains valid in today's more connected educational landscape.

3. Materials and methods

3.1. Data collection and participants

We utilized the OECD PISA 2018 dataset, focusing on the reading achievement of 15-year-olds from the United States. The dataset encompassed 4838 students across 164 US schools.

The 2018 PISA assessments focused on reading as a major domain. Approximately 600,000 students from 79 participating countries (37-OECD, and 42 partner countries) completed the assessments, representing around 31 million 15-year-olds [3]. Following two-stage sampling procedures, 150 schools were selected from each country, with 42 15-year-olds randomly selected per school [26,27].

Results from PISA use scales to show proficiency degrees in the respective domains. Two-thirds of the OECD country students scored between 400 and 600 points, with a mean scale of 500 and a standard deviation of 100.

Missing data

Missing data analysis revealed that 273 students (5.6%) had incomplete data on key predictors: COM_HOM (1.3% missing), ICTHOME (4% missing), and INTERNET (5.3% missing). Little's MCAR test indicated that data were not missing completely at random ($\chi^2 = 847.2, p < 0.001$) [28].

Following PISA technical recommendations for secondary analysis, we conducted missing data analysis to examine potential bias. Students with missing ICT data had significantly lower reading scores ($M = 463.2, SD = 98.4$) compared to students with complete data ($M = 509.2, SD = 104.6$), $t(4836) = 8.43, p < 0.001$. However, given the relatively low proportion of missing cases ($< 6\%$) and robust nature of weighted survey analysis with plausible values, we employed listwise deletion as recommended for PISA secondary analyses when missing data rates are below 10% [26]. This approach resulted in a final analytic sample of 4565 students, maintaining representativeness of the U.S. 15-year-old population through appropriate survey weights.

3.2. Measures of reading achievement

Reading achievement was measured using PISA 2018 plausible values, which represent the range of abilities that students might reasonably have given their observed responses. PISA provides 10 plausible values (PV1READ through PV10READ) for each student to account for measurement uncertainty in complex assessments. These plausible values were used as dependent variables in all regression analyses following established PISA technical standards [26,27].

The reading assessment comprised three cognitive processes: locating information (LOC_INFO), understanding text (UNDERSTD), and evaluating and reflecting (EVAL_REF). Additionally, scores were provided for single text (SINGLE), and multiple text (MULTIPLE) scenarios, with the composite reading score weighted 65% single text and 35% multiple texts.

3.3. Measures of home ICT

This study focused on three key aspects of home ICT access representing first-level digital divide indicators.

- Internet access (INTERNET): An ordinal variable classifying students based on home internet availability. It was coded as (0) for no access, (1) for access without academic/reading usage, and (2) for usage needed.
- Home computers (COM_HOME): A dichotomous variable represented availability, with (1) access to a home computer and (0) otherwise.

- Available ICT devices (ICTHOME): A continuous variable representing the total count of technological tools in the household (range 1–12), including computers, smartphones, tablets, e-readers, and gaming consoles.

3.4. Procedures and data analysis

All analyses followed PISA technical standards for complex survey data and plausible values methodology. We used survey-weighted regression with student final weights (W_FSTUWT) to account for the complex sampling design. For each model, we conducted 10 separate weighted regressions using each plausible value as the dependent variable, then combined results using Rubin's rules to properly account for both sampling and measurement uncertainty.

Six progressive models were estimated:

- Model 1: Null model.
- Model 2: Computer access only.
- Model 3: Computer and Internet access with interaction terms.
- Model 4: Full ICT model with all variables and interactions.
- Model 5: Quadratic ICT relationship addressing non-linear associations.
- Model 6: Fully moderated quadratic model examining how computer and Internet access moderate the ICT device-achievement relationship.

Model comparison was used Akaike Information Criterion (AIC) averaged across plausible values. All analyses were conducted using R with the {survey package} for complex survey design and the {mitools package} for multiple imputation inference [29]. Statistical significance was evaluated at $\alpha = 0.05$, with effect sizes interpreted using Cohen's guidelines.

Our analytical approach intentionally focused on first-level digital divide indicators without including socioeconomic covariates such as ESCS (Economic, Social and Cultural Status) or gender. This decision was made to isolate the direct associations between basic technology access and reading achievement, consistent with foundational digital divide research that examines whether fundamental access gaps remain educationally relevant. While socioeconomic factors undoubtedly influence both technology access and academic outcomes, including them as controls could mask the very inequalities that first-level digital divide research seeks to document. By focusing exclusively on access indicators, we can assess whether basic technology disparities continue to be associated with achievement differences in today's more connected educational landscape, providing essential baseline evidence for digital equity policies.

4. Results

Before proceeding with the proposed statistical analyses, we conducted a thorough set of parametric tests to ascertain the basic assumptions were met, including exploratory data analyses, Levene's Test, Durbin-Watson statistics, and measures of skewness and kurtosis. The data were found to meet essential assumptions for regression analysis, and all analyses were conducted using R [29] with survey weights and plausible values methodology.

Table 1. Descriptive statistics and pairwise correlation for all measures.

		Correlation coefficients								
		1	2	3	4	5	6	7	8	
Variables	Mean	SD	COM_HOM	INTERNET	ICTHOME	LOC_INFO	UNDERSTAND	EVAL_REF	SINGLE	MULTIPLE
COM_HOM	n/a	n/a	-	-	-	-	-	-	-	-
INTERNET	n/a	n/a	0.254***	-	-	-	-	-	-	-
ICTHOME	9.41	2.09	0.381***	0.320***	-	-	-	-	-	-
LOC_INFO	496.89	102.77	0.205***	0.168***	0.033*	-	-	-	-	-
UNDERSTAND	495.75	106.55	0.210***	0.167***	0.055***	0.974***	-	-	-	-
EVAL_REF	504.97	110.50	0.221***	0.178***	0.065***	0.967***	0.980***	-	-	-
SINGLE	497.33	108.28	0.206***	0.167***	0.043**	0.970***	0.987***	0.976***	-	-
MULTIPLE	500.00	106.29	0.212***	0.171***	0.057***	0.975***	0.985***	0.981***	0.983***	-
READ_SCR	505.00	104.98	0.207***	0.170***	0.048**	0.970***	0.984***	0.975***	0.982***	0.983***

Note: COM_HOM = index of availability of computer at home; INTERNET = index of availability of internet at home; ICTHOME = number of available information and computer technology devices at home; LOC_INFO = students’ scores on the locating information component of the PISA 2018 assessment; UNDERSTAND = students’ score on understanding the text component; EVAL_REF = students’ scores on the evaluation and reflection section of the PISA 2018 assessment; READ_SCR = students’ composite reading scores; SD = standard deviation; n/a = not applicable. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 1 provides descriptive statistics and correlations among the variables. The predictors—computer availability at home, home internet access, and number of ICT devices—were significantly correlated with reading scores and other outcomes. Correlations ranged from weak to medium ($r_s = 0.17$ to 0.38), following Cohen’s guidelines [30]. Access to a computer at home demonstrated the strongest correlations ($r_s = 0.205$ to 0.221), followed by home internet access. Strong correlations were also noted among the outcome variables ($r_s = 0.970$ to 0.987), indicating a high reliability in predicting overall reading scores.

Around 13% of the students lacked access to computers at home, and under 4% reported they did not have home internet access. Interestingly, 3% had internet but didn’t use it. Most students without home computers reported access to the internet, and the average number of ICT devices was lower among students without access to computers or the internet.

Within the larger context, the average number of household ICT devices for 15-year-old PISA test takers in 2018 was 9.41, with a standard deviation of 2.09, ranging from 1 to 12 devices. These statistics offer a detailed perspective on the distribution and use of ICT resources among the surveyed student population.

4.1. Progressive regression analysis

A progressive regression analysis evaluated five sequential models against a Null Model (M0; Pseudo $R^2 = 0.0000$) to examine the association between first-level digital divide indicators and reading achievement. Model 1 (M1), incorporating home computer access (COM-HOM), explained 4.41% of the variance in reading scores (Pseudo $R^2 = 0.0441$, mean AIC = 18,455.83). The subsequent addition of internet access (INTERNET) and its interaction with computer access in Model 2 (M2) significantly improved explanatory power (Pseudo $R^2 = 0.0769$, mean AIC = 18,406.63), indicating that the effects of these access variables were interdependent.

Model 3 (M3) introduced (ICTHOME) and its comprehensive interactions with COM_HOM and INTERNET, resulting in a marginal increase in variance explained (Pseudo $R^2 = 0.0802$) but a slightly less parsimonious fit compared to M2 based on its AIC (18,407.00), despite identifying a significant three-way interaction.

Model 4 (M4) refined the specification by incorporating a quadratic term for ICTHOME ($ICTHOME^2$) while retaining the COM_HOM X INTERNET interaction. This substantially improved model fit (Pseudo $R^2 = 0.0973$) and yielded lower AIC (18,374.81), supporting a non-linear, inverted U-shaped relationship between ICTHOME and reading achievement. The final specification, Model 5 (M5), tested the moderation of this quadratic (ICTHOME) relationship by both COM_HOM and INTERNET statuses. M5 demonstrated the best overall fit, explaining 10.63% of the variance in reading scores and achieving the lowest AIC (18,364.65). This most complex model indicated that the quadratic effect of ICTHOME was specifically moderated by the “Internet (Not Used)” status, while the significance of other interactions, such as COM_HOM X INTERNET (Used), was attenuated compared to similar models, reflecting a nuanced interplay of digital divide components.

4.2. Research question 1: Home computer and internet access effects

Model 1 (Table 2) established that home computer access alone was significantly associated with reading achievement, $R^2 = 0.044$, $F(1, 4563) = 214.98$, $p < 0.001$. Students with computer access demonstrated substantially higher reading scores than those without, confirming basic digital divide effects.

Table 2. Weighted regression models predicting reading achievement using plausible values analysis.

Variable	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5
	Null Model	Computer Only	Computer + Internet	Full ICT	Quadratic ICT	Moderated Quadratic
Panel 1: Main Effects						
Intercept	509.93*** (1.71) [506.56, 513.30]	448.35*** (4.74) [439.03, 457.68]	437.89*** (11.31) [415.69, 460.10]	378.20*** (25.24) [328.71, 427.69]	290.02*** (19.88) [251.03, 329.00]	313.32*** (33.39) [247.86, 378.78]
Computer access	-	69.68*** (5.02) [59.81, 79.54]	29.40 (17.56) [-5.04, 63.84]	94.26* (48.02) [0.09, 188.44]	6.58 (17.54) [-27.82, 40.98]	-49.64 (47.95) [-143.68, 44.41]
Internet access	-	-	-	-	-	-
Has Internet (Not Used)	-	-	-26.19 (18.97) [-63.40, 11.01]	66.87 (45.95) [-23.47, 157.20]	-52.86** (19.83) [-91.74, -13.97]	23.12 (82.57) [-139.40, 185.65]
Has Internet (Used)	-	-	15.50 (12.42) [-8.87, 39.86]	118.12*** (31.69) [56.00, 180.24]	-17.26 (13.02) [-42.81, 8.29]	-70.98 (53.31) [-175.52, 33.55]
ICT Devices (Linear)	-	-	-	12.00* (4.78) [2.60, 21.38]	46.36*** (5.26) [36.04, 56.68]	55.78*** (12.47) [31.32, 80.24]
ICT Devices (Quadratic)	-	-	-	-	-2.74*** (0.30) [-3.32, -2.15]	-5.05*** (1.07) [-7.16, -2.95]

Table 2. (Continued).

Variable	Model 0	Model 1	Model 2	Model 3	Model 4	Model 5
	Null Model	Computer Only	Computer + Internet	Full ICT	Quadratic ICT	Moderated Quadratic
Panel 2: Two-way interactions						
Computer X Internet (Not Used)	-	-	-41.61 (25.55) [-91.71, 8.49]	-134.04 (80.59) [-291.61, 24.53]	-17.19 (25.78) [-67.74, 33.35]	-73.70** (28.29) [-129.18, -18.23]
Computer X Internet (Used)	-	-	39.26* (18.36) [3.25, 75.27]	-53.07 (52.71) [-156.42, 50.28]	59.67*** (18.18) [24.01, 95.32]	6.85 (20.41) [-33.17, 46.88]
Computer X ICT Devices	-	-	-	-12.78 (7.51) [-27.50, 1.95]	-	13.41 (12.58) [-11.26, 38.08]
Computer X ICT Devices ²	-	-	-	-	-	-0.08 (0.76) [-1.58, 1.41]
Internet (Not Used) X ICT Devices	-	-	-	-15.87* (7.08) [-29.73, -2.01]	-	-23.26 (23.55) [-69.56, 23.03]
Internet (Used) X ICT Devices	-	-	-	-17.51*** (5.32) [-27.94, -7.08]	-	6.10 (16.16) [-25.60, 37.80]
Internet (Not Used) X ICT Devices ²	-	-	-	-	-	2.56 (1.62) [-0.63, 3.39]
Internet (Used) X ICT Devices ²	-	-	-	-	-	-
Panel 3: Three-way interactions						
Computer X Internet (Not Used) X ICT	-	-	-	16.10 (10.44) [-4.43, 36.63]	-	-
Computer X Internet (Used) X ICT	-	-	-	16.63* (7.95) [1.14, 32.31]	-	-
Panel 4: Model statistics						
R^2	0.00	0.044	0.077	0.80	0.097	0.106
Average AIC across plausible values	51,675,328	18,455.83	18,406.63	18,407.00	18,374.81	18,364.65
n	4565	4565	4565	4565	4565	4565

Note: All models use plausible values methodology with appropriate survey weights (W_FSTUWT). Coefficients represent unstandardized regression coefficients with standard errors in parentheses and 95% confidence intervals in brackets. Computer Access: 0 = No computer, 1 = Has Computer; Internet Access: 0 = No Internet, 1 = Has Internet (Not Used), 2 = Has Internet (Used); ICT devices = number of ICT devices at home (1–12 scale). Model 1 = Computer access only; Model 2 = Computer and Internet access with interaction; Model 3 = Full model with all ICT variables; Model 4 = Quadratic ICT model; Model 5 = Fully moderated quadratic model. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$. The computer-internet interactions revealed the technology access alone was insufficient, the combination of access and usage patterns determined the relationship with reading achievement. Students with both computer access and active internet usage showed the strongest positive associations, while students with internet access but no computer or no usage showed weaker or negative patterns.

Model 2 revealed complex interaction patterns when both computer and internet access were considered together, $R^2 = 0.077$, $F(1, 4559) = 75.68$, $p < 0.001$. The analysis showed that internet access effects were contingent on both availability and usage. Students with internet access who actively used it showed positive associations with reading achievement, while those with access but no reported usage showed negative coefficient estimates. Crucially, these internet effects were moderated by computer availability, indicating that the benefits of internet access were enhanced

when combined with home computer access.

4.3. Research question 2: Home ICT devices quantity relationships

Models 4 and 5 (Table 2, Models 4–5) revealed a significant curvilinear relationship between ICT device quantity and reading achievement. Model 4 demonstrated a clear inverted-U pattern with a significant positive linear ICT coefficient ($b = 46.36$, $SE = 5.26$, $p < 0.001$, 95% CI [36.04, 56.68]) and negative quadratic coefficient ($b = -2.74$, $SE = 0.30$, $p < 0.001$, 95% CI [-3.32, -2.15]), confirming that reading scores increased up to approximately 8–9 devices, then declined with additional devices. This non-linear relationship is visually depicted in Figure 1, which illustrates the inverted-U pattern across the full range of ICT device quantities.

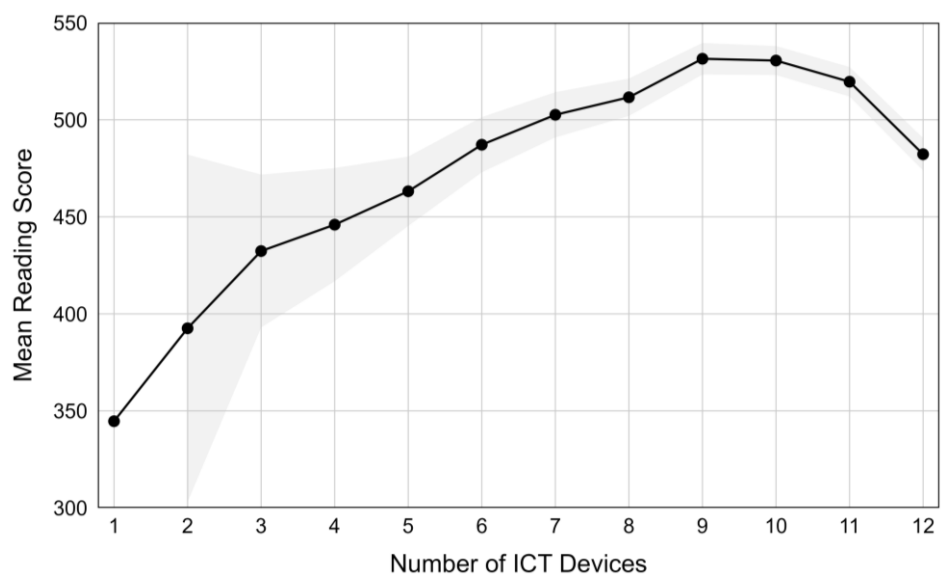


Figure 1. Relationship between number of ICT devices and reading achievement scores.

Model 5 (Table 2, Model 5) addressed the second part of Research Question 2 by examining whether the ICT device-achievement relationship varied by computer and internet access. The linear ICT coefficient ($b = 55.78$, $SE = 12.47$, $p < 0.001$, 95% CI [31.32, 80.24]) and quadratic coefficient ($b = -5.05$, $SE = 1.07$, $p < 0.001$, 95% CI [-7.16, -2.95]) remained statistically significant, while significant interaction terms revealed that the optimal number of ICT devices differed depending on students' foundational technology access and usage patterns.

Students with computer access showed different ICT device relationships compared to those without computers. Similarly, internet usage patterns significantly moderated the curvilinear ICT device relationship. Active internet users showed more pronounced benefits from moderate device quantiles, while non-users showed flatter or negative relationships across device levels.

The moderated analyses confirmed that the relationship between ICT devices and reading achievement was not uniform across students. The optimal device thresholds (8–9 devices) applied primarily to students with active technology usage patterns. Students with passive technology environments showed diminished returns from

additional devices at much lower thresholds.

To conclude, the progressive model development from simple computer access (Model 1) to complex moderated relationships (Model 5) demonstrated substantial improvement in explained variance (R^2 increased from 0.044 to 0.106) and model fit (AIC improved by over 90 points). These analyses provided clear answers to both research questions:

Research Question 1: Home computer and internet access showed significant individual and combined associations with reading achievement, but these relationships were contingent on usage patterns and interactive effects rather than simple access.

Research Question 2: ICT device quantity showed a significant curvilinear relationship with reading achievement, and this relationship was substantially moderated by both computer ownership and internet usage patterns, confirming that technology effects cannot be understood in isolation from the broader home technology environment.

5. Discussion

This research examined how home ICT access, representing first-level digital divide indicators, is associated with reading achievement among U.S. 15-year-old students. Using plausible values methodology and survey-weighted regression analysis, we found that fundamental gaps in technology access remain significantly linked to reading performance, accounting for approximately 10.6% of the variance in reading achievement. Progressive model development further revealed that while basic access plays an important role, the relationships between home computer availability, internet connectivity, and the number of ICT devices are complex and interdependent.

5.1. How do access to home computers and the Internet, individually and combined, relate to the reading assessment scores for 15-year-old U.S. students?

Our investigation confirmed that basic home computer access remains significantly associated with reading achievement differences among 15-year-old U.S. students. As shown in **Table 2**, Model 1 established that computer access alone explained 4.4% of variance in reading scores ($b = 69.68$, $SE = 5.02$, $p < 0.001$), with students having some computers demonstrating substantially higher achievement than those without. **Figure 2** illustrates this pattern consistently across all reading components, students with computer access scored higher on locating information, understanding text, evaluating and reflecting, single text, multiple text, and composite reading scores. This finding supports the foundational premise of digital divide research that basic technology access continues to be associated with educational outcomes, even in today's more connected landscape.

However, the addition of internet access variables in Model 2 (**Table 2**) revealed more nuanced patterns. Internet access showed complex associations that depend on both availability and reported usage patterns. The interaction effects in Model 2 demonstrated that students with internet access who reported using it showed positive

associations (Computer X Internet Used: $b = 39.26$, $SE = 18.36$, $p < 0.05$), while the main effect for internet access without usage showed negative coefficients. **Figure 3** clearly illustrates this pattern, showing that students with internet access but no reported usage performed worse than those without any internet access, while students with active internet usage achieved the highest reading scores. This pattern suggests that mere productivity availability is insufficient, i.e., the relationship between internet access and reading achievement appears contingent on active engagement.

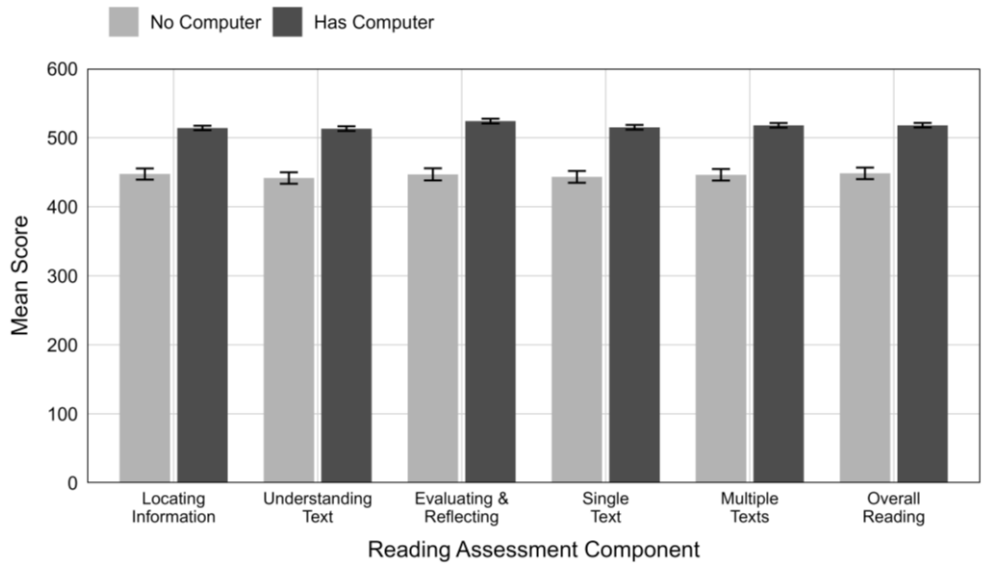


Figure 2. Bar diagram showing students’ reading achievement scores on locating information, understanding information, evaluating and reflecting, single text, multiple text, and reading score based on access to a home computer.

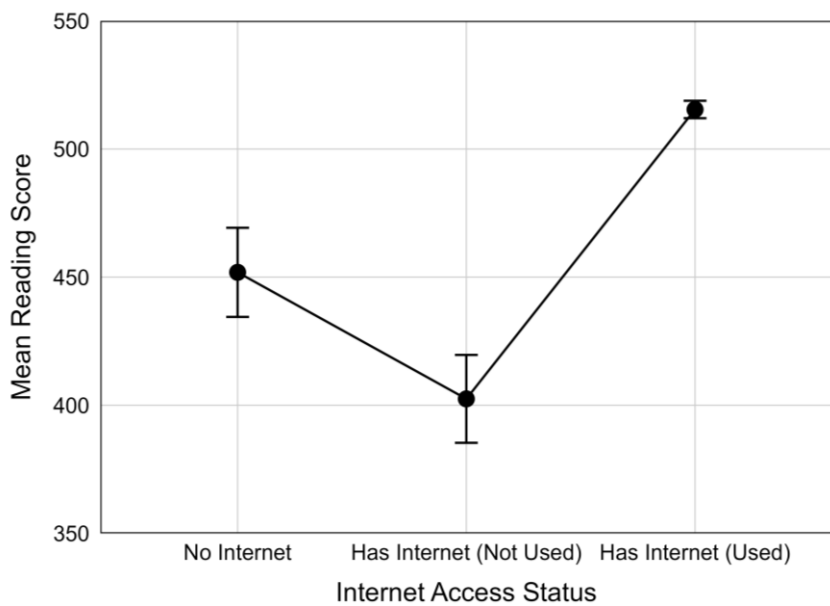


Figure 3. Mean reading achievement scores by internet access and usage status.

These findings align with contemporary digital divide research emphasizing that access alone does not guarantee positive outcomes [7,23]. Recent research by Sanfo [11] using Japanese PISA 2018 data supports our findings, demonstrating that subject-related

ICT use positively influenced reading outcomes while leisure use showed negative associations. Similarly, Hu and Yu [12] analyzed longitudinal PISA data from 2009–2018 across 57 countries, revealing that the relationship between digital technology and reading varies significantly by purpose and engagement patterns. The interaction effects between computer and internet access (Model 2, **Table 2**) demonstrated that technology benefits were enhanced when students had both foundational tools and engaged with them actively. Students with both computer access and active internet usage showed the strongest positive associations, while students with internet access but no computer or no reported usage showed weaker or negative patterns.

From a theoretical perspective, these results support Rogers' [31] Diffusion of Innovation Theory, suggesting that successful technology adoption requires not just access but also the capacity and motivation for meaningful use. The finding that students with internet access but no reported usage underperformed compared to those without access (**Figure 3**) suggests that passive technology environments may not provide the engagement necessary for academic benefits. This interpretation is supported by recent research showing that the purpose and quality of technology use matter more than mere access. Li and Petersen [13] demonstrated that ICT use outside school for academic purposes showed positive effects, while leisure and social use had negative direct effects but positive indirect effects through student autonomy and interest.

5.2. What is the relationship between the number of ICT devices in the home reading assessment scores for 15-year-old U.S. students, and does this relationship vary by access to home computers and the Internet?

Models 4 and 5 (**Table 2**) revealed a significant curvilinear relationship between ICT device quantity and reading achievement, addressing our second research question about whether device relationships vary by foundational access. The inverted-U patterns demonstrated that reading scores increased with additional devices up to approximately 8–9 devices, then declined with further increases. This non-linear relationship was robust across different reading components, as detailed in **Table 3**, which shows consistent patterns across locating information, understanding text, evaluating and reflecting, single text, multiple text, and composite reading scores. **Table 3** demonstrates that students with 9 devices achieved peak performance (mean reading score = 530.4), while those with 12 devices showed substantially lower scores (mean = 475.0), confirming the threshold effect observed in **Figure 1**.

The quadratic relationship (Model 4, **Table 2**: linear coefficient $b = 46.36$, $SE = 5.26$, $p < 0.001$; quadratic coefficient $b = -2.74$, $SE = 0.30$, $p < 0.001$) suggests that moderate device availability shows positive associations with achievement, but excessive device quantities may be associated with diminished performance. This pattern contradicts simple “more is better” assumptions about technology access and suggests threshold effects in the technology-achievement relationship.

Model 5's moderated analysis (**Table 2**) revealed that this curvilinear relationship was significantly influenced by students' foundational technology access and usage patterns. The linear ICT coefficient ($b = 55.78$, $SE = 12.47$, $p < 0.001$) and quadratic coefficient ($b = 55.78$, $SE = 12.47$, $p < 0.001$) remained statistically significant, while

significant interaction terms revealed that optimal device thresholds differed depending on students' computer and internet access. The optimal device threshold (8–9 devices) applied primarily to students with active technology usage patterns, while students with passive technology environments showed diminished returns from additional devices at much lower thresholds. This finding suggests that the benefits of multiple devices depend on students' capacity to use technology purposefully.

Table 3. Distribution of students' reading achievement scores based on the number of ICT devices at home.

ICT_HOME Mean (SD)	LOC_INFO Mean (SD)	UNDERSTAND Mean (SD)	EVAL_REF Mean (SD)	SINGLE Mean (SD)	MULTIPLE Mean (SD)	READ_SCR Mean (SD)
1-device	362.2 (73.9)	346.9 (82.3)	346.1 (86.3)	351.9 (86.3)	349.8 (87.6)	345.4 (96.8)
2-devices	402 (110)	397 (122)	408 (119)	400 (130)	396 (120)	400 (121)
3-devices	445 (68.5)	448.1 (68.4)	449.4 (70.4)	446.8 (67.8)	449.5 (68)	446.1 (74.9)
4-devices	440 (102)	433 (103)	437 (108)	434 (105)	433 (101)	439 (102)
5-devices	462.8 (91.5)	457.8 (93.7)	458.1 (100.1)	458.1 (95.1)	459.9 (92.2)	463.7 (91.7)
6-devices	485.3 (89.1)	476.9 (93)	483.2 (100)	481.6 (95.1)	482.4 (92.7)	484.5 (92.6)
7-devices	495.7 (91.6)	490.6 (95.6)	498.9 (102.3)	493.8 (97.6)	495.9 (96.2)	497 (95.5)
8-devices	506.5 (94.4)	502.2 (97.6)	511.9 (102.4)	506.5 (100.5)	508.1 (98)	509 (97.6)
9-devices	527.2 (95)	524.7 (98.6)	535.3 (101.5)	527.2 (99.8)	528.4 (97.9)	530.4 (96.4)
10-devices	522.2 (98.5)	520.2 (104.3)	532.1 (106.9)	523 (105.3)	525.6 (103)	525.7 (101.7)
11-devices	507 (100)	508 (107)	518 (110)	509 (108)	512 (106)	511 (105)
12-devices	471 (107)	471 (110)	480 (112)	470 (112)	476 (109)	475 (107)

Note: COM_HOM = index of availability of computer at home; INTERNET = index of availability of internet at home; ICT_HOME = number of available information and computer technology devices at home; LOC_INFO = students' scores on the locating information component of the PISA 2018 assessment; UNDERSTAND = students' score on understanding the text component; EVAL_REF = students' scores on the evaluation and reflection section of the PISA 2018 assessment; READ_SCR = students' composite reading scores; SD = standard deviation.

Table 3 provides compelling evidence for this threshold effect across all reading dimensions. Students with 1–2 devices showed the lowest performance (mean composite scores of 345.4 and 400 respectively), while performance steadily increased through 9 devices (530.4), then declined through 12 devices (475.0). This consistent pattern across locating information, understanding the text, evaluating and reflecting, single text, and multiple text components suggests that the curvilinear relationship is not specific to particular reading skills but represents a general phenomenon in the technology-achievement association.

These results extend previous research by demonstrating that device quantity effects cannot be understood in isolation from the broader home technology environment. While some studies have found negative associations with high ICT availability [5,6], this analysis suggests these effects may reflect overabundance rather than technology use per se. Recent research provides additional context for understanding these complex relationships. Arpaci et al. [16] examined PISA 2015 data across 35 countries and found that ICT factors explained more variance in countries with lower technology development, suggesting that context matters significantly. Huang et al. [17] analyzed East Asian PISA 2015 data and found that while ICT self-efficacy positively predicted ICT use, excessive ICT use in learning

showed negative associations with science achievement, consistent with our curvilinear findings. Conversely, Agasisti et al. [18] provided evidence from Latin American contexts that ICT availability was more influential than ICT use in improving educational outcomes, highlighting the persistent importance of basic access that our study confirms.

The moderated effects shown in **Table 2** (Model 5) indicate that students with strong foundational access (computers and active internet use) can benefit from moderate device quantities, while those without such foundations may experience technology overload at lower thresholds. The detailed breakdown in **Table 3** supports this interpretation, showing that the benefits of additional devices plateau around 9–10 devices before declining, regardless of the specific reading component measured. This pattern aligns with Li and Petersen’s [13] findings using multilevel structural equation modeling with PISA 2015 data, which demonstrated that ICT use outside school for academic purposes showed positive effects, while excessive leisure and social use had negative direct effects.

5.3. Implications for digital divide research

Our findings offer important contributions to digital divide scholarship. First, they reinforce that first-level digital divide indicators, namely basic access to computers, internet, and devices, remain significantly associated with reading achievement among U.S. students. This suggests that, despite widespread technology adoption, fundamental access disparities continue to contribute to educational inequalities. This finding aligns with Agasisti et al. [18], who demonstrated that ICT availability had a stronger impact on educational outcomes than usage patterns, underscoring the ongoing relevance of measuring basic access.

Second, the complex interaction patterns demonstrate that digital divide effects are more nuanced than simple access versus no-access. The finding that internet access without reported usage shows negative associations (**Figure 3**) suggests that measuring access alone may be insufficient for understanding technology’s educational role. This complexity is supported by recent international research: Hu and Yu [12] found that recreational email and online news consumption were positively associated with achievement, while recreational social networking and gaming showed negative associations. Similarly, Sanfo [11] demonstrated that subject-related ICT use positively influenced reading outcomes while leisure use showed negative associations across all domains.

Third, the curvilinear device relationship (**Table 3, Figure 1**) highlights the importance of considering optimal rather than maximal technology provision. The threshold effect around 8–9 devices suggests that educational technology policies should focus on ensuring adequate access rather than promoting unlimited device availability. This finding resonates with Huang et al.’s [17] discovery that excessive ICT use showed negative associations with achievement and supports Li and Petersen’s [13] finding that while academic ICT use showed positive effects, excessive leisure use had negative direct effects. Recent work by Ghimire and Mokhtari [24] using the same PISA 2018 data found similar patterns, while Ghimire and Regmi [25] extended these findings internationally, demonstrating that home technology access showed stronger positive effects in technology-poor schools, suggesting

compensatory mechanisms.

6. Conclusion

This study examined whether first-level digital divide indicators—home ICT access—are associated with reading achievement among 15-year-old students in the United States. Using proper plausible values methodology with survey-weighted regression analysis, our findings revealed that fundamental technology access gaps continue to show significant associations with reading performance, explaining approximately 10.6% of the variance in reading scores.

We found that students with home computer access consistently demonstrated higher reading achievement across all reading components. However, the mere presence of technology access does not guarantee positive educational benefits; our analyses revealed that internet connectivity without active usage was associated with lower performance compared to no internet access at all. This finding underscores the importance of considering both availability and engagement patterns when examining digital divide patterns.

Moreover, our results revealed a curvilinear relationship between the number of ICT devices and reading scores, with peak performance associated with approximately 8–9 devices before declining with additional devices. This finding suggests that moderate technology access may be more beneficial than excessive device availability, particularly for students without strong foundational access patterns.

Interpreted through the lens of diffusion theory, these insights highlight the complexity of technology-achievement relationships and suggest that basic access effects remain relevant even in today's more connected educational landscape. However, they also demonstrate that simple access provision is insufficient—the relationship between technology and achievement depends on broader patterns of engagement and foundational combinations.

Our findings contribute to digital divide scholarship by confirming that first-level access indicators continue to be associated with educational outcomes while revealing the nuanced nature of these relationships. The study emphasizes the need for educational technology policies that focus on ensuring adequate rather than maximal access, coupled with support for meaningful technology engagement to optimize educational benefits.

7. Limitations and future directions

While the present study revealed a significant correlation between home ICT access and the reading proficiency of U.S. 15-year-old PISA 2018 participants, the interpretation of these results requires cautious consideration of several key limitations. Our intentional focus on first-level digital divide indicators meant we did not examine critical components that may mediate these relationships, including socioeconomic status, gender, household composition, parental guidance in ICT usage, prior academic performance, and student motivation. Furthermore, home technology access variables are likely associated with higher household income and other socioeconomic advantages that independently influence academic achievement. Future analyses incorporating these variables would provide a more comprehensive

understanding of the mechanisms underlying technology-achievement associations.

The study's methodology and scope present additional limitations. First, reliance on self-reported PISA survey measures necessitates consideration of potential response inaccuracies from 15-year-old participants. Second, while we properly implemented plausible values methodology with survey weights, our analytical approach focused on associations rather than causal mechanisms, advanced techniques like multilevel structural equation modeling could better illuminate causal pathways in future studies. Third, our focus on U.S. participants restricts broader applicability, as previous research demonstrates considerable cross-national variation in ICT-achievement relationships [6,16]. Finally, the cross-sectional design prevents causal inferences about technology's role in achievement development.

Future research should address these limitations by examining second-level digital divide factors, including digital literacy skills, quality of technology use, and support systems that mediate first-level access effects. Longitudinal studies tracking students' technology access and achievement trajectories would provide stronger evidence about directional relationships. Additionally, research incorporating resources, and community support could identify conditions that optimize technology benefits for reading achievement.

Moreover, international comparative studies examining how first-level digital divide effects vary across different educational and technological contexts would enhance understanding of when and where basic access remains most crucial. Qualitative research exploring students' lived experiences with home technology could provide valuable insights into the mechanisms underlying the quantitative patterns observed, particularly regarding the counterintuitive finding that internet access without usage was associated with lower achievement than no access at all.

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