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The influence of age at first regular digital device access on digital reading performance: the mediating effect of cognitive flexibility

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Younger generations are receiving their first regular digital device access at progressively earlier ages than previous generations on average, whereas disparities in their early digital device access are still being observed globally. The inequality of first regular digital device access may have profound long-term effects on one's information and communication technology (ICT) skills, but no evidence has suggested how unequal first regular digital device access impacts one's digital reading, which enables one to process and comprehend information in this digitized world. Thus, the current study investigated the relationship between the age at which children first regularly access digital devices and their digital reading performance at age 15 while considering the potential mediating effect of cognitive flexibility. A multilevel mediation model was proposed and tested using data from a cross-national sample of 156,277 15-year-old students from 18 OECD countries from the Programme for International Student Assessment (PISA). The results suggested that first regular digital device access after age 9 exerted a negative influence on digital reading scores in countries that generally had high levels of early digital access, and after age 13 in countries that had lower levels of early digital access. Additionally, cognitive flexibility mediated the association between the age at first regularly accessing digital devices and digital reading performance. Starting using digital devices regularly only after age 6, more evident at ages 9 to 12, was associated with lower levels of cognitive flexibility, which in turn led to worse digital reading performance. These findings demonstrated the importance of early first regular access to digital devices before school age (age 6) and highlighted the need for the cultivation of cognitive flexibility in family and school uses of digital devices.

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Introduction

Age at first regular digital device access is an important factor influencing digital device users' digital-related abilities (Juhaňák et al., 2019). In the 21st century, adolescents have their first digital device access experience generally at earlier ages than previous generations (Kirschner & Bruyckere, 2017). These adolescents, known as "digital natives", grow up immersed in an increasingly digitized society in which the use of digital tools is pervasive and intensive (Kucirkova et al., 2017; Schriever, 2021). However, the digital divide, derived from digital infrastructure, family economic status, and parental regulations, persists and impedes early digital device access in a proportion of children (Chaudron et al., 2018). Therefore, the so-called digital natives' actual access to digital devices and their digital literacy, which is the ability to access, evaluate, obtain, and create useful information through digital devices, are lower than what society has expected (Livingstone & Helsper, 2007; Nichols & Stornaiuolo, 2019).

Despite that studies have addressed the age at first regular digital device access and its relationship with digital skills and learning abilities (Han, 2022; Juhaňák et al., 2019; Li et al., 2023), its relationship with digital reading, a combined sphere of digital skills and academic learning, has received scant attention. Digital reading, or the use of digital devices to read, is a basic activity of digital device use as well as a key aspect of digital literacy (Yu et al., 2023). More importantly, digital reading features a fundamental skill in one's learning in digital environments, paving the way for lifelong learning, social engagement, and personal success (Naumann, 2015; Sage et al., 2019). Therefore, assessing digital reading performance is important as it concerns not only disciplinary domain-specific constructs but also general digital literacy, which further enhances one's long-term development in future education and work (Pokropek et al., 2022). Discovering the association between how early individuals start regularly using digital devices and their digital reading performance in adolescence provides clear guidance for early family and school information and communication technology (ICT) regulations and has attracted policy attention (Papadakis et al., 2022).

The association between age at first regular digital device access and digital reading performance requires explanations from identifying the underlying cognitive pathways. Digital reading activities initiate from the very start of digital device use and are cognitively demanding as they require evaluating, navigating, locating, corroborating, and organizing information often in noncontinuous texts (Kiili et al., 2023; Ronconi et al., 2022). In turn, digital reading involves prominently higher levels of cognitive resources, especially the cognitive flexibility that deals with task switching and multitasking (Alexander, 2020). Additionally, cognitive flexibility has been revealed to be an intermediate influencing variable in the relationship between digital device use and learning outcomes (Wang & Jou, 2023). In this regard, the exploration of cognitive flexibility promises to yield crucial insights into the bridging intersection of age at first regular digital device access and digital reading performance.

The above-mentioned background demonstrates the growing importance of investigating the relationship between the age at which children start to regularly access digital devices and their reading performance in adolescence, along with the mechanism of this relationship explained through cognitive flexibility. To achieve this aim, the international large-scale assessment Programme for International Student Assessment (PISA) 2018 was utilized for analysis. PISA 2018 featured the latest reading-themed PISA cycle and assessed 15-year-old students' digital reading performance, with its background questionnaire embodying our focused topic of the age at first digital devices and cognitive flexibility. PISA 2018 has been frequently drawn as the data source for discovering factors influencing digital reading performance (e.g., Bernardo & Mante-Estacio, 2023; Hu & Wang, 2022; Yeung et al., 2022), and would provide robust data to reach solid conclusion and conduct cross-country comparisons (Lim & Jung, 2019). Therefore, this study drew on internationally representative evidence from PISA to explore the cognitive flexibility influencing mechanisms of different age groups at first regular digital device access and digital reading performance in different countries.

Literature review

Early digital device use and age at first regular digital device access. In the PISA context, digital devices are defined as all categories of ICT-related digital tools, including computers, mobile phones, multimedia players, etc. (OECD, 2019). In recent years, early digital device use, generally considered as digital device use before school age, has extensively focused on digital device types (e.g., Blank & Groselj, 2014; Papadakis et al., 2022), duration (e.g., Hu et al., 2020; Papadakis et al., 2022; Sharkins et al., 2016), parental mediation (e.g., Kucirkova & Flewitt, 2022; Marsh et al., 2017), purpose (e.g., Mourgela & Pacurar, 2018; Sivrikova et al., 2020) and pedagogy (e.g., Oades-Sese et al., 2021). However, the majority of these investigations presume that students already possess digital resources at an early age, leaving the disparities of early digital device access levels and their influence a globally understudied issue (Cabello et al., 2021).

Age at first regular digital device access refers to the starting age at which one regularly accesses digital devices, which differs from the more widely used concept of early digital device that centers one's general use of digital devices before school age. This study focuses on age at first regular digital devices because it targets a wider population by including discussion about people who access digital devices only after school age. Previous studies associated the age at first regular digital device access with early digital device use experience by indicating that individuals who first regularly accessed digital devices earlier also enjoyed more frequent and richer early digital device use experiences, which emphasized the theoretical importance of the age at first regular digital device access in understanding early digital device use and its further impacts on individual development (van Deursen & van Dijk, 2011). Surveys have also indicated that a proportion of students first access digital devices later than others, mostly due to low family socioeconomic status or disadvantaged school conditions (Hussain et al., 2023). In this regard, research on the topic of age at first regular digital device access seeks evidence to promote educational equity.

Despite that early digital device access was confirmed to influence one's cognitive, behavioral, and attitudinal development in the short and long run (e.g., Hatzigianni & Margetts, 2012; Hurwitz & Schmitt, 2020; Mallawaarachchi et al., 2021, Papadopoulou et al., 2023; Zheng & Sun, 2022), very limited evidence has directly pointed at the influence of the age at first regular digital device access. Within extant literature, Sergi et al. (2017) reported better perceived cognitive development, linguistic skills, and memory improvement in children who started using digital devices in early and primary education years. However, this study only discovered short-term effects by assessing primary-schoolers. The lasting effect of age at first regular digital device access in the long run, especially into adolescence or adulthood, was examined only in relation to ICT competence (Juhaňák et al., 2019; Li et al., 2023; Zounek et al., 2022), learning ability (Han, 2022), and problematic Internet behaviors (Nakayama et al., 2020). Age at first regular use of digital devices was found to be negatively associated with ICT competence and

autonomy; to be specific, individuals who accessed digital devices at 9 years of age and earlier were more proficient and willing to use digital access during adolescence (Juhaňák et al., 2019; Zounek et al., 2022). Li et al. (2023) also reported higher ICT self-efficacy among those who first possessed personal computers or smartphones at age 8 or earlier. Regarding digital device access and learning ability, age at first regular smartphone access negatively predicted self-learning abilities, mediated through smartphone use for entertainment (Han, 2022). However, adverse effects existed as digital device users were prone to addiction and problematic behaviors in adolescence if they first regularly accessed the internet at 9 years of age or earlier (Nakayama et al., 2020).

These studies contributed to the understanding of the age at first regular digital device use, ICT-related abilities, and learning abilities but none of them focused on ICT-related academic achievement, a topic of broader interest in linking early digital device use to future educational interventions. Among academic disciplines, digital reading stands at the intersection between digital device use and academic achievement and is fundamental in empowering learning other disciplines in digitized learning environments (Pokropek et al., 2022). Therefore, the current study sought to address this gap by exploring the relationship between age at first regular digital device access and digital reading performance.

Early digital device use experience and digital reading performance. Digital reading refers to reading digitally organized texts, where characteristics of non-linear texts, hyperlinks, and multimodal information are usually embodied (Cliton, 2019). Digital reading contrasts with print reading in its reading medium, with the former being laden on screens of various digital reading devices such as mobile phones, tablets, and e-book readers, featuring an indispensable part in 21st century's learning and individual development (Furenes et al., 2021; Hu et al., 2022; Jing et al., 2015). Omnipresent digital media permeates not only adults' work and life but also adolescents' and children's educational and entertainment experiences, enabling digital reading a daily activity for digital device users (e.g., Jiang et al., 2021; Kucirkova et al., 2017).

Early digital device use has been found to have mixed effects on students' digital reading performance in the short and long run (e.g., Furenes et al., 2021; Gremmen et al., 2016; Chi-San Ho et al., 2023; Li & Bus, 2023; Navarro-Martinez & Peña-Acuña, 2022; Strouse & Ganea, 2017). A study examining predictors of children's digital reading performance suggested that digital device use, especially computer use, positively predicts digital reading performance (Chi-San Ho et al., 2023). Vocabulary gains and more engaged reading behaviors were also observed in 17- to 26-month-olds in their early digital reading experience than in their print reading experience (Strouse & Ganea, 2017). In addition, digital books' visual and auditory information led to higher levels of story comprehension and book-based vocabulary in young children of different ages (Li & Bus, 2023). Among adolescents, Skryabin et al. (2015) showed that digital device use contributed to adolescents' digital reading performance, which was also corroborated by Hu and Yu (2021), who discovered students' increased digital reading performance among students who regularly used digital devices for entertainment purposes after school.

Nevertheless, adverse impacts on digital reading performance were detected with the excessive use of digital devices both during the week and on weekends for adolescents (Navarro-Martinez & Peña-Acuña, 2022). Three- to four-year-old children who had digital reading habits scored lower in receptive vocabulary than did those who read print books (Gremmen et al., 2016). A meta-analysis examined studies investigating early digital reading practices in children aged 1 to 8 years and reported worse comprehension scores than did print reading (Furenes et al., 2021). These divergences in the findings studies might result from students' different previous digital device access levels and different social contexts (Furenes et al., 2021). Age at first regular digital device access is an indicator of one's early digital access levels (van Deursen & van Dijk, 2011), but it has not, to our knowledge, been explored with the relationship with digital reading performance. Therefore, further investigations regarding the age effects of first regular digital device access on digital reading performance are imperative. In addition, large samples from various geographic regions would provide more robust insights into the generalizability or differentiation of the conclusion (Clinton, 2019).

Notably, socioeconomic and cultural status (ESCS) and gender were two important predictive demographic factors that influenced digital reading performance and were suggested to be included as control variables to improve model precision, especially when analyzing data from large international assessments (Navarro-Martinez & Peña-Acuña, 2022; Xiao et al., 2019, Yeung et al., 2022). Therefore, the current held ESCS and gender constant when comparing how age at first regular digital device access was associated with digital reading performance to avoid biases in data interpretation.

To further validate and explain the relationship between age at first regular digital device access and digital reading performance, intermediary paths should be drawn to establish the influencing mechanisms (Juhaňák et al., 2019). In the extant literature, the mechanisms bridging digital device access and its influences have been explored primarily through behavioral factors, leaving cognitive factors understudied as potential mediating factors (e.g., Han, 2022; Juhaňák et al., 2019; Zheng & Sun, 2022). As a rare case, Dempsey et al. (2019) discovered that mobile phone ownership before 9 years of age led to both decreased reading and math performance due to cognitive functioning. Their findings elucidated cognitive pathway research, while more detailed aspects of cognitive functioning, such as cognitive flexibility, were not specifically examined.

Cognitive flexibility. Cognitive flexibility, a core dimension of executive function, is commonly defined as "the dynamic activation and modification of cognitive processes in response to changing task demands" (Deak, 2003: 275) and is considered a higher-order property of the cognition system (Ionescu, 2012). To better align cognitive flexibility research with the topic of digital reading performance and 21st-century skills (Webb et al., 2018), PISA 2018, with digital reading as a focus, supplemented the connotation of cognitive flexibility by "adaptability in dealing with unfamiliar, challenging or difficult situations" (OECD, 2019: 21). Correspondingly, assessment methods varied as the broadened definition of cognitive flexibility extended from a cognitive process to a quality that adapts people to process intricate information in this digitized society. Traditional assessments of cognitive flexibility utilized simple simulating tasks in cognitive tests but did not picture the flexibility in real-life comprehensive tasks (Bilgin, 2009). To respond, scales of cognitive flexibility were devised to gain insights into perceived cognitive flexibility in complex problem-solving and multitasking abilities (e.g., Dennis & VanderWal, 2010; Martin & Rubin, 1995), and have attracted wide use in empirical studies (e.g., Fu et al., 2023; Orakci, 2021).

Supported by Weir's (2005) sociocognitive framework and its extensions to reading comprehension (Khalifa & Weir, 2009), the cognitive process plays a decisive role in decoding information

and is therefore pivotal in reading performance (Cirino et al., 2019; Hung, 2021; Spencer et al., 2020). Digital reading is more cognitively demanding than print reading (Furenes et al., 2021); specifically, digital reading involves enhanced cognitive flexibility to navigate, search, locate, process, evaluate, and synthesize information often in nonlinear and noncontinuous text forms (Jian, 2022; OECD, 2019). It was empirically supported that in the digital learning environment, cognitive flexibility prominently contributed to reading comprehension among all cognitive processes (Filipe et al., 2023).

An approach to developing cognitive flexibility is to build digital environments by introducing digital devices use (Chieu, 2007). Digital devices encourage multitasking in multimodal functions and help showcase an intricate virtual world where young individuals learn to cope with complex issues, therefore facilitating the cognitive flexibility of users (Dempsey et al., 2019). Wang and Jou (2023) also reported that low-achievement students perceived a greater level of cognitive flexibility in mobile-learning classrooms than in offline-learning classrooms. These studies underscored the importance of digital device access in cultivating cognitive flexibility, while Kirschner and Bruyckere (2017) noted that the digital native generation did not naturally acquire cognitive flexibility and that divergences existed in the age at which individuals first access digital devices, suggesting further investigation on how early individuals obtained digital device experience and its relationship with their cognitive flexibility development.

Previous researchers stated that the relationship between digital device access and cognitive outcomes should be explained through mediating variables (Skryabin et al., 2015), while existing studies mainly focused on behavioral factors (such as purpose and frequency) as mediating channels (Juhaňák et al., 2019). Recently, evidence has suggested cognitive flexibility as a mediating channel by which digital device use experience affects educational outcomes. For instance, Schmid et al. (2009) emphasized that facilitating cognitive flexibility development might be a major way through which technology could benefit learning. Karpinski et al. (2013) confirmed this finding by linking multitasking on the internet with positive academic performance. Specifically, for reading, cognitive flexibility was a mediator in explaining children's reading achievement from kindergarten to primary school years (Huang et al., 2022). These findings elucidated the cognitive flexibility pathway in linking digital device access and reading, but its effects have not been empirically explored in digital reading contexts. Therefore, cognitive flexibility potentially mediates our focused relationship between age at first regular digital device access and digital reading performance, but to our knowledge, no study has revealed this mechanism.

To summarize, three main research gaps existed regarding the topic of early digital device use and digital reading performance: a) although early digital device access has been proven to contribute to digital reading performance, the age at first regular digital device access was an important but understudied factor; b) relationships between digital device access and learner performance were primarily explored through behavioral mediators, while the cognitive pathway, especially cognitive flexibility, has been scantly investigated; and c) the samples of most studies exploring age at first regular digital device access are restricted to a single and highly contextualized region, leaving cross-country differences underexplored.

Therefore, the current study aimed to address these gaps by utilizing a cross-national database to identify the relationship between age at first regular digital device access and digital reading and to explore the potential mediating effects of cognitive flexibility, as well as the cross-national differences of these relationships. Three research questions (RQs) that addressed these identified gaps were proposed to guide this investigation.

RQ1: Do individual differences in age at first regular access to digital devices influence the digital reading performance of adolescents? If so, what age group(s) of first regular digital device access contributes to higher digital reading scores? Are there any cross-country differences?

RQ2: How does individuals' cognitive flexibility associate with the relationship between age at first regular digital device access and digital reading performance?

RQ3: How do student gender and socioeconomic and cultural status (ESCS) affect adolescents' digital reading performance as control variables?

A conceptual model (see Fig. 1) shows our hypotheses that age at first regular access to digital devices influences the digital reading performance of adolescents and that cognitive flexibility mediates the relationship between age at first access to digital devices and digital reading performance in adolescence. To validate the model, PISA 2018 data were drawn for analysis to enable robust cross-country comparisons.

Methods

Data source and participants. This study used internationally representative data from the PISA 2018 (student questionnaire data file, URL: https://www.oecd.org/pisa/data/2018database/). Implemented by the Organization for Economic Co-operation and Development (OECD), the PISA targets 15-year-old adolescents' subject and overall development since these students are finishing their compulsory education when educational assessments are needed to ensure the effectiveness of their former education experience and their readiness to be involved in society and further education.

The PISA yields internationally comparable results following the nested educational structure. In the PISA 2018, reading was designated as the main subject for assessment; consequently, the background questionnaires focused on students' reading-related abilities and supportive conditions. More importantly, the PISA centered on socially required abilities that help adolescents develop skills to integrate into their 21st-century social life, and the questionnaire encompassed ICT and cognitive dimensions, which lends matching support to our research topic that relates age at first regular digital device access, cognitive flexibility, and digital reading performance.

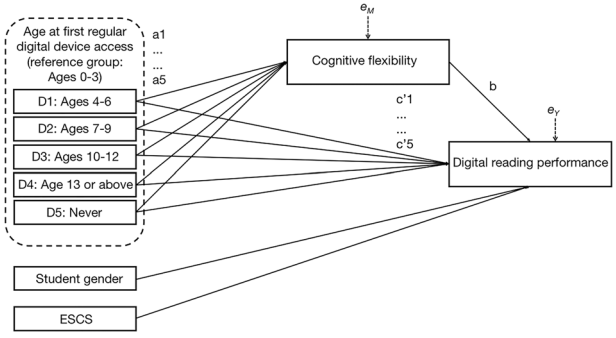

Fig. 1 The conceptual framework of the current study. *Note.* D1, D2, D3, D4, and D5 refer to the five dummy variables for age at first regular digital device access, with "age 0–3" serving as the reference group. a1 to a5 denote the coefficients from the predictor variables to the mediating variable. b denotes the coefficient from the mediating variable to the dependent variable. c1 to c5 denote the coefficients of the direct effects from the predictor variable to the dependent variable. e_m and e_y denote the estimated errors of the mediating variable and the dependent variable, respectively.

For participants in the current analysis, data from OECD countries were selected because they have generally high development levels that help prevent bias from divergent socioeconomic backgrounds in analysis and enable more comparable results (Juhaňák et al., 2019). Additionally, OECD countries have invested largely in ICT infrastructure since the beginning of the century and generally have higher digital device access levels than other areas at the beginning decade of the century (Habibi & Zabardast, 2020), a time matched with the current study's focus on one's early digital device use experience. As reported by the OECD (2023), more than 70% of OECD countries reported digital access rates for more than 50% of individuals and households in 2006, and this number has been steadily growing in the second and third decades of the century to a level above 90% access rates. This practically supports the design of the current study, as the OECD context provides valuable data to discover the differences in age at first regular digital device access in societies that provided rich ICT resources.

Considering that PISA background questionnaires were optional, we excluded countries that did not respond to the corresponding questionnaires or had missing values above 20%. 18 OECD countries were included in the final dataset, of which the sample comprised of 156,277 students from 6397 schools. The basic demographic and descriptive statistics of the surveyed countries are shown in Table 1.

Variables

Dependent variable: plausible value 1 of digital reading performance. Reading literacy was described as "an individual's capacity to understand, use, evaluate, reflect on and engage with texts to achieve one's goals, develop one's knowledge and potential, and participate in society" in the PISA 2018 framework (OECD, 2019: 15). Following this description, the PISA adopted a collection of thematically related texts to simulate real-life scenarios and therefore elicited students' higher-order thinking in such goal-oriented reading. The reading texts were selected from various sources, such as textbooks, websites, and policy documents (OECD, 2019). Complex tasks that required students to contribute their own response, including synthesizing across texts, evaluating web search results, or inter-corroborating through multiple texts, were introduced alongside traditional task formats (e.g., multiple choices), bridging reading tests to real-life cognitive tasks.

The students completed the computer-based reading test, which lasted for two hours, during which the tasks progressed from easy to difficult. Test scores that represent students' digital reading performance, scaled from the mean score and standard deviation, were reported through 10 plausible values, each containing possible numerical scores for the sampled students. According to the official explanation in the PISA Data Analysis Manual, using one or more plausible value(s) does not cause significant differences in the results for large samples, and adopting any single plausible value is effective in explaining students' disciplinary achievement (OECD, 2009: 48). We followed previous research and selected the first plausible value (PV1READ) for convenience purposes (e.g., Xiao et al., 2019; Yeung et al., 2022; Hu & Yu, 2023). The item response theory (IRT) framework was adopted to ensure comparability across cycles of PISA tests and across regions/countries within a single cycle of tests.

Predictor variable: age at first regular digital device access. The PISA investigated students' age at first digital device access by offering the question "How old were you when you first used a digital device?" in the self-reported student questionnaire. To sort out the regular digital device users and shield from potential biases or imprecision and achieve fine-grained survey results at the same time, two measures were taken: First, according to the PISA, age groups, rather than exact ages, were set as options. Students needed to choose only the age groups at their first time regularly accessing digital devices rather than the precise year. Second, through the data preprocessing of the current analysis, students whose answers to the related questions (see below in the procedures section) did not match their answers in their first digital device access experience were manually excluded from the analysis. The participating students recalled and chose one option from the age groups "3 years old or younger", "4–6 years old", "7–9 years old", "10–12 years old", "13 years old or older", and "I have never used a digital device until today", corresponding to the PISA's focus on 15-year-old adolescents (OECD, 2020). Therefore, the credibility of this question was further guaranteed.

Potential mediating variable: cognitive flexibility. The cognitive flexibility construct of the PISA was defined as students' perceived ability to mentally adapt to different real-life situations and whether they can assess whether they can come up with reasonable solutions to unusual circumstances (OECD, 2020). Aligning with the PISA's emphasis on students' social skills to adapt to a technology-filled, digitally saturated, and ever-changing human society, its survey of cognitive flexibility placed particular stress on the macro perspective of students' performance in complex real-life tasks and projects, which involved consecutive multiple decisions that aim for the same project. Therefore, the PISA operationalized cognitive flexibility in the scientific self-report questionnaire with a construct of 5 items adapted from Martin and Rubin (1995) as well as Dennis and VanderWal (2010). These five items are "I can deal with unusual situations", "I can change my behavior to meet the needs of new situations", "I can adapt to different situations even when under stress or pressure", "When encountering difficult situations with other people, I can think of a way to resolve the situation", and "I am capable of overcoming my difficulties in interacting with people from other cultures" (OECD, 2019). Students were asked to indicate their choices based on a five-point scale ranging from "never" to "every time". The scale reliability ranged from 0.796 to 0.903 across the investigated countries, indicating good reliability for further analysis. The scale reliability for each country is provided in the supplementary materials (see Table S1).

Control variables: student gender and ESCS. As mentioned in the literature review section, student gender and ESCS were considered two important extraneous variables in surveying students' digital reading performance and were therefore taken as control variables in the current study.

Student gender was surveyed during the demographic part of the questionnaire and was recoded as a dummy variable for analysis and interpretation convenience (female=1; male=0).

The ESCS in the PISA was constructed based on students' parents' occupational status, educational level, and wealth, in addition to the cultural and educational resources that they could provide for their children. Processed by the PISA, the ESCS was derived as a standardized continuous variable.

Procedures. The data were preprocessed through data imputation, data cleaning, standardization, and conversion from factor variables to dummy variables. First, missing data for the continuous variables were processed with expectation maximization (EM), and the factor variables were processed with the median imputation that targeted noncontinuous factors. Second, another

Table 1 Demographic and general descriptive statistics of the sample and the variables.

Country	*N* (% female)	n (school)	Ages 0–3	Ages 4–6	Ages 7–9	Ages 10–12	Age 13 or above	Never	Proportion of early users	COGFLEX		Digital reading performance		ESCS	
										Mean	SD	Mean	SD	Mean	SD
Australia	12,375 (49.5%)	724	897 (7.2%)	3,253 (26.3%)	4,935 (39.9%)	2,616 (21.1%)	574 (4.6%)	100 (0.8%)	33.5%	0.115	0.960	504.534	109.430	0.318	0.890
Chile	7569 (50.1%)	255	493 (6.5%)	1,991 (26.3%)	3,547 (46.9%)	1,268 (16.8%)	246 (3.3%)	24 (0.3%)	32.8%	−0.023	0.910	470.068	93.245	−0.310	1.097
Estonia	5,294 (49.9%)	230	514 (9.7%)	2,577 (48.7%)	1,732 (32.7%)	374 (7.1%)	61 (1.2%)	36 (0.7%)	58.4%	0.108	0.943	523.772	92.576	0.097	0.791
France	6,247 (48.9%)	252	362 (5.8%)	1,484 (23.8%)	2,488 (39.8%)	1,511 (24.2%)	352 (5.6%)	50 (0.8%)	29.6%	−0.164	0.917	484.944	104.952	−0.112	0.964
Hungary	5,109 (50.8%)	238	331 (6.5%)	1,529 (29.9%)	2,030 (39.7%)	1,000 (19.6%)	196 (3.8%)	23 (0.5%)	36.4%	−0.060	0.896	483.255	96.569	−0.065	0.912
Iceland	3,272 (50.3%)	142	275 (8.4%)	1,069 (32.7%)	1,363 (41.7%)	484 (14.8%)	56 (1.7%)	25 (0.8%)	41.1%	0.095	1.040	473.122	103.205	0.537	0.807
Italy	11,658 (48.2%)	542	483 (4.1%)	2,150 (18.4%)	5,080 (43.6%)	3,265 (28.0%)	612 (5.2%)	68 (0.6%)	22.6%	−0.330	0.828	480.900	93.607	−0.218	0.876
Ireland	5,257 (50.4%)	157	149 (2.8%)	1,315 (25.0%)	2,238 (42.6%)	1,367 (26.0%)	177 (3.4%)	11 (0.2%)	27.8%	0.101	0.920	518.034	90.240	0.117	0.861
Korea	6,634 (48.0%)	188	195 (2.9%)	1,459 (22.0%)	2,734 (41.2%)	1,764 (26.6%)	467 (7.0%)	15 (0.2%)	24.9%	−0.102	1.020	515.633	101.211	0.086	0.771
Latvia	5,170 (50.7%)	308	320 (6.2%)	1,976 (38.2%)	2,239 (43.3%)	489 (9.5%)	119 (2.3%)	27 (0.5%)	44.4%	−0.056	0.944	475.952	88.446	−0.013	0.814
Lithuania	6,895 (49.1%)	362	582 (8.4%)	2,679 (38.9%)	2,714 (39.4%)	694 (10.1%)	155 (2.3%)	71 (1.0%)	47.3%	−0.006	1.041	470.919	94.006	0.033	0.844
Mexico	7,242 (52.5%)	286	228 (3.1%)	1,113 (15.4%)	3,034 (41.9%)	1,937 (26.7%)	886 (12.2%)	44 (0.6%)	18.5%	0.204	0.916	428.153	82.096	−1.070	1.161
New Zealand	6,143 (51.2%)	192	383 (6.2%)	1,632 (26.6%)	2,385 (38.8%)	1,404 (22.9%)	305 (5.0%)	34 (0.6%)	32.8%	0.086	0.930	508.006	104.531	0.170	0.956
Poland	5,580 (50.8%)	240	481 (8.6%)	2,121 (38.0%)	2,283 (40.9%)	580 (10.4%)	77 (1.4%)	38 (0.7%)	46.6%	0.072	0.975	513.676	96.746	−0.143	0.840
Slovakia	5,920 (50.5%)	376	205 (3.5%)	1,098 (18.5%)	2,782 (47.0%)	1,434 (24.2%)	335 (5.7%)	66 (1.1%)	22.0%	−0.267	0.911	460.825	100.484	−0.175	0.910
Slovenia	6,359 (46.9%)	345	426 (6.7%)	1,785 (28.1%)	2,865 (45.1%)	1,030 (16.2%)	203 (3.2%)	50 (0.8%)	34.8%	−0.025	0.846	480.067	94.400	−0.014	0.789
Spain	35,735 (50.0%)	1,089	3,083 (8.6%)	10,334 (28.9%)	14,635 (41.0%)	6,348 (17.8%)	1,186 (3.3%)	149 (0.4%)	37.5%	0.293	0.916	483.331	76.916	−0.045	1.020
United Kingdom	13,818 (50.6%)	471	736 (5.3%)	6,056 (43.8%)	5,460 (39.5%)	1,349 (9.8%)	191 (1.4%)	26 (0.2%)	49.2%	−0.065	0.460	500.535	97.795	0.235	0.858
Total	156,277	6,397	10,143 (6.5%)	45,621 (29.2%)	64,544 (41.3%)	28,914 (18.5%)	6,198 (4.0%)	857 (0.5%)	35.7%	0.050	0.911	487.004	98.384	−0.032	0.968

The "age(s)" in the table refers to the students' age at first regular digital device access, and the ratio under the ages(s) columns refer to its proportion in the surveyed sample of this country. Cognitive flexibility and reading performance were assessed at age 15. Early users were defined as students who first accessed digital devices at age 6 or earlier. Since the PISA reported that the missing data in the United Kingdom were mainly due to the questionnaire administered only to a subset of students, we included the United Kingdom for analysis despite the relatively high amount of missing data level.

indicator from the PISA, "the age at first internet access", was introduced to help rule out inconsistent digital device users in our sample. Since age at first internet access was surveyed in the PISA with the same choice options of six age groups ("ages 0–3", "ages 4–6", "ages 7–9", "ages 10–12", "age 13 and above", and "never"), students who chose the answer that was two groups apart from their answer to our focused question (age at first regular digital device access) were excluded from the sample data. For instance, a student who first accessed digital devices at ages 4–6 but only first accessed the internet above age 13 was considered to have very limited use and variety of digital devices after their first access; thus, exclusion of these samples from the main analysis would improve the validity of the results. Third, Z score standardization was performed to ensure that all the data were comparable in terms of scale. Fourth, the factor variable "the age at first regular digital device access" was converted into five dummy variables: D1 (ages 4–6), D2 (ages 7–9), D3 (ages 10–12), D4 (age 13 and above), and D5 (never use a digital device until being investigated), with the "ages 0–3" serving as the reference group. The variable "student gender" was recoded as a dummy variable (female=1; male=0).

The main analysis, which is a multilevel mediation analysis in the present study, was carried out with the *lavaan* package of R (R Core Team, 2019). The intraclass correlation coefficients (ICCs) between schools within each country were calculated to determine the necessity of multilevel model use. Hayes and Preacher (2014) discussed the methods of mediation when the independent variable is a multicategorical variable and proposed the concepts of relative total effects, relative direct effects, and relative indirect effects. That is, researchers choose a category as the reference group based on the research aims, and the coefficients of other categories are considered relative effects compared with the reference group. This study followed this operation and interpretation scheme, and the effects in the following results were relative effects compared to those of the reference group of "ages 0–3".

Research results

Model establishment. ICCs (Intraclass correlation coefficients) were tested to account for the impact of cross-school differences on students' digital reading performance (see Table 2). The lowest ICC was observed in Iceland (0.070), and all the other surveyed countries exhibited ICCs higher than 0.1, with the highest occurring in France (0.511). This suggested that a considerable part of the digital reading performance variance in our study can be explained by divergence across schools, highlighting potential biases if variances across schools were not controlled for in statistical models (Konstantinidou & Scherer, 2022; Snijders & Bosker, 2012). Therefore, multilevel analysis was adopted in our model to include potential differences derived from cross-school divergence.

For model identification, since the only latent variable, cognitive flexibility, was officially processed by the PISA and reported as a composite value (see OECD, 2020), our hypothesized mediation model, a simple mediation model with only one mediator, was a saturated model with zero chi-square and zero degrees of freedom (Agler & De Boeck, 2017), where model fit indices showed a perfect fit with the data for each analyzed country (CFI = 1.000, TLI = 1.000, RMSEA = 0.000). Previous studies have suggested that fit indices cannot be used to evaluate saturated models, and the focus should be on the path coefficients (e.g., Steeger & Gondoli, 2013).

Table 2 Intraclass correlation of digital reading performance.

Country	ICC	Country	ICC	Country	ICC
Australia	0.181	Italy	0.444	New Zealand	0.165
Chile	0.381	Ireland	0.140	Poland	0.184
Estonia	0.202	Korea	0.262	Slovakia	0.449
France	0.511	Latvia	0.212	Slovenia	0.484
Hungary	0.262	Lithuania	0.318	Spain	0.154
Iceland	0.070	Mexico	0.382	United Kingdom	0.178

Relative direct effects of the age at first regular digital device access on digital reading performance. Descriptive statistics of the COGFLEX, PV1READ, and ESCS for each age group of first digital device access (see Table S2 in the supplementary materials) suggested that most surveyed countries showed a reverse "U" shape rising-falling trend in the digital reading score as the age at first digital access increased. In addition, a large proportion of surveyed countries exhibited higher mean scores on the COGFLEX and ESCS among adolescents who first regularly accessed digital devices earlier. To indicate clearer differences between the groups and the correlational relationships of our examined constructs, a multilevel mediation model was used to examine the relationship between age at first use of digital devices and adolescents' digital reading performance, with cognitive flexibility serving as the potential mediator.

The relative total effects were displayed in Table S3, with significant effects suggesting the need to analyze relative direct effects and relative mediation effects. The relative direct effects (c_1, c_2, c_3, c_4, and c_5), which addressed the first research question of the relationship between age at first regular digital device access and digital reading performance in adolescence, were reported in Table 3. To ensure the comparability between the dummy variables of the predictor variable, unstandardized model coefficients (B) were reported instead of standardized coefficients (Hayes & Preacher, 2014).

The results showed that, among all surveyed countries, no significant negative relationships were observed in the relative direct effects of the "ages 4–6" group compared to the reference group of "ages 0–3". Significant positive associations were detected in Australia, Latvia, Lithuania, Poland, Slovenia, Spain, Chile, France, Italy, Ireland, and Slovakia, with unstandardized model coefficients ranging from 0.102 to 0.330. However, in Estonia, Hungary, Iceland, the United Kingdom, Korea, Mexico, and New Zealand, the relative direct effects in the 4- to 6-year-old group were not significant, as demonstrated by their 95% confidence intervals, which included 0. These findings consistently suggested across countries that adolescents who first regularly accessed digital devices at ages 4–6 were likely to achieve equal or greater digital reading performance than adolescents who first regularly accessed digital devices at ages 0–3.

Regarding adolescents who first regularly accessed digital devices at ages 7–9, divergent results existed between countries. In a way to resort to commonalities in discussing these divergences and to avoid reaching only by-country conclusion that cannot be generalized, these 18 investigated OECD countries were categorized into countries where more than one-third of adolescents were early digital device users (ages 0–6) and otherwise for cross-national variation discussion purposes, based on the descriptive data in Table 1. Countries where more than one-third of adolescents were early digital device users showed that those who first regularly accessed digital devices at age 7–9 had digital reading performance that was worse than (Estonia, Iceland, Lithuania, Hungary, Poland, Spain, and the United Kingdom) or equivalent to (Australia, Hungary, and Latvia) that of the reference group. In contrast, countries that held less than a third

Table 3 Relative direct effects of age at first regular digital device access on digital reading performance.

Country	c_1 (ages 4–6)		c_2 (ages 7–9)		c_3 (ages 10–12)		c_4 (age 13 and above)		c_5 (never)	
	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE
Countries where more than one-third of adolescents are early digital device users (ages 0–6)										
Australia	**0.223*** [0.148, 0.298]**	0.039	0.029 [−0.039, 0.105]	0.036	**−0.078* [−0.146, −0.011]**	0.034	**−0.404*** [−0.505, −0.309]**	0.050	**−0.793*** [−0.983, −0.595]**	0.101
Estonia	0.020 [−0.074, 0.112]	0.048	**−0.191*** [−0.287, −0.090]**	0.049	**−0.394*** [−0.512, −0.270]**	0.064	**−0.651*** [−0.950, −0.377]**	0.140	**−1.110*** [−1.450, .−779]**	0.166
Hungary	0.096 [−0.017, 0.213]	0.059	0.030 [−0.078, 140]	0.055	**−0.084** [−0.141, −0.028]**	0.036	**−0.588*** [−0.733, −0.424]**	0.079	**−0.874*** [−1.180, −0.520]**	0.165
Iceland	0.051 [−0.065, 0.183]	0.060	**−0.230*** [−0.348, −0.112]**	0.059	**−0.321*** [−0.459, −0.185]**	0.068	**−0.791*** [−1.047, −0.535]**	0.135	**−0.832*** [−1.304, −0.360]**	0.215
Latvia	**0.291*** [0.170, 0.406]**	0.063	0.095 [−0.031, 0.211]	0.063	**−0.098* [−0.169, −0.027]**	0.051	**−0.257* [−0.474, −0.067]**	0.101	**−0.404* [−0.764, −0.038]**	0.180
Lithuania	**0.102* [0.016, 0.183]**	0.042	**−0.119** [−0.193, −0.030]**	0.042	**−0.246*** [−0.345, −0.144]**	0.052	**−0.676*** [−0.825, −0.530]**	0.076	**−0.888*** [−1.080, −0.696]**	0.097
Poland	**0.245*** [0.144, 0.344]**	0.051	**−0.063* [−0.132, −0.005]**	0.036	**−0.113* [−0.216, −0.018]**	0.051	**−0.375** [−0.615, −0.168]**	0.115	**−0.927*** [−1.190, −0.652]**	0.137
Slovenia	**0.127* [0.027, 0.236]**	0.053	**−0.112* [−0.176, −0.047]**	0.043	**−0.154** [−0.268, −0.047]**	0.057	**−0.467*** [−0.623, −0.317]**	0.077	**−0.839*** [−1.070, −0.580]**	0.122
Spain	**0.126*** [0.086, 0.162]**	0.020	**−0.039* [−0.078, −0.002]**	0.019	**−0.154*** [−0.196, −0.114]**	0.021	**−0.508*** [−0.573, −0.448]**	0.032	**−0.920*** [−1.100, −0.771]**	0.085
United Kingdom	0.059 [−0.022, 0.145]	0.041	**−0.148*** [−0.220, −0.066]**	0.038	**−0.235*** [−0.323, −0.151]**	0.044	**−0.508*** [−0.660, −0.368]**	0.076	**−0.665*** [−0.967, −0.313]**	0.168
Countries where less than one-third of adolescents are early digital device users (ages 0–6)										
Chile	**0.165** [0.079, 0.256]**	0.044	−0.021 [−0.107, 0.066]	0.043	−0.103 [−0.212, 0.005]	0.056	**−0.376*** [−0.504, −250]**	**0.067**	**−0.843*** [−1.130, −0.560]**	0.151
France	**0.466*** [0.381, 0.542]**	0.041	**0.496*** [0.417, 0.575]**	0.040	**0.235*** [0.153, 0.312]**	0.041	**−0.110* [−0.205, −0.004]**	0.056	**−0.484*** [−0.773, −0.205]**	0.144
Italy	**0.241*** [0.151, 0.333]**	0.048	**0.110** [0.013, 0.189]**	0.046	**0.155*** [0.057, 0.234]**	0.046	**−0.148** [−0.264, −0.043]**	0.056	**−0.860*** [−1.090, −0.592]**	0.127
Ireland	**0.127* [0.003, 0.243]**	0.060	−0.029 [−0.134, 0.073]	0.057	−0.066 [−0.185, 0.055]	0.060	**−0.139*** [−0.256, −0.021]**	0.090	**−1.580*** [−2.250, −0.741]**	0.365

Table 3 (continued)

Country	c_1 (ages 4–6)		c_2 (ages 7–9)		c_3 (ages 10–12)		c_4 (age 13 and above)		c_5 (never)	
	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE	B [95%CI]	BootSE
Korea	0.046 [−0.088, 0.170]	0.067	−0.022 [−0.129, 0.086]	0.064	−0.060 [−0.181, 0.062]	0.066	**−0.532*** [−0.691, −0.392]**	0.076	**−1.590*** [−1.890, −1.240]**	0.168
Mexico	0.070 [−0.086, 0.210]	0.075	0.034 [−0.114, 0.171]	0.072	−0.074 [−0.222, 0.069]	0.074	**−0.258** [−0.415, −0.102]**	0.080	**−0.953*** [−1.240, −0.659]**	0.149
New Zealand	0.081 [−0.023, 182]	0.051	−0.112 [−0.238, 0.013]	0.058	**−0.248*** [−0.348, −0.153]**	0.049	**−0.677*** [−0.807, −0.549]**	0.067	**−1.350*** [−1.640, −1.070]**	0.141
Slovakia	**0.330*** [0.200, 0.473]**	0.070	**0.266*** [0.139, 0.395]**	0.065	**0.209** [0.076, 0.348]**	0.068	**−0.174* [−0.322, −0.013]**	0.078	**−0.399*** [−0.630, −0.160]**	0.119

B: unstandardized model coefficient; 95% CI: 95% confidence interval, BootSE: Bootstrapping standard error; $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. 95% CIs that do not contain zero indicate significant results. Bold numbers indicate significant results.

of the adolescents who first regularly accessed digital devices in preschool-aged cohorts reported better (France, Italy, and Slovakia) or equal (Chile, Ireland, Korea, Mexico, and New Zealand) digital reading performance than the reference group, and no negative associations were found.

Such divergence persisted in groups of adolescents who first regularly accessed digital devices at ages 10–13. Among countries that held more than one-third of adolescents who first regularly accessed digital devices in preschool-aged cohorts (aged 0–6), adolescents who first regularly accessed digital devices at age 10–13 showed significantly worse performance than did those in the reference group who first regularly accessed digital devices before or at 3 years of age (95% CIs not including zero). Comparatively, the results were mixed for countries in which less than one-third of adolescents first regularly accessed digital devices in preschool-aged cohorts. New Zealand reported negative relative direct effects (B = −0.248, 95% CI = [−0.348, −0.153]). However, the remaining countries either reported significant positive direct effects (B∈[0.155, 0.235], 95% CIs not containing zero) or nonsignificant direct effects.

The results from all investigated countries suggested significantly worse digital reading performance for adolescents who first regularly accessed digital devices only after 13 years of age (B∈[−0.791,−0.110], 95% CIs not containing zero) or never had digital device use experience (B∈[−1.590, −0.399], 95% CIs not containing zero). These students were retarded in digital access and did not develop adequate digital literacy to fulfill digital reading tasks well compared with those who regularly accessed digital devices as early as before or at age 3.

Relative indirect paths: cognitive flexibility as a mediator. The relative indirect path coefficients are reported in Table 4. The coefficients a1, a2, a3, a4, and a5 denoted the relationship between age at first regularly accessing digital devices and cognitive flexibility among each different first digital access age cohort group compared with the reference group of ages 0–3. The results indicated that, except in Spain, no significant effects were found for a1. A large proportion of surveyed countries (Australia, Estonia, France, Hungary, Italy, Latvia, Lithuania, Poland, and Spain) reported significant negative effects in a2, and all surveyed countries reported significant negative results in a3 (B∈[−0.199, −0.092], 95% CIs not including zero). However, a4 and a5 showed rather mixed effects, with a large proportion of countries suggesting nonsignificant results. The path from cognitive flexibility to digital reading performance, represented by b, showed significant positive effects across countries (B∈[0.037, 0.143], 95% CIs not including zero).

The relative indirect effects (a1b, a2b, a3b, a4b, a5b) were reported in Table 5. These relative indirect effects, i.e., relative mediation effects, showed that cognitive flexibility was not a significant mediator for the "4–6 years old" group (except in Spain) relative to the reference group. In the age cohorts of 7–9 years old when first regularly accessing digital devices, 12 out of 18 countries reported significant mediating effects of cognitive flexibility. For students who first regularly accessed digital devices between the ages of 10 and 12, cognitive flexibility had a significant mediating effect on the association between age at first regularly accessing digital devices and digital reading performance in all surveyed countries (B∈[−0.028, −0.006], SE∈[0.003, 0.009], 0 not included in the 95% CIs). For age cohorts of 13 years and older, and never (using a digital device), mixed results of negative effects and nonsignificant effects were reported across countries. Importantly, no significant positive relative indirect effects were discovered compared to those in the reference group, suggesting that later first access to digital devices was less likely to

Table 4 Path coefficients.

Country	a1 (ages 4–6)		a2 (ages 7–9)		a3 (ages 10–12)		a4 (age 13 and above)		a5 (never)		b	
	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE
Countries where more than one-third of adolescents are early digital device users (ages 0–6)												
Australia	−0.079 [−0.160, 0.001]	0.045	**−0.071* [−0.139, 0.−003]**	0.040	**−0.092* [−0.176, −0.012]**	0.044	**−0.127* [−0.258, −0.001]**	0.064	**−0.356* [−0.675, −0.049]**	0.168	**0.121*** [0.105, 0.138]**	0.008
Estonia	−0.056 [−0.156, 0.045]	0.050	**−0.108* [−0.213, −0.014]**	0.049	**−0.181** [−0.312, −0.054]**	0.068	−0.124 [−0.425, 0.199]	0.154	−0.371 [−0.878, 0.134]	0.250	**0.088*** [0.065, 0.114]**	0.013
Hungary	−0.117 [−0.246, 0.015]	0.066	**−0.174** [−0.299, −0.041]**	0.065	**−0.155* [−0.291, −0.021]**	0.070	−0.131 [−0.327, 0.065]	0.097	−0.147 [−0.615, 0.380]	0.240	**0.092*** [0.066, 0.121]**	0.014
Iceland	−0.083 [−0.215, 0.047]	0.067	−0.086 [−0.219, 0.033]	0.064	**−0.156* [−0.305, −0.005]**	0.080	0.018 [−0.338. 324]	0.167	−0.173 [−0.861, 0.553]	0.353	**0.129*** [0.095, 0.162]**	0.017
Latvia	−0.097 [−0.221, 0.025]	0.063	**−0.211*** [−0.343, −0.088]**	0.063	**−0.191* [−0.345, −0.045]**	0.075	−0.217 [−0.518, 0.056]	0.143	−0.054 [−0.111, 0.001]	0.160	**0.090*** [0.058, 110]**	0.013
Lithuania	−0.073 [−0.173, 0.028]	0.051	**−0.176*** [−0.273, −0.073]**	0.050	**−0.166** [−0.288, −0.055]**	0.060	**−0.398*** [−0.600, −0.209]**	0.099	**−0.327* [−0.626, −0.025]**	0.153	**0.136*** [0.114, 0.157]**	0.011
Poland	−0.110 [−0.217, 0.004]	0.053	**−0.137* [−0.247, −0.031]**	0.053	**−0.129* [−0.253, −0.005]**	0.064	**−0.287* [−0.562, −0.019]**	0.138	**−0.860*** [−1.290, −0.380]**	0.227	**0.080*** [0.057, 0.106]**	0.012
Slovenia	0.012 [−0.094, 0.124]	0.056	−0.039 [−0.145, 0.073]	0.056	**−0.119* [−0.233 .−0.005]**	0.059	0.142 [−0.021, 0.317]	0.085	−0.286 [−0.747, 0.123]	0.223	**0.058*** [0.033, 0.080]**	0.012
Spain	**−0.120*** [−0.149, −0.090]**	0.021	**−0.140*** [−0.180, −0.102]**	0.020	**−0.118*** [−0.163, −0.073]**	0.023	**−0.109** [−0.181, −0.032]**	0.037	**−0.487*** [−0.692, −0.278]**	0.108	**0.067*** [0.057, 0.078]**	0.005
United Kingdom	−0.059 [−0.173, 0.051]	0.057	**−0.107* [−0.209, −0.009]**	0.051	**−0.106* [−0.202, −0.010]**	0.050	−0.086 [−0.288, 0.103]	0.099	−0.344 [−0.846, 0.185]	0.265	**0.143*** [0.125, 0.164]**	0.010
Countries where less than one-third of adolescents are early digital device users (ages 0–6)												
Chile	−0.061 [−0.154, 0.046]	0.051	−0.092 [−0.180, 0.027]	0.051	**−0.111* [−0.224, .− 003]**	0.056	−0.014 [−0.171, 145]	0.082	0.078 [−0.331, 0.562]	0.221	**0.089*** [0.067, 0.109]**	0.011
France	−0.075 [−0.164, 0.012]	0.043	**−0.100** [−0.181, −0.017]**	0.041	**−0.102* [−0.181, −0.016]**	0.041	−0.084 [−0.214, 0.061]	0.074	−0.219 [−0.523, 0.063]	0.150	**0.075*** [0.054, 0.097]**	0.011
Italy	−0.021 [−0.132, 0.083]	0.053	**−0.121* [−0.234, −0.026]**	0.052	**−0.118* [−0.228, −0.020]**	0.052	−0.023 [−0.156, 0.108]	0.068	−0.237 [−0.535, 0.052]	0.147	**0.060*** [0.044, 0.077]**	0.009
Ireland	−0.119 [−0.258, 0.007]	0.068	−0.119 [−0.241, 0.015]	0.065	**−0.156* [−0.299, −0.026]**	0.069	−0.018 [−0.242, 0.185]	0.106	−0.017 [−0.602, 0.768]	0.343	**0.046*** [0.023, 0.072]**	0.013

Table 4 (continued)

Country	a1 (ages 4–6)		a2 (ages 7–9)		a3 (ages 10–12)		a4 (age 13 and above)		a5 (never)		b	
	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE	B [95% CI]	SE
Korea	−0.121 [−0.282, 0.042]	0.081	**−0.166* [−0.327, −0.012]**	0.078	**−0.199* [−0.368, −0.041]**	0.081	−0.101 [−0.275, 0.076]	0.088	−0.441 [−1.130, 0.372]	0.375	**0.037** [0.011, 0.063]**	0.013
Mexico	−0.108 [−0.248, 0.028]	0.073	−0.107 [−0.253, 0.029]	0.073	**−0.126* [−0.246, −0.007]**	0.070	−0.092 [−0.252, 0.055]	0.076	**−0.410** [−0.663, −0.108]**	0.143	**0.126*** [0.104, 0.149]**	0.012
New Zealand	−0.122 [−0.272, 0.030]	0.059	**−0.189** [−0.305, −0.080]**	0.058	**−0.185** [−0.306, −0.077]**	0.061	−0.095 [−0.260, 0.082]	0.087	**−0.780*** [−1.250, −0.372]**	0.221	**0.080*** [0.057, 0.106]**	0.012
Slovakia	−0.056 [−0.235, 0.121]	0.091	−0.130 [−0.320, 0.026]	0.086	**−0.170* [−0.371, −0.002]**	0.092	**−0.230* [−0.422, −0.035]**	0.099	−0.275 [−0.597, 0.081]	0.169	**0.037** [0.014, 0.061]**	0.012

$^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$. Bold numbers indicate significant results.

contribute to higher levels of cognitive flexibility. Notably, mediation with the independent variable as a multicategorical variable suggested relative effects of comparison with the reference group. Therefore, the effect size, which denotes the ratio of indirect effects to total effects (the sum of indirect effects and direct effects), was statistically inapplicable following Hayes and Preacher's (2014) theory. Hence, the effect size of cognitive flexibility in mediation was not reported.

Control variable effects: student gender and ESCS. Controlling for these two extraneous but predictive factors increased the explanatory power of our model. Table 6 shows how student gender and ESCS affect adolescents' digital reading performance as control variables (RQ3). The model coefficients ranged from 0.160 to 0.487 for student gender in all sample countries and from 0.212 to 0.407 for ESCS in all sample countries, with 95% CIs suggesting consistent significant results. These coefficients indicated that female adolescents had better digital reading performance than their male counterparts and that individuals with higher ESCS usually had better digital reading scores, as evidenced by numerous studies (e.g., Hu & Wang., 2022; Navarro-Martinez & Peña-Acuña, 2022; Yeung et al., 2022; Yu & Hu, 2023).

Discussion

The current study utilized data from the PISA and revealed the unbalanced levels of age at first regular digital device access in OECD countries, and more importantly, presented both generalized and comparative evidence on the different ages at which digital devices were first regularly accessed and their profound long-term influence on adolescents' digital reading performance. Theoretically, this study was the first research attempt to establish the mechanism through which cognitive flexibility mediated the age at first regular digital device access and adolescents' digital reading performance. It specified the non-linear negative relationship between different age cohorts at first regular digital device access and adolescents' digital reading performance, and paved the way for future research schemes that scrutinize early digital device use through the lens of cognitive flexibility. This section discussed these findings in relation to existing evidence, explored possible explanations, and provided practical implications for OECD countries and beyond to position ICT policy for individual digital device access in societal and educational settings.

The age at first regular digital device access and digital reading performance. This subsection set out to discuss the results that answered the first research question, which concerned the influence of age at first regular digital device access on digital reading performance for adolescents and its cross-national variations, as well as the age group(s) at first regular digital device access that led to the highest digital reading performance on average.

The findings showed that although the influence of age at first accessing digital devices on digital reading performance in adolescents displayed a reverse U-shaped trend within each country, its exact influence was associated with countries' general early digital device access levels, exhibiting cross-country variations that enriched previous conclusion reached in single-region investigations (e.g., Papadakis et al., 2022). This finding aligned with previous evidence that countries' ICT availability influenced individuals' digital reading performance (Hu et al., 2015) and contributed to the age effects of first regular digital device access to theoretical explorations linking early digital device access and digital reading performance.

Table 5 Mediating effect of cognitive flexibility.

Country	a1b (ages 4–6)		a2b (ages 7–9)		a3b (ages 10–12)		a4b (age 13 and above)		a5b (never)	
	B [95% CI]	**BootSE**	**B [95% CI]**	**BootSE**	**B [95% CI]**	**BootSE**	**B [95% CI]**	**BootSE**	**B [95% CI]**	**BootSE**
Countries where more than one-third of adolescents are early digital device users (ages 0–6)										
Australia	−0.010 [−0.022, 0.001]	0.006	**−0.009* [−0.018, 0.−001]**	0.005	**−0.011* [−0.017, −0.005]**	0.005	**−0.015* [−0.032, −0.001]**	0.008	**−0.043* [−0.087, −0.006]**	0.021
Estonia	−0.005 [−0.014, 0.004]	0.004	**−0.010* [−0.020, −0.001]**	0.005	**−0.016** [−0.028, −0.004]**	0.006	−0.011 [−0.040, 0.017]	0.014	−0.033 [−0.080, 0.010]	0.023
Hungary	−0.011 [−0.024, 0.001]	0.006	**−0.016* [−0.032, −0.004]**	0.007	**−0.014* [−0.029, −0.002]**	0.007	−0.012 [−0.031, 0.006]	0.009	−0.014 [−0.057, 0.037]	0.023
Iceland	−0.011 [−0.029, 0.006]	0.009	−0.011 [−0.031, 0.004]	0.008	**−0.020* [−0.032, −0.010]**	0.011	0.002 [−0.046, 0.043]	0.022	−0.022 [−0.115, 0.067]	0.046
Latvia	−0.009 [−0.026, 0.008]	0.006	**−0.019** [−0.033, −0.008]**	0.006	**−0.017* [−0.033, −0.004]**	0.007	−0.019 [−0.047, 0.005]	0.013	−0.005 [−0.094, 0.087]	0.017
Lithuania	−0.010 [−0.024, 0.003]	0.007	**−0.024*** [−0.040, −0.012]**	0.007	**−0.023** [−0.041, −0.008]**	0.008	**−0.054*** [−0.087, −0.029]**	0.014	**−0.044* [−0.086, −0.005]**	0.021
Poland	−0.009 [−0.021, 0.003]	0.006	**−0.011* [−0.022, −0.001]**	0.005	**−0.010* [−0.023, −0.001]**	0.004	**−0.023** [−0.037, −0.010]**	0.006	**−0.069** [−0.127, −0.012]**	0.013
Slovenia	0.001 [−0.006, 0.007]	0.003	−0.002 [−0.009, 0.004]	0.003	**−0.007* [−0.013, −0.001]**	0.004	0.008 [0.000, 0.021]	0.005	−0.017 [−0.051, 0.006]	0.014
Spain	**−0.008** [−0.014, −0.003]**	0.002	**−0.009*** [−0.012, −0.007]**	0.001	**−0.008*** [−0.011, −0.005]**	0.001	**−0.007** [−0.012, −0.002]**	0.003	**−0.033*** [−0.049, −0.019]**	0.008
United Kingdom	−0.008 [−0.025, 0.007]	0.008	**−0.015* [−0.031, −0.002]**	0.007	**−0.015* [−0.030 .−001]**	0.007	−0.012 [−0.042, 0.015]	0.014	−0.049 [−0.120, 0.026]	0.038
Countries where less than one-third of adolescents are early digital device users (ages 0–6)										
Chile	−0.005 [−0.014, 0.004]	0.005	−0.008 [−0.017, 0.002]	0.005	**−0.010* [−0.020, −0.001]**	0.005	−0.001 [−0.016, 0.013]	0.007	0.007 [−0.029, 0.051]	0.020
France	−0.006 [−0.013, 0.000]	0.003	**−0.007* [−0.015, −0.001]**	0.003	**−0.008* [−0.015, −0.001]**	0.003	−0.006 [−0.017, 0.005]	0.006	−0.016 [−0.041, 0.004]	0.011
Italy	−0.001 [−0.008, 0.005]	0.003	**−0.007* [−0.014, −0.002]**	0.003	**−0.007* [−0.015, −0.001]**	0.003	−0.001 [−0.009, 0.007]	0.004	−0.014 [−0.034, 0.002]	0.009
Ireland	−0.005 [−0.010, 0.000]	0.003	−0.006 [−0.015, 0.001]	0.004	**−0.008* [−0.018, −0.002]**	0.004	−0.001 [−0.013, 0.008]	0.005	−0.001 [−0.031, 0.035]	0.016

Table 5 (continued)

Country	a1b (ages 4–6)		a2b (ages 7–9)		a3b (ages 10–12)		a4b (age 13 and above)		a5b (never)	
	B [95% CI]	BootSE	B [95% CI]	BootSE	B [95% CI]	BootSE	B [95% CI]	BootSE	B [95% CI]	BootSE
Korea	−0.004 [−0.014, 0.001]	0.003	**−0.006* [−0.016, −0.001]**	0.003	**−0.007* [−0.018, −0.001]**	0.004	−0.004 [−0.013, 0.002]	0.004	−0.016 [−0.054, 0.009]	0.015
Mexico	−0.014 [−0.035, 0.003]	0.009	−0.014 [−0.030, 0.004]	0.009	**−0.016** [−0.025, −0.009]**	0.007	−0.011 [−0.032, 0.006]	0.010	**−0.052* [−0.087, −0.013]**	0.019
New Zealand	−0.010 [−0.025, 0.007]	0.005	**−0.015** [−0.027, −0.006]**	0.004	**−0.015** [−0.027, −0.006]**	0.004	−0.008 [−0.021, 0.006]	0.007	**−0.063** [−0.111, −0.029]**	0.020
Slovakia	−0.002 [−0.011,0.004]	0.004	−0.005 [−0.016, 0.000]	0.004	**−0.006* [−0.017, −0.001]**	0.003	**−0.008* [−0.020, −0.001]**	0.004	−0.010 [−0.029, 0.001]	0.007

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$. Bold numbers indicate significant results.

Analysis revealed that countries with generally greater proportions of early digital device users had an earlier age threshold, specifically at age 9, regarding first regular digital device access, after which age adolescents in these countries fell short in digital reading performance compared with the reference group who started regularly accessing digital devices at ages 0–3. Similar findings were reached by Juhaňák et al. (2019), who found that first internet access at age 9 was a threshold for subsequent ICT competence and autonomy development in OECD contexts. While the results reported by Juhaňák et al. (2019) accounted for general abilities in ICT use, the current investigation, for the first time, specified the focused skill of digital reading performance on the influence of age at first regular digital device access. This provided theoretical insights for future domain-specific explorations with respect to the influence of the first use of digital devices.

Within countries with fewer than one-third of early digital device users, however, the results suggested that only adolescents who first regularly accessed digital devices after 13 years of age or never accessed digital devices performed significantly worse than the reference groups in the digital reading assessment at age 15. This meant that in these countries, whether adolescents possessed early digital device experience before adolescence did not affect their digital reading performance, which differed from existing evidence that emphasized the facilitating effect of digital device access before adolescence (e.g., Chi-San Ho et al., 2023). Therefore, analysis conducted at the country level contributed to the understanding of cross-country differences, and findings specific to each country were otherwise veiled if the analysis was conducted only at the global level (Hu & Yu, 2023).

To further illustrate the cross-country divergence, evidence from OECD and UNESCO reports was drawn to provide references for country backgrounds. Although OECD countries were selected for analysis to make the results more comparable in terms of socioeconomic context, the analysis results demonstrated different patterns across countries, mainly in terms of individual early digital device access levels. Our categorization of countries in the current study was based on the proportion of early digital device users (aged 0–6). This categorization was theoretically supported because early digital device users, mainly preschool-aged individuals, reflected both household ICT access and individuals' general early digital experience in society (Papadakis et al., 2022). Of the countries investigated, those that had more than one-third of early digital device users (e.g., Estonia, Hungary, Lithuania, etc.) also had a greater than 50% household ICT access rate early into the first decade of the century, with countries such as Australia, Iceland, and the United Kingdom reaching over 70% (OECD, 2023), suggesting the impact of a country's general ICT access level on individuals' early digital device access. This was also supported by a previous report stating that levels of digital access at home, rather than at school, were more likely to affect individuals' academic achievement (OECD, 2010). In addition, ICT policies on education also require sufficient digital infrastructure and digital device access (UNESCO, 2022), highlighting countries' ICT investment in providing better digital infrastructure. Regarding this, countries that held more than one-third early digital device users in the current study were all European countries (except Australia), whose ratios of broadband subscription and individual internet access levels in population were leading in the first two decades of this century (UNESCO, 2020). Additionally, OECD data revealed that countries with more than one-third of early digital device users in this study invested more in ICT on average (OECD, 2024).

The conclusion reached in this study was in line with Sergi et al. (2017), who found that digital device access before and

Table 6 Control variable effects: student gender and ESCS.

Country	Student gender			ESCS		
	B	95% CI	BootSE	B	95% CI	BootSE
Australia	0.283***	[0.250, 0.315]	0.016	0.304***	[0.288, 0.321]	0.008
Chile	0.212***	[0.174, 0.251]	0.020	0.390***	[0.370, 0.412]	0.011
Estonia	0.374***	[0.327, 0.425]	0.026	0.231***	[0.207, 0.257]	0.013
France	0.252***	[0.209, 0.293]	0.022	0.407***	[0.385, 0.428]	0.010
Hungary	0.310***	[0.260, 0.359]	0.025	0.403***	[0.377, 0.429]	0.013
Iceland	0.422***	[0.355, 0.482]	0.033	0.212***	[0.181, 0.248]	0.017
Italy	0.283***	[0.251, 0.316]	0.017	0.271***	[0.254, 0.288]	0.009
Ireland	0.247***	[0.200, 0.297]	0.025	0.308***	[0.280, 0.333]	0.013
Korea	0.174***	[0.131, 0.224]	0.023	0.247***	[0.225, 0.270]	0.012
Latvia	0.413***	[0.364, 0.462]	0.025	0.215***	[0.188, 0.242]	0.014
Lithuania	0.390***	[0.345, 0.433]	0.022	0.306***	[0.284, 0.329]	0.011
Mexico	0.160***	[0.118, 0.201]	0.021	0.317***	[0.292, 0.340]	0.012
New Zealand	0.294***	[0.247, 0.341]	0.024	0.326***	[0.302, 0.349]	0.012
Poland	0.328***	[0.275, 0.374]	0.025	0.321***	[0.294, 0.347]	0.014
Slovakia	0.334***	[0.290, 0.379]	0.022	0.403***	[0.381, 0.426]	0.011
Slovenia	0.487***	[0.444, 0.534]	0.023	0.309***	[0.288, 0.330]	0.011
Spain	0.277***	[0.259, 0.300]	0.010	0.274***	[0.264, 0.284]	0.005
United Kingdom	0.258***	[0.226, 0.287]	0.016	0.224***	[0.206, 0.241]	0.009

***$p < 0.001$.

during primary education stages improved students' linguistic skills. To explain, early digital device users were more adapted to the digital format of reading, and encountered fewer difficulties in familiarizing with and processing digital reading tasks. In addition, early digital device users had absorbed dense information delivered on the screen with taps of fingers, and the interactive interface of digital devices required a larger amount of reading to operate (Alexander, 2020), which provided more opportunities to read than non-early digital device users. However, this study suggested that first regular digital device use at or before age 3 was not associated with better digital reading performance than first regular use at ages 4–6, which was inconsistent with the findings of previous studies (e.g., Sergi et al., 2017). One possible explanation was that young children did not develop mature morphological or orthographic knowledge to comprehend texts (Sanchez et al., 2012). Therefore, they learned to comprehend more frequently through graphic and auditory information than verbal information on screens and were more likely to experience information saturation at an early age, all of which potentially hindered reading development (Alexander, 2020). This further corroborated our study's contribution in adopting fine-grained age cohorts for analysis, which revealed more nuanced information than previous studies that listed "age 0–9" as a single age cohort group when studying early access age groups (Dempsey et al., 2019).

Through answering RQ1, the current study addressed the research gap about the relationship between age at first regular digital device access and long-term digital reading performance. Integrating students' age at first regular digital device access helps scope a more complete picture of students' digital reading development and is, therefore, an important contribution of the current study.

Cognitive flexibility mediates the relationship between age at first regular digital device access and digital reading performance. This study enriched existing literature about early digital device access and digital reading performance development by incorporating cognitive flexibility as one influencing mechanism. Different from previous investigations that mainly adopted behavioral factors (e.g., digital device use at home and school) as mediators between first regular digital device access and digital-related competence (Juhaňák et al., 2019), this current research contributed the cognitive pathway through which age at first regular digital device access partially affected young users' long-term cognitive flexibility development, and in turn influenced their long-term digital reading performance. This finding entailed that age at first regular digital device access mattered not only for early and school years' digital device access opportunities and use preferences, as reported by previous studies (van Deursen & van Dijk, 2011), but also partly shaped one's cognitive development, and further continued these cognitive effects in cognitive tasks such as digital reading.

Regarding the specific mediating effects of cognitive flexibility (RQ2), the indirect effects observed significantly suggested that cognitive flexibility partially mediated the relationship between age at first regular use of a digital device and digital reading performance in specific first digital device access age groups. Specifically, this mediating effect was found to be significantly negative for the groups who had their first regular digital device access at ages 7–9 in more than half of the surveyed countries and at ages 10–12 in all surveyed countries, regardless of the countries' general early digital access levels. In other words, students with first regular access to digital devices at ages 7–12 were more likely to suffer from significantly lower levels of cognitive flexibility development manifested in their adolescence than those who started regularly using digital devices before or at 3 years old, and this negative influence would pass on to their digital reading performance. In contrast, the majority of adolescents who first regularly accessed digital devices at ages 4–6 did not report a significant difference from the reference age group.

This conclusion conformed to previous evidence suggesting that early first regular access to digital devices helped cultivate higher levels of cognitive flexibility (Oades-Sese et al., 2021). More importantly, this study contributed to the understanding of the mediating role of cognitive flexibility in the relationship between first regular digital device access and digital reading performance. Practically, individuals who accessed digital devices earlier would receive more multimodal information such as

images, audios, videos, and hyperlinks (Gremmen et al., 2016), which exercised their cognitive functioning into more flexible processing approaches, a skill transferable to digital reading practice. In addition, those early digital device users got in touch with the complicated virtual world earlier. Therefore, an early age at first regular digital device access offered children more opportunities not only to exercise their multitasking abilities but also to witness and cope with complex real-life problems, which in turn shaped children into more flexible thinkers and readers in the long run (Martín et al., 2018; Bernardo & Mante-Estacio, 2023). The current study extended this positive relationship formerly discovered in the print reading context to the digital reading scenarios (Colé et al., 2014; Hu, 2017; Ruffini et al., 2023).

Interestingly, the results of this study revealed that, compared with individuals who had been in regular contact with digital devices as early as 3 years old or even younger, some individuals who regularly accessed digital devices only after they were 13 years old or never had access to digital devices until they were surveyed did not exhibit consistent cognitive flexibility mediating effects across countries. To explain, some students were limited by their family ESCS and school conditions to afford digital devices, but they might be deeply engaged in offline activities as alternatives, which built their cognitive flexibility through goal-oriented social interaction and problem solving (Hodson et al., 2021). It was also likely that some students were strictly regulated from digital device access by their families for fear of problematic digital device use, whereas these families paid high attention to education and fostered their children's cognitive development through other educational interventions (Buttelmann & Karbach, 2017). Considering the small proportion of participants who never had or only had late access to digital devices, as well as the large standard deviation of their cognitive flexibility, the above reasons might account for some of their high levels of cognitive flexibility. Therefore, that these "digital-device-free" students perceived good cognitive flexibility did not imply that not providing digital access to children could shape them into more flexible learners, as these students were disadvantaged in digital reading, as previously reported.

Although cross-country variations existed in the degree to which cognitive flexibility mediated the relationship between age at first regular digital device access and digital reading performance, similarities were observed for the significant mediating effect in the 10–12 age group across countries. No distinctive patterns, however, were observed in other age groups among countries that had more than or less than one-third of adolescents who were early digital device users. This indicated that the mediating effect of cognitive flexibility depended less on the general ICT access levels of countries. The literature suggested that the influences of cognitive flexibility should be discussed in terms of the interplay with sociocultural factors (Zheng, 2023); thus future research should focus on the cultural-cognitive path to statistically clarify country differences.

In summary, to avoid lagging behind in cognitive and reading development, children should be introduced to digital devices no later than the age of 6. Given that students performed better or equally in digital reading when they first regularly accessed digital devices at ages 4–6 than at ages 0–3 and that there were almost no significant differences of mediating effects of cognitive flexibility between these two age groups, teachers and parents may consider introducing digital devices to children at ages 4–6 to maximize the cognitive benefits of early digital device use while alleviating possible health and problematic digital device use behaviors arising from overly early use of digital devices (Nakayama et al., 2020). This provided some relief to parents who were too anxious about being late in introducing digital device access to their children. However, it is also acknowledged that in educational practices, extant literature positioned demographic factors (such as student gender and ESCS in the current study) and educational intervention pedagogy (Díaz et al., 2024) to be important factors that shape adolescents' digital reading performance, therefore warranting caution in interpreting the results in this study.

Practical Implications. The findings of this study offered practical implications for OECD countries and beyond to improve ICT policies targeting young digital device users and to help parents and early education and formal education teachers gain a more nuanced understanding of the appropriate age at which to introduce digital devices to children. For policymakers, measurements of how digital devices are accessible to young generations are worthy of attention and can supplement general indices such as total ICT investment or ICT investment in education. Governments should consider providing more public digital device resources to increase the availability of early digital access experience for wider populations as an approach to alleviating the digital divide and promoting digital equity (Yang & Zhang, 2023). Additionally, due to the observed cross-country differences in the relationship between age at first regular digital device access and digital reading performance, countries should use their ICT development and digital access levels as references for locally materializing the OECD's ICT policies (Yasukawa et al., 2017).

For implications at the home and school levels, parents and early education instructors should avoid over-relying on digital devices to teach and entertain children at or before age 3, as minimal cognitive and academic benefits are gained through digital device access during this period. Instead, more face-to-face communications, either for learning or recreational purposes, are suggested as alternatives. However, late first regular digital device access after 9 years of age is also not recommended. Schools are suggested to invest in ICT equipment to benefit those who are disadvantaged in digital access at home due to low family socioeconomic status (González-Betancor et al., 2021). Additionally, cognitive flexibility cultivation should be incorporated when providing children with digital device access at both home and school (Hu et al., 2020). For instance, gamification in learning, chatbots, online learning platforms, and interactive videos that invoke cognitive engagement can be planned into early digital device use experience, as a means to improve cognitive flexibility through the interplay with the digital world (Hu, 2014).

Conclusion, limitations, and future research

Through the lens of the age at first regular digital device access, this study used internationally representative data from 18 countries and the multilevel mediation analysis approach, and theoretically identified a fine-grained influencing mechanism of the relationship between age at first regular digital device access and digital reading performance. More importantly, the study contributed a theoretical basis from a cognitive perspective for future empirical exploration of the long-term academic performance associated with the age at first regular digital device access. Two major findings were highlighted in this study. First, the results suggested the trend that adolescents who first accessed digital devices only after age 9 exhibited significantly lower digital reading scores in countries that generally had higher levels of early digital access, and all surveyed countries reported significantly lower digital reading scores among adolescents who first regularly accessed digital devices only after 13 years of age. Second, adolescents were likely to experience retardation in cognitive flexibility development if they started regularly using digital devices only after the age of 6 and were more likely to perceive lower levels of cognitive flexibility if their initial regular

digital device access was at age 9 to 12, which in turn led to low digital reading performance.

Taken together, these findings corroborated the importance of early ICT access while indicating that first accessing ICT regularly at age 4–6 was likely to result in more favorable long-term cognitive flexibility and digital reading performance development altogether, although country differences persisted. These results revealed to parents and educational practitioners the importance of early digital device access while rebutting the notion of "the earlier, the better" in some digital educational practices.

This study has several limitations that should be considered. First, the mediation method adopted in this study did not yield causal relationships. Second, this study only selected OECD countries, considering their relatively high-level digital availability and infrastructure in the 2000s and early 2010s, when those investigated students in this study were in their childhood and adolescence. This selection criterion would inevitably lead to including more European countries, which potentially limits the generalizability of the conclusion to other countries. Recent developments in digital device availability in less-developed economies suggested greater potential to include more countries and regions for future analysis to extend the generality of the conclusion and address more influences from the worldwide digital divide (Aguilar, 2020). Third, the multicategorical independent variable in the mediation analysis highlighted the cross-group comparison with the reference group but also confined the comparison between any two age groups that were not the reference group (Hayes & Preacher, 2014). Fourth, although digital reading performance was assessed through rigorously designed tests, this study utilized self-report questionnaires to collect cognitive flexibility data, with potential reporting biases to be addressed.

Future work could assess students' cognitive flexibility by adopting cognitive tests in project tasks using experimental or quasi-experimental methods. Additionally, longitudinal studies investigating the influence of age at first regular digital device use on other aspects of cognitive domains might also yield revealing findings regarding the interplay between first regular digital device access, cognitive development, and academic performance.

Data availability

The datasets utilized in the current study are available at the official website of Programme for International Student Assessment, https://www.oecd.org/pisa/data/2018database/.

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Jie Hu was a member of the Editorial Board of this journal at the time of acceptance for publication. The manuscript was assessed in line with the journal's standard editorial processes, including its policy on competing interests.

Ethical approval

The project was granted ethical approval from the medical ethics committee, Department of Psychology and Behavioral Sciences, Zhejiang University (ID: [2021]074).

Informed consent

Written informed consent to participate in PISA was provided by the participants' legal guardian.

Additional information

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