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Impacts of broadband internet on adolescents' academic outcomes: heterogeneous effects among lower secondary school students in Norway

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ABSTRACT

The expansion of internet is likely to influence adolescents' academic outcomes. Yet, how internet coverage impacts students' educational performance remains poorly understood. To address this major knowledge gap, this study uses a quasi-experimental approach with Norwegian data to causally examine how the gradual introduction of home broadband internet across municipalities impacted the academic outcomes of lower-secondary school graduates (N = 103,796). Analyses apply sibling fixed-effects models with micro-level registry data from adolescents aged 15–16, and compare differences in effects by gender, social background, migrant status, and academic achievement levels. Findings show that the introduction of broadband internet across municipalities brought moderate grade improvements concentrated among boys in the subject areas of Mathematics, Arts and Crafts, Social Sciences, and Norwegian. The positive effect of broadband internet coverage on academic performance was three times larger for boys than for girls. For boys, broadband internet coverage led to strong grade improvements among the lower-achieving and socioeconomically disadvantaged, and to moderate grade benefits among those of Norwegian background, while boys from higher-achieving and socioeconomically privileged groups reduced their grades moderately. By contrast, for girls, broadband internet coverage worsened substantially the academic performance of those from disadvantaged socioeconomic backgrounds, whereas girls of migrant background obtained higher grades with this expansion of internet. The study findings reveal how the growth of internet coverage impacts adolescent educational performance, but differently across groups, showing a complex intersection across gender, social background, migrant status, and academic achievement levels.

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Introduction

In recent decades, information and communication technologies (ICTs) have become increasingly embedded into young people's lives and schools' functioning (Bulman & Fairlie, 2016; Livingstone et al., 2011) Broadband internet coverage is today vital for education, as schools are globally transitioning toward hybrid systems that need continuous access to high-quality internet (Iglesias-Pradas et al., 2021; OECD, 2021, 2022). High-speed internet is likely to create a range of critical learning opportunities for students' personal, technical and academic skills that foster their academic performance and future labour market opportunities (Correa et al., 2020; Tyagi et al., 2020; United Nations, 2015). Yet, the introduction of high-speed internet could also bring educational risks to students. For example, high-quality internet can increase the chances that adolescents experience attention deficits (Ernst et al., 2011) and sleep disruptions (Billari et al., 2018) and this may in turn harm students' academic performance. Providing an answer to this puzzle is essential as societies become increasingly digitalised.

Previous research found that the intensity and type of internet use (Bohnert & Gracia, 2023; Chen & Ji, 2015; Thiessen & Dianne Looker, 2007; Wang & Cheng, 2021), level of digital competence (Livingstone et al., 2011; Mehrvarz et al., 2021), and differential use of technologies across age and socioeconomic groups (Bohnert & Gracia, 2023; Corkin et al., 2022; Xu et al., 2019; Zhang, 2015) predict variations in adolescents' academic outcomes. However, research on the causal effect of internet coverage on student educational outcomes is limited. To our knowledge, only three studies, two with US data (Dettling et al., 2018; Vigdor et al., 2014) and one with UK data (Faber et al., 2015), have implemental a causal design to study how broadband internet coverage influences student performance. Despite their contributions, these three studies used diverse causal modelling strategies, provided mixed results (*i.e.*, from null to substantive effects in various directions), and were restricted to English-speaking countries. This calls for new research addressing causality in different national contexts.

In this study, we investigate the effect of the expansion of broadband internet coverage on adolescents' academic performance in Norway. We apply a novel quasi-experimental design that exploits the unique gradual rollout of broadband internet across municipalities between 2002 and 2007. Our approach offers a precise understanding of how broadband internet growth across municipalities impacts adolescent academic performance. We specifically contribute to the literature by analysing (1) the causal effect of internet broadband coverage on adolescents' GPA results across graduates in lower secondary education, and (2) the levels of heterogeneity in these effects across students from different population subgroups, considering variations across gender, socioeconomic background, migrant status, and academic achievement groups. We adopt an exploratory approach, as previous theoretical perspectives offer conflicting explanations of how broadband internet coverage may impact student performance, and the literature lacks robust evidence that we can build from. Although our study is exploratory, we develop an original intersectional approach that brings new evidence on how broadband internet coverage influences academic outcomes across adolescents from different demographic groups.

Our contribution is summarised at three main levels. First, at the *analytical level*, we add to this literature by implementing a novel causal approach. Benefiting from the unique gradual introduction of broadband internet coverage across Norwegian municipalities, we adopt a quasi-experimental design that is ideal to test how technological transformations influence students' outcomes (Bhuller et al., 2020). We combine this quasi-experimental approach with a sibling fixed-effects design, a methodology that is particularly suited to test causality by adjusting for unobserved confounders at the family level and comparing siblings from the same family unit, while also controlling for multiple variations that happen at the school and municipality levels (De Neve & Oswald, 2012; Firebaugh et al., 2013; Hermansen, 2017)

Second, at a *substantive level*, our study brings an intersectional perspective that, albeit linked to existing debates on ICTs and adolescent outcomes, is original within the literature addressing how broadband internet expansion impacts student academic outcomes. Our approach establishes dialogue with sociological, media and communication research that has discussed whether young people from different socioeconomic and demographic groups are differently exposed to the opportunities and dangers that ICTs bring to their well-being and life chances (e.g., Becker, 2022; Gracia et al., 2023; Helsper, 2021; van de Werfhorst et al., 2022; van Dijk, 2020). Thus, our study speaks to broader digital divide literature by establishing whether different groups of students are unevenly affected by the arrival of broadband internet coverage to their geographical area. We do this by focusing on four key sociological dimensions: gender, socioeconomic background, migrant status, and academic achievement levels.

Third, regarding the *case study*, we investigate a relevant national context for the literature on ICTs and student performance. Norway is not only culturally diverse from countries previously analysed in this literature. Compared to countries like the UK and US, Norway shows lower income inequalities and more generous universal welfare policies, as well as fairly egalitarian systems in promoting educational success and inclusion among students of different social groups and ability conditions (Esping-Andersen, 1990; World Bank, 2022). This indicates that the arrival of broadband internet coverage to a Scandinavian context like Norway could have different consequences for adolescents' educational performance (e.g., equalising effects), compared to English-speaking countries like the UK and US. Thus, our focus on Norway expands this literature to new policy, geographical, and cultural contexts.

Background

Theoretical and conceptual approaches to broadband internet and adolescent outcomes

Our study adopts an exploratory framework. However, we discuss here key conceptual and theoretical issues that are relevant to our study. First, while our main unit of analysis is the student within the family, we conceptualise changes in broadband internet coverage at the municipality level. This is primarily because broadband internet infrastructures in Norway (2002-2007) were measured at the municipality level, not at a smaller geographical scale. By examining the extent to which the Norwegian broadband internet policies implemented at the municipality level impacted adolescent educational outcomes, and after holding constant variations at the municipality, school and family levels, we aim to assert how students' school performance was impacted by the introduction of existing broadband internet coverage policies in the country.

We engage with theoretical approaches that focus on both 'global effects' (i.e., how broadband internet coverage affects students on average) and 'heterogeneous effects' (i.e., how broadband internet coverage influences students across groups). Regarding the *global effects*, one strand of literature suggests that the arrival of broadband internet coverage at a municipality provides students with better opportunities to access multiple online educational resources and information that improve their learning conditions and ability to do homework (e.g., Fairlie et al., 2010). Thus, compared to students from areas with reduced broadband internet coverage, students from places where broadband internet is expanding could access faster and more frequent internet at home, and this may lead to higher quality educational resources and online support (Bulman & Fairlie, 2016; Fox et al., 2012; Lenhart et al., 2001). Similarly, as neighbours, families and peers from the same municipality get higher chances of using broadband internet in their communities, students could share information through interacting with adults and young people by using such online resources. For example, peers may refer to online tools or share information when getting higher quality internet in their geographical area, which may positively impact student academic performance (Asterhan & Bouton, 2017; Caldarulo et al., 2023).

Yet, another strand of scholarship argues that broadband internet coverage allows students to concentrate more energy and time on non-strictly educational digital activities (*e.g.*, social media use, texting online, streaming entertainment videos), thus reducing time in activities like studying, exercising or sleeping that cause worsening their academic performance (Ernst et al., 2011). The dissemination of these negative effects could operate at the community level, not only at the family level. For example, as adolescents often engage in social media and internet gaming with peers that they met offline (i.e., peers from the same school within a municipality) (Blasiman et al., 2018; Junco & Cotten, 2012; Rideout et al., 2010), living in a municipality with increasing broadband internet coverage may augment the risks of getting distracted online or using internet excessively, as adolescents' social networks are strongly structured within communities.

Regarding the *heterogeneous effects*, we apply an intersectional framework. Following Collins (2019), we can define intersectionality as an analytical tool that conceptualises different analytical categories such as class, gender, race, sexuality or age as interrelated and mutually shaping one another. While the concept of intersectionality was originally developed to stress a 'matrix of domination' that reflects double inequalities faced by racialised minority women (Collins, 2019), digital divide scholars have recently called for the need to adopt an intersectional perspective to understand how offline and online divides operate across diverse groups in society (Helsper, 2021). Along these lines, Helsper (2021) has emphasised the importance of considering the intersection of different demographic groups that face divergent levels of inclusion or exclusion within the digital world.

We use an intersectional approach to discuss potential scenarios that can lead to higher or lower educational opportunities among adolescents during the expansion of broadband internet in society. Scholars have argued that vulnerable students (e.g., from disadvantaged socioeconomic backgrounds; ethnic and racialised minorities; lower-achieving) may be more harmed – or benefit less – from technological transformations, as existing inequalities in society would amplify the divides in the risks and opportunities that adolescents face in the digital world (Chen & Li, 2022; Ignatow & Robinson, 2017; Lenzi et al., 2022; North et al., 2008; Robinson & Schulz, 2013). By contrast, others have claimed that vulnerable groups, like students from less-educated or disadvantaged migrant backgrounds, can benefit more from high-quality internet coverage, as better internet connection can foster peer collaboration and learning opportunities among students who lack educational support at home (Asterhan & Bouton, 2017; Mitra & Dangwal, 2010).

Finally, the role of gender can be approached from different theoretical angles. On the one hand, better municipal internet coverage may harm girls more – or benefit girls less – than boys. For example, girls are more vulnerable to social media and body image comparisons in online settings that are linked to poorer mental health and educational distractions (Nesi & Prinstein, 2015; Yau & Reich, 2019), while boys may improve academically from their higher online ICT engagement (Qazi et al., 2022). On the other hand, as boys can suffer higher risks of facing externalising behavioural problems through online settings (Booker et al., 2018) and higher internet gaming addictions (Su et al., 2020), boys could be more harmed academically than girls after having faster and better internet coverage in their geographical area.

Previous research on student ICTs and broadband internet effects

Most empirical studies on the relationship between ICTs and student performance (Bauer et al., 2020; Biagi & Loi, 2013; Fairlie et al., 2010; Kubiatko & Vlckova, 2010; Luu & Freeman, 2011; Notten et al., 2009) have omitted a (quasi-)experimental strategy. While descriptive evidence is highly important, the literature has been unable to test causally how changes in ICT coverage impact student performance. For example, previous correlational studies were unable to account for the fact that availability of ICT is determined by family background and school characteristics that may influence student educational performance (Woessmann & Fuchs, 2004). Therefore, these studies cannot robustly control for potential correlations between family educational motivation and ICT availability (Bulman & Fairlie, 2016). For this to be tackled, an exogenous variation (*e.g.*, new broadband internet coverage in a municipality) is needed to obtain a robust estimation of the causal effect of ICT coverage on student academic performance.

To date, studies using (quasi-)experimental methods in this field have mostly looked at access to computers. Studies on computer access used a variety of methods, including instrumental variable techniques (Fairlie, 2005; Fairlie et al., 2010; Fiorini, 2010), regression discontinuity (Malamud & Pop-Eleches, 2011), individual-student fixed effects (Fairlie et al., 2010; Vigdor et al., 2014), falsification tests (Fairlie et al., 2010; Schmitt & Wadsworth, 2006), and field experiments (Fairlie & London, 2012; Fairlie & Robinson, 2013; Malamud & Pop-Eleches, 2011; Whitacre & Higgins, 2021). This research is relevant in indicating that access to computers can lead to some small improvements in educational performance (Fairlie & London, 2012), particularly if coupled with internet availability (Whitacre & Higgins, 2021). Other related research found both negative (Malamud & Pop-Eleches, 2011) and zero-findings (Fairlie & Robinson, 2013) on educational outcomes. However, these studies did not examine the role of effect of internet coverage on students' academic performance. While computers allow adolescents to access the internet, having access to a new computer is not equivalent to having better internet coverage.

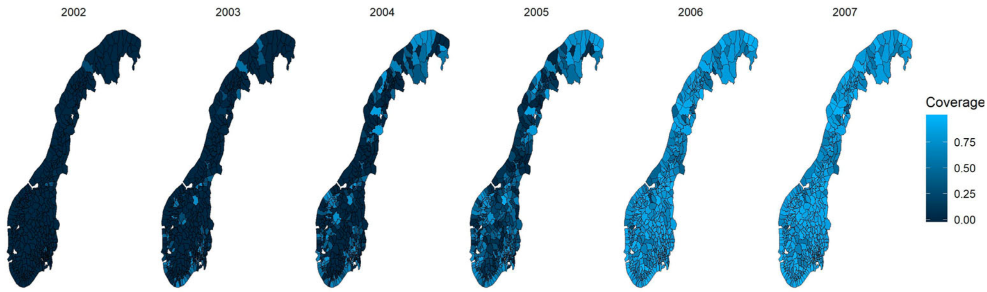
To our knowledge, only three studies, two using US data and one using UK data, have used (quasi-)experimental methods to test the causal effect of broadband internet coverage on students' academic performance. These studies provided quite mixed and inconclusive results. Vigdor et al. (2014) used data from North Carolina by applying fixed-effects models to broadband coverage that allow for the test of within-student variation. The authors found that broadband coverage negatively impacted math test scores for 5th to 8th graders, with negative effects being concentrated among boys, students from disadvantaged socioeconomic status (SES) groups, and black students. Faber et al. (2015) used a regression discontinuity design to estimate the effect of broadband connection speed (Mbits/s) on the educational attainment of primary and secondary school students in England, using administrative data and special-temporal internet variation. This study reports no relevant associations between access to high-speed internet and students' educational attainment. Dettling et al. (2018) used US College board, SAT and PSAT data on US high-school graduates to study the impact of broadband coverage on the transition to college. This latter study found that the rollout of high-speed internet improved students' SAT scores and college application rates, while this effect was concentrated among high-SES students.

Existing research on how broadband internet coverage impacts student performance presents some limitations that we address in this study. First, previous literature focused on English-speaking countries, raising the question of whether different results can be obtained in other countries (e.g., Norway). Second, while previous studies implemented advanced statistical approaches, their methodological strategies present limitations too. For example, Vigdor et al. (2014) did not include time fixed-effects, making their estimates susceptible to time-varying confounders that are not captured by the set of students' characteristics. Also, Dettling et al. (2018) relied on an estimation strategy that uses both time fixed-effects and postal code fixed effects (i.e., two-way fixed effects designs), an approach susceptible to bias in cases of effect heterogeneity (Callaway & Sant'Anna, 2021; De Chaisemartin & D'Haultfoeuille, 2020). The latter can be problematic as online content and ICT technologies change over time.

To advance the literature, we apply a quasi-experimental approach to rich national registry data on grades for all lower secondary school graduates in Norway. We not only benefit from the gradual rollout of broadband internet coverage across hundreds of Norwegian municipalities over years, but also from implementing a new casual design within this literature: sibling fixed-effects models. The sibling fixed-effects design allows to estimate the causal effect of broadband internet coverage on student academic outcomes by controlling for confounders at the municipality, school, and family levels, and so reducing the estimation bias that studies may get when lacking data on siblings (see Allison, 2009; Halaby, 2004).

The Norwegian case

Norway offers an interesting national context of study. Figure 1 shows how broadband internet coverage was gradually implemented in Norway from 2002 (with only 6%



Note: The figure displays our explanatory variable, the geographical distribution of broadband internet coverage across Norway per year from 2002 to 2007. Data source Norwegian Communication Authority (NKOM).

Figure 1. The rollout of broadband internet in Norway. Note: The figure displays our explanatory variable, the geographical distribution of broadband internet coverage across Norway per year from 2002 to 2007. Data source Norwegian Communication Authority (NKOM).

coverage) to 2007 (with up to 85% coverage). A study with nationally representative data found that 86% of Norwegians aged 13–15 years had broadband internet at home by 2007 (Norsk Mediebarometer, 2021). The same study found that the percentage of 13–15 year-olds who used internet on a daily basis matched the evolution of broadband coverage rates across municipalities between 2002 and 2007 (Norsk Mediebarometer, 2021). Compared to dialup modem internet, broadband internet allowed for faster, less restricted, and uninterrupted connection that did not interfere with the phone line and allowed for multiple simultaneous users in the same home. This meant users would experience much higher quality internet use with broadband internet than with dialup internet.

To date, research on the relationship between ICTs and students' educational performance in Norway has been restricted to three cross-sectional studies, none focusing on broadband internet coverage. Torgersen (2004) investigated the relationship between parental education, computer use, and academic performance among Norwegian adolescents, finding that higher parental education links to higher use of all kinds of computer activities, and computer use is positively associated with Math and English grades. Examining computer use and academic performance for 10th graders in Bergen, Nævdal (2004) found that boys use computers more than girls, and also that girls' computer use is positively correlated with academic performance, while boys' computer use has an inverse u-shape correlation with performance (i.e., boys using computers for more than 2 h a day had almost as poor academic performance as boys who never used computers). Finally, Brandtzæg et al. (2005) examined gender differences in media usage in Norway, with results indicating that boys, compared to girls, use internet in their bedrooms more, and engage more in web surfing, information gathering, chatting and newsgroups.

Overall, studies on Norway, and most studies in this field, used a correlational approach, missing a (quasi-)experimental causal approach to identify how ICTs impact student educational outcomes. Additionally, none of these previous studies with data from Norway focused on broadband internet coverage. Our study fills these major gaps.

Methodology

Data and sample

Our analyses link individual-level administrative registry data, assembled by Statistics Norway, with municipality-level data on broadband coverage, provided by The Norwegian Communications Authority (Nkom). These data offer precise information on the exact internet broadband coverage at each municipality from the country, as well as exact data on the grades for all subjects among all lower secondary school graduates in Norway. The primary broadband technology used during this period was xDSL, but there were other broadband technologies used, including mobile broadband, internet through cable-TV, Radio-technologies, and fibre-optic connections (Akerman et al., 2015; Bhuller et al., 2013, 2020; Teleplan Consulting AS, 2008).[1] On top of broadband coverage data, all information that we use comes from administrative registry data with annual measures on every registered inhabitant in Norway. We use data on lower secondary school graduation, including grades, year of graduation, and municipality of residence, as well as data on the age of graduation and residential information for all the years covered in our analysis.

In our data, each graduate had a set of observations of grades in each subject. Student data were linked to a school ID number to ensure we are comparing siblings graduating from the same school.[2] Grades were then averaged to produce the student GPA. Each student was assigned a broadband coverage value according to their municipality of residence for each graduation year. This means every student graduating in the same municipality and year was assigned the same broadband coverage value. The family unit was identified by combining and matching the registry ID number of the graduate's mother and father.

Our dataset is restricted to years for which we had overlapping information on broadband coverage and grades during the period of internet expansion: from 2002 to 2007. Our sample included siblings who had the same registered mother and father. For comparability issues our sample only contained students who turned 16 years old in each year of observation. To strengthen the comparativeness of our siblings, we further restricted our sample to families with two siblings graduating from the same school in different years so that our sibling fixed-effects models could be effectively implemented (Callaway & Sant'Anna, 2021). Our final sample consists of 103,796 students. Table 1 presents the study sample distributions.

Dependent variables

Our outcome variable is the final *grades* from the last lower secondary school year. The original grades range from 0 (lowest) to 6 (highest). We transformed the grades to a 0–100 scale by multiplying all combined grades by a factor of 100/6. To compute the GPA, we took students' arithmetic mean of the final grades, including exams grades. This GPA is the mark that is used when assessing students' admissions to Upper secondary school in Norway. We further examined grades across seven academic subjects: 'Arts and crafts', 'English', 'Gymnastics', 'Mathematics', 'Natural sciences', 'Norwegian', and 'Social sciences'. These seven subjects came from thirteen original subject exams. For comparison purposes we merged written Norwegian, oral Norwegian and Norwegian dialects as

Table 1. Summary statistics of study variables.

Variable	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD	N	Mean	SD
Year	2002			2003			2004			2005			2006			2007		
GPA	16080	66.954	13.357	16186	67.511	13.273	17736	67.616	13.355	18522	67.491	13.377	17483	66.814	13.286	17789	66.656	13.527
Broadband coverage	16080	0.059	0.126	16186	0.348	0.325	17736	0.528	0.327	18522	0.637	0.272	17483	0.886	0.114	17789	0.922	0.085
Gender	16080			16186			17736			18522			17483			17789		
… Girls	7728	48.1%		7885	48.7%		8573	48.3%		8945	48.3%		8450	48.3%		8593	48.3%	
… Boys	8352	51.9%		8301	51.3%		9163	51.7%		9577	51.7%		9033	51.7%		9196	51.7%	
Highest parental education	15967			16066			17608			18378			17365			17671		
… Compulsory education	1517	9.5%		1509	9.4%		1541	8.8%		1617	8.8%		1468	8.5%		1449	8.2%	
… Intermediate education	7538	47.2%		7554	47%		8060	45.8%		8273	45%		7966	45.9%		8074	45.7%	
… Tertiary education	6912	43.3%		7003	43.6%		8007	45.5%		8488	46.2%		7931	45.7%		8148	46.1%	
imgroup	16080			16186			17736			18522			17483			17789		
… 1 nonwestern parent*	368	2.3%		456	2.8%		517	2.9%		593	3.2%		513	2.9%		535	3%	
… 1 western parent*	728	4.5%		742	4.6%		924	5.2%		964	5.2%		858	4.9%		874	4.9%	
… 2 parents nonwestern	554	3.4%		675	4.2%		765	4.3%		847	4.6%		793	4.5%		780	4.4%	
… 2 parents Norwegian	14430	89.7%		14313	88.4%		15530	87.6%		16118	87%		15319	87.6%		15600	87.7%	

one subject, combined oral English and written English in one subject, and put all social science subjects together. Additional analyses (not shown) revealed internal consistency in the effects for each of these categories.

Explanatory variable

Our key independent variable is *broadband coverage*, defined as the proportion of households in the municipality with internet connection of at least 256 kb/s download speed. We use yearly data within every municipality fraction of households that are covered with broadband from 2002-01-01 to 2007-01-01. Thus, we use an aggregate measure of broadband availability for individuals within each municipality fraction of households that ranges from 0 and 1.

Group variables

We use four subgroup samples to assess effect heterogeneity. First, we use gender as the binary measure provided in the census: boys and girls. Second, we use parental educational level as in the registered NUS classification (Barrabés & Østli, 2016), based on three categories of the highest level of education from the more highly educated parent: (1) 'Compulsory education': primary and lower secondary education; (2) 'Intermediate education': upper secondary and vocational education; (3) 'Tertiary education': undergraduate, graduate, and postgraduate education. Third, we use migration status by classifying students into four groups based on parent country of birth (Hermansen, 2017; Hermansen et al., 2022; Lillehagen & Birkelund, 2022): (1) 'Two Norwegian': both parents were born in Norway; (2) 'Two non-western': both parents were born in non-western countries; (3) 'One western parent': one parent was born in a western country and the other was born in either a western country or in Norway, but not in a non-western country; (4) 'One non-western parent': only one parent was born in a non-western country and the other parent was either western or Norwegian born. Students with two western-born parents were grouped in the category 'One western parent', as this group represented a very small subsample to run separated analyses (n = 166). Fourth, we assigned families into GPA quintiles, defined by the GPA of the sibling with the lowest broadband coverage, calculated for year and gender separately.

Control variables

We include several control variables. We use a set of family-level dummies to account for unobserved family characteristics. While our method is quite effective to account for potential bias from unobserved family-specific differences, sibling fixed-effects models may still produce bias due to unobserved heterogeneity that is unique to each sibling. For this reason, we address potential bias between siblings by including additional control variables that could cause siblings within the same family to perform differently. We control for the child's birth cohort (Barclay & Myrskylä, 2016), child's birth order in the family (Lillehagen & Isungset, 2020), and mother's age at birth (Myrskylä & Fenelon, 2012). As we explain below, our empirical design further allows to control for factors at the school and municipality levels.

Analytical strategy

We conduct a sibling fixed-effects design. Fixed-effects models estimate causal effects in analyses with repeated observations of units (e.g., individuals, families, schools) by eliminating the effects of confounding variables without measuring them, as long as they are stable within unit set observations (Firebaugh et al., 2013). By including a set of family dummy variables (each dummy indicates a particular family) we can construct a sibling fixed-effects model. These dummy variables cancel out any confounding variables that are stable between families, like genetics and social inheritance. Because we only include siblings graduating from the same school, this also implies that the family dummies also control for higher level confounders such as schools and municipalities. Previous studies have used sibling fixed-effects models to eliminate omitted variable bias at the family level in researching students' educational outcomes and well-being (De Neve & Oswald, 2012; Hermansen, 2017).

The association between broadband internet coverage and adolescent educational performance can be confounded by family variables that are not provided at the municipal level. For example, recent trends of urbanisation and centralisation across Norwegian municipalities are correlated with employment rates. As a result, families who settled in urban areas are likely to be different than families remaining in rural areas in multiple dimensions (e.g., motivation for residential mobility, aspirations, family relations, and student performance) (Andersson et al., 2019). Further, the level of broadband coverage and educational performance at the municipality level is expected to be correlated with residential patterns, meaning that broadband coverage and educational performance become spuriously correlated at municipality levels. While municipality fixed-effects would not be sufficient to account for urbanisation and centralisation dynamics, because such differences are not stable over time, sibling fixed-effects models consider variations between siblings that allow to address factors such as residential mobility. By applying fixed-effects models, we are not only accounting for differences at the school and municipality level, but also for differences at the family level.

We define our theoretical estimand, namely the theoretical quantity we seek to estimate, as in Lundberg et al. (2021). We estimate the effect of broadband on the grades of lower secondary school graduates, measured as the difference between the grades that student i gets with full municipality broadband coverage rate and the grades that student i gets without municipality broadband coverage rate. We target different estimands for different subsets of the population. For each subset $s = \{1, \ldots, n\}$ we target the average treatment effect for the subset β_s. The formal model is specified as follows:

$$\beta_s = \frac{1}{n}\sum_{i=1}^{n}\left(Y_i(broadband = 1) - \ Y_i(broadband = 0)\right)$$

Because we only observe individuals with a single value of broadband coverage, the estimand is not directly measurable. To measure the estimand we would need to observe the same individuals at the exact same time in parallel moments with different broadband coverage levels. We instead estimate $\hat{\beta}$ by comparing siblings with different values of broadband coverage, meaning that we include dummy variables of the family (the combined IDs of parents) as a control variable through. This approach accounts for all potential confounders related to the family. Of course, there may be systematic bias between siblings from birth order effects, birth cohort effects or mothers' age at birth that are likely to covary with grades and broadband coverage. For this reason, we run fixed-effects control variables to correct for all these potential confounders.

We further split the data into different subsamples according to the relevant background characteristics to study effect heterogeneity:

$$Y_i = \hat{\alpha}_f + \hat{\beta}X_m + \hat{\gamma}Z + \varepsilon$$

α_f = Family dummies

X_m = Municipality Broadband Coverage Rate.

Z = Set of control variables {gender, birth-order, birth-cohort, and mother's age at birth}

ε = Random error

Splitting the sample into subsamples has two key advantages, compared to approaches that use a single model and interact broadband coverage with subgroup measures. First, with this approach all the control variable coefficients are automatically adapted to the subgroup, and we do not need to assume that these are similar across subgroups. Second, a subsample approach produces individual model parameters like the number of observations and adjusted r^2 for each subgroup. This increases transparency in our analysis and facilitates potential use of results in future meta-analyses, as shown in Online Supplements (from Tables S1 to S5). Our analyses intersect most of our categories of study. Yet, we do not intersect some of our group categories due to reasons of focus, space, and statistical power. For example, as some migrant status groups in our sample are small and quite selective, we were unable to run robust analyses by migrant group combined with academic achievement and parental education. Future studies should further investigate these group comparisons.

Finally, all estimations were conducted in R version 4.0.3 with the 'fixest' package, and figures were created using the 'ggplot2' package. Standard errors are clustered at the family level.

Results

Figure 2 shows the sibling fixed-effects analyses of the effect of broadband coverage on students' GPA for the whole sample (Panel A) and separately by gender (Panel B). In Panel A we observe that broadband internet coverage has a very small positive effect on student GPA for the whole sample (b = 0.39, $p < 0.1$). Panel B shows that boys display a statistically significant positive effect of 1.1 points from broadband coverage ($p < 0.001$), while the estimate for girls was not statistically different from zero (b = 0.28). Overall, boys on average improved their grades by 1 point in a 0–100 scale, while girls were largely unaffected.

Figure 3 shows the sibling fixed-effects results on the impact of broadband coverage on students' performance (GPA) by parental education for the whole sample (Panel A) and separately by gender (Panel B). In Panel A we observe a slightly positive effect of broadband internet on GPA results for students with parents having intermediate levels of education (b = 0.7, $p < 0.05$), a null effect for students with lower-educated parents (b = 0.007) and a very small positive effect, not statistically significant, for students with

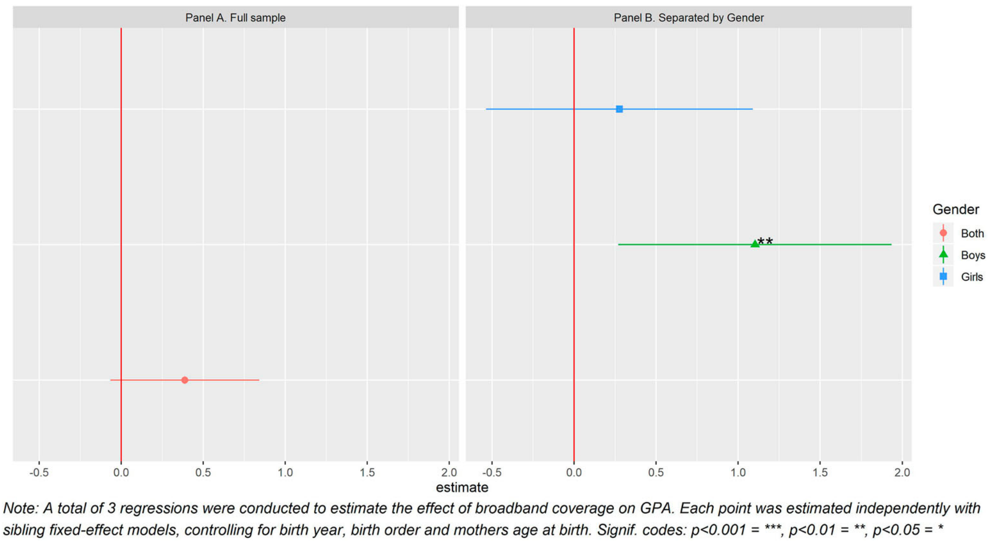


Figure 2. Sibling fixed-effect models of broadband coverage on GPA estimated for full sample and by gender. Note: A total of 3 regressions were conducted to estimate the effect of broadband coverage on GPA. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif codes: $p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = *.

higher-educated parents (b = 0.28). However, Panel B shows clear gender differences by parental education. Boys with compulsory educated parents had a high estimated

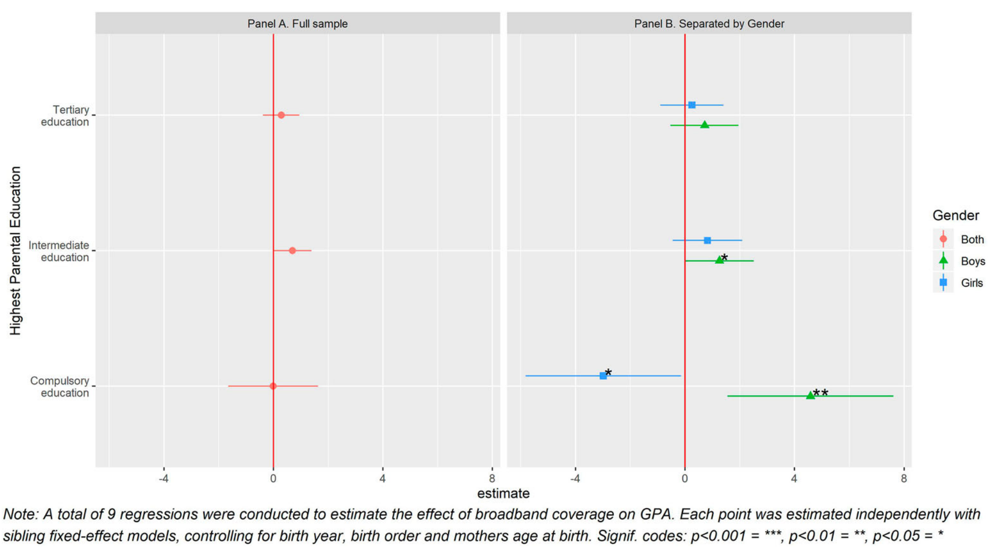


Figure 3. Sibling fixed-effect models of broadband coverage on GPA by gender and parental education. Note: A total of 9 regressions were conducted to estimate the effect of broadband coverage on GPA. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif codes: $p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = *.

improvement of 4.53 points in their GPA ($p < 0.01$) and boys with parents in the intermediate level of education had a non-trivial improvement of 1.27 points ($p < 0.05$), with sons of tertiary educated parents experiencing no relevant change in GPA from broadband internet coverage. By contrast, girls whose parents have compulsory levels of education experienced a substantive decline in GPA scores of −2.98 points ($p < 0.05$), compared to small and not statistically significant changes among daughters of parents in both intermediate and high educational groups. Overall, we observe gendered patterns in the effect of broadband on GPA across levels of education: boys with less educated parents see strong grade improvements from broadband internet coverage and girls with less-educated parents experience substantive negative effects.

Figure 4 presents the sibling fixed-effects results of broadband coverage on student performance by GPA quintile groups.[3] Panel A shows negative broadband coverage effects on GPA for highest achieving students (b = −1.5, $p < 0.01$), while lowest achieving students experience GPA increases (b = 2.14, $p < 0.001$). Panel B indicates gender differences in effects for lowest achievement students, with improvements of 4.5 points among lowest achieving boys ($p < 0.001$) and of 1 point for lowest achieving girls. Panel C shows that the effect of broadband internet coverage by parental education and achievement levels is quite uniform for girls, with statistically significant differences observed only for lowest achieving girls with intermediate educated parents (b = 2.8, $p < 0.05$). Finally, Panel D illustrates strong GPA increases from broadband internet coverage levels among boys with less-educated parents in the second lowest achievement quintile (b = 6.7, $p < 0.05$) and boys in the lowest achievement quintile with parents having intermediate levels of education (b = 5.39, $p < 0.001$). By contrast, we find negative effects for boys with

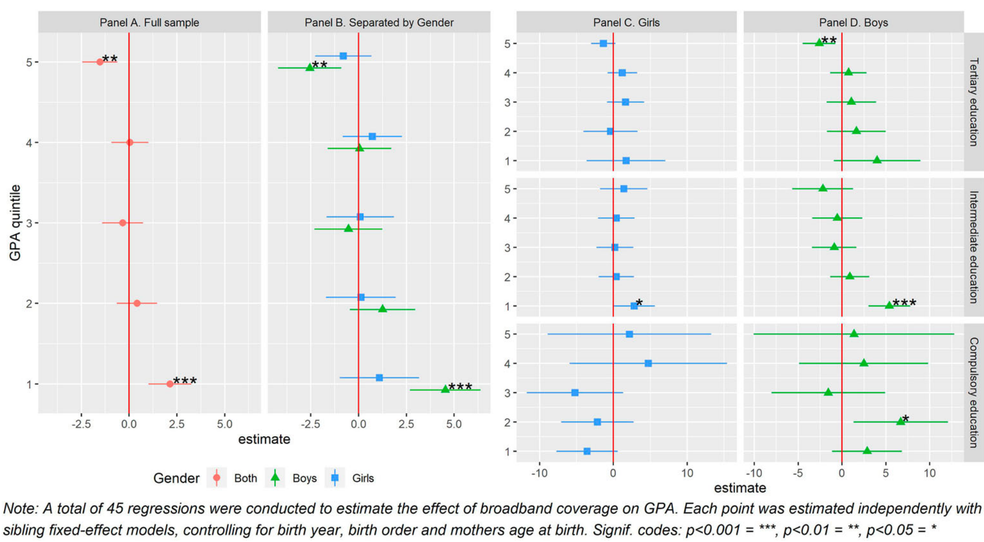
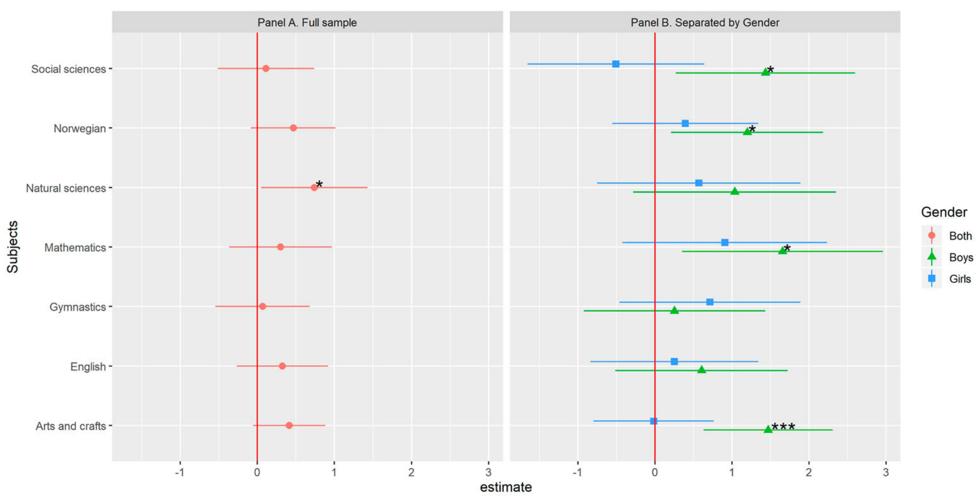


Figure 4. Sibling fixed-effect models of broadband coverage on GPA by gender, GPA quintile, and parent education. Note: A total of 45 regressions were conducted to estimate the effect of broadband coverage on GPA. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif codes: $p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = *.

tertiary educated parents who are in the highest achievement quintile group (b = −2.61, $p < 0.01$).

Figure 5 shows the sibling fixed-effects results of broadband internet coverage on students' performance by study subjects, both for the whole sample (Panel A) and by gender (Panel B). In Panel A, we observe estimates close to zero, with the only subject yielding statistically significant results being *Natural sciences* (b = 0.74, $p < 0.05$), albeit with a small effect size. In Panel B, we observe that only boys show statistically significant estimates, particularly in *Mathematics* (b = 1.65, $p < 0.05$), *Arts and crafts* (b = 1.47, $p < 0.001$), *Social sciences* (b = 1.43, $p < 0.05$), and *Norwegian* (b = 1.2, $p < 0.05$). For girls, broadband internet coverage has a small and not statistically significant effect on student performance across all academic subjects.

Figure 6 presents the sibling fixed-effects findings on how broadband coverage influenced students' GPA scores by migration status for the whole sample (Panel A) and by gender (Panel B). In Panel A, we observe a negative effect of broadband coverage on GPA results among students with one non-western parent, but with low statistically significant levels (b = −2.76; $p < 0.10$). The only group of Panel A with statistically significant estimates is the group of students with two Norwegian born parents, even if effects are small (b = 0.51, $p < 0.05$). Panel B reveals a more complex gendered pattern. Boys with two Norwegian born parents, but not girls with two Norwegian born parents, experience positive effects of broadband internet on their GPA results (b = 1.38, $p < 0.01$). By contrast, among girls, those with at least one western immigrant parent (b = 3.9, $p < 0.05$) and two non-western parents (b = 4.13, $p < 0.1$) are those who experience clear GPA improvements with the arrival of broadband internet coverage. Overall, boys with two



*Note: A total of 12 regressions were conducted to estimate the effect of broadband coverage on subject grades. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif. codes: p<0.001 = ***, p<0.01 = **, p<0.05 = **

Figure 5. Sibling fixed-effect models of broadband coverage on grades by gender and subjects. Note: A total of 12 regressions were conducted to estimate the effect of broadband coverage on subject grades. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif codes: $p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = *.

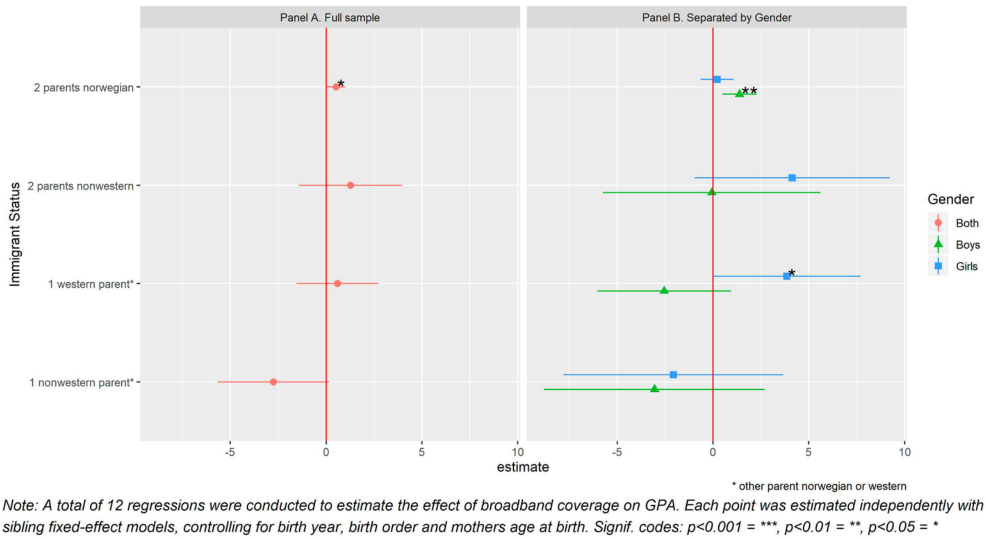


Figure 6. Sibling fixed-effect models of broadband coverage on GPA by gender and immigrant status. Note: A total of 12 regressions were conducted to estimate the effect of broadband coverage on GPA. Each point was estimated independently with sibling fixed-effect models, controlling for birth year, birth order and mothers age at birth. Signif codes: $p < 0.001 = ***$, $p < 0.01 = **$, $p < 0.05 = *$.

Norwegian-born parents experience moderate academic benefits from broadband internet coverage, whereas girls with one western migrant parent and girls with two non-western parents improve their academic performance quite markedly.

Discussion

This study has examined the causal impact of the expansion of broadband internet coverage on students' academic performance. Our study benefits from access to unique registry data from Norway containing rich measures of broadband coverage across all municipalities and detailed records of student grades for all lower secondary school graduates in the country. We implement a novel quasi-experimental design with sibling fixed-effects models, taking advantage of the gradual growth of broadband internet that Norwegian municipalities underwent from 2002 to 2007.

Our study shows important heterogeneity in the effects of broadband internet coverage on students' academic outcomes. Broadband internet brought small improvements to students' academic performance, with effects applying largely to boys. Globally, boys benefited from broadband internet coverage with effects about three times larger than girls. These gendered patterns strongly intersected with social background. While boys with lower-educated parents benefited by 4.5 points on a scale from 0 to 100 – from the municipal expansion of broadband coverage (i.e., a third of the standard deviation in points for boys), girls with lower-educated parents experienced negative effects of 3 points. Also, broadband internet coverage reduced grade gaps by academic achievement for girls, and particularly for boys. We found that boys in lower levels of academic achievement strongly improved their grades, just as much as boys with less-educated parents. By contrast, boys in higher academic achievement levels reduced their performance, but only if their parents were highly educated. Finally, girls of migrant origin tended to improve academically with the expansion of broadband internet, while grade improvements for boys applied only, and moderately, to students of non-immigrant background.

Our study has important implications for the literature on ICTs and adolescent school outcomes at four main levels. First, our finding that boys improve their educational performance more than girls when broadband internet expands needs to be contextualised. Previous studies using data from Norway and other countries (Brandtzæg et al., 2005; Livingstone & Helsper, 2007; Nævdal, 2004; Notten et al., 2009) indicate that boys use computers more than girls. Computers were the sole electronic device used to access internet in the years covered in our study (2002-2007), which may explain why broadband internet coverage benefited boys more than girls. These findings interestingly contradict the results of Vigdor et al. (2014) who found particularly negative schooling effects for boys after the rollout of broadband internet in the US state of North Carolina. Future studies should further explore such gendered patterns by addressing mechanisms of actual use and analysing more recent data on social media use.

Second, our study shows intersections between social background, gender, and levels of educational achievement that contribute to understanding ICT impacts on adolescent school outcomes. The fact that broadband internet expansion strongly improves the academic performance of lower-achieving boys and boys from disadvantaged socioeconomic backgrounds, implies that internet resources can lower the home disadvantage and academic challenges that students – boys in particular – from less-educated and lower-achievement groups face. Interestingly, previous US research found that students, specifically boys, from disadvantaged social backgrounds worsened their academic performance with broadband internet coverage (Dettling et al., 2018; Vigdor et al., 2014). The more egalitarian and socially inclusive context of Norway, compared to the US, may explain why the expansion of broadband internet in municipalities reduced inequalities in school performance in Norway among boys. It is important to stress that Norway has a universalist Scandinavian welfare model and an education system aiming at providing equal and customised training for all social strata (Esping-Andersen, 1990; Jantti et al., 2006). However, the fact that girls from less-educated families worsened their academic performance with the introduction of broadband internet shows a worrying pattern of socio-digital disadvantage among girls from socially vulnerable families in Norway. Future studies should further examine the reasons of opposite gender effects of broadband internet expansion on student educational outcomes across different socioeconomic backgrounds.

Third, our analyses by academic subjects provided inconclusive results. When pooling girls and boys together, we found small improvements across all subjects, with largest, but small, effects for 'Natural sciences'. These findings limit any clear conclusions. Among boys, we found grade improvements in four subjects, namely 'Mathematics', 'Arts and Crafts', 'Social sciences' and 'Norwegian'. While it seems reasonable that grades in subjects like 'Gymnastics' were unaffected by the expansion of broadband internet, why 'Norwegian' and not 'English' saw improvements among boys is less obvious. These findings may indicate that graduates did not engage much with English online content and used digital content in Norwegian language.

Fourth, and last, the finding that students from different migrant groups are not similarly influenced by broadband internet across genders captures a relevant gendered pattern to understand the role of ethnicity and race in digital contexts. That boys from non-immigrant Norwegian background are advantaged from accessing broadband internet echoes US research showing that black students are particularly disadvantaged with the expansion of broadband internet, compared to white students (Vigdor et al., 2014). Yet, the finding that girls from non-Norwegian minority groups, unlike boys, benefited academically from broadband internet coverage expansion indicates a certain gendered equalising effect of broadband expansion by migration status. Future research should further expand this important area of research.

Our findings have important scientific and policy implications that involve various actors. Previous research found that boys typically obtain worse grades than girls, and also that academic inequalities within boys are particularly strong (DiPrete & Jennings, 2012). Our finding of grade improvements for boys who underperform and are socially excluded implies that broadband internet can benefit disadvantaged boys if programmes target them adequately. Also, that girls from migrant groups tend to experience grade improvements suggests that school digital programmes should consider the potential educational benefit that internet connectivity can bring to this traditionally excluded group of female students. Also, educators and policy makers can provide resources to girls from less-educated and working-class families who were found to reduce substantially their school performance with broadband internet expansion (*e.g.*, via ICT support and academic guidance in class to facilitate that these socially vulnerable girls benefit more from opportunities linked to broadband internet coverage). While socioeconomically privileged and higher-achievement students are only partly hindered, our findings can inform teachers, educators and parents about the moderate negative academic effects of expanding broadband internet among more advantaged students, and particularly boys.

We can further summarise the potential explanatory mechanisms behind our results. Globally, the rollout of broadband internet may provide students with better chances to frequently access online educational resources, and with the ability to share online information with peers in ways that foster their learning opportunities and homework performance. Boys may benefit more than girls from broadband internet expansion as they use computers with internet more frequently, also in the context of our study (i.e., the Norwegian context of the early 2000s). Gender differences in internet use and ICT engagement may explain such differential effects between boys and girls. Additionally, boys from less-educated family backgrounds could disproportionally benefit from having high-quality internet coverage through using digital resources that compensate for lacking certain educational resources at home. Likewise, low-achieving students could engage more with alternative online educational resources as broadband internet expands, which may be more effective than traditional pedagogical tools. By contrast, girls from unprivileged socioeconomic contexts may engage with internet in potentially detrimental ways, leading them to achieve worse academic performance when broadband internet expands. Finally, the reason why high-achieving privileged students moderately reduce their academic performance with broadband internet, and why gender and migrant status are intersecting in complex ways, is unclear. Future studies should address these mechanisms that we cannot examine, not only for reasons of focus and space, but also due to data limitations.

We must acknowledge some limitations in our study. First, we have excluded one-child families from the analysis to provide causal estimates with high internal validity via sibling fixed-effects models. This means we cannot extrapolate results to one-child families. Second, our study cannot disentangle the behavioural mechanisms that drive the observed effects (*e.g.*, how students use internet and how it impacts their academic grades). We call for further research to disentangle these mechanisms. Third, we examine the expansion of broadband internet coverage in the early 2000s. Significant changes in broadband quality, online content, use of mobile technologies, social media engagement or school curricula have occurred in recent years. Still, our study guides future studies on geographical contexts where broadband internet expanded more recently or can guide research on longer-term effects of broadband internet. Fourth, our key measure of study is restricted to GPA results. Access to broadband internet could impact other school-related outcomes too, such as educational aspirations, study behaviours or outcome like SATs (Hampton et al., 2021). Students may learn valuable information and skills via broadband internet that is not captured with GPA scores. Still, in our context of study (i.e., lower-secondary school graduates in Norway) GPA is a key outcome that directly determines the chances for upper secondary school and future employment opportunities (Markussen, 2019). Fifth, and last, we use broadband coverage at a quite large level: municipalities. While this is a policy relevant geographical setting to study broadband coverage effects, having lower-level information on broadband coverage could have helped to gain further explanatory power (*e.g.*, at the neighbourhood level). Future studies should address smaller community-level measures of broadband internet coverage.

Overall, and despite the mentioned shortcomings, our study shows heterogeneity across the population in how broadband internet expansion impacted adolescent academic outcomes in Norway. The expansion of broadband coverage had more positive academic effects for boys than for girls. Specifically, boys from less-educated homes and low-performing students (particularly low-performing boys) experienced clear academic benefits. Conversely, girls from socially vulnerable families worsened their academic performance with the expansion of broadband internet. Also, higher-performing students did worsen their grades moderately, particularly among boys from socioeconomically privileged families. While boys from non-immigrant Norwegian background benefited moderately from broadband internet expansion, girls from migrant origin tended to be the ones who experienced substantial grade improvements. We hope future studies will further investigate the heterogeneous effects of the expansion of internet coverage on young people's well-being and life chances in contemporary societies.

Notes

1. The data account for overlapping suppliers to avoid overestimation from double counting suppliers.
2. Some siblings attend different schools (e.g., the family moves to a new region once one sibling has already graduated from lower secondary school). As the school area is correlated

with broadband coverage rates and schools differ in their curricula and conditions, we include sibling pairs which graduated from the same lower secondary school.

3. The quintiles were defined by the GPA of the student with the lowest broadband coverage. This choice was made to avoid statistical endogeneity in the analyses. All quintile groups were calculated for each year and gender separately to enable within-group comparisons.

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