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SCALING THE DIGITAL DIVIDE:
HOME COMPUTER TECHNOLOGY AND STUDENT ACHIEVEMENT

Jacob L. Vigdor
Helen F. Ladd

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ABSTRACT

Does differential access to computer technology at home compound the educational disparities between rich and poor? Would a program of government provision of computers to early secondary school students reduce these disparities? We use administrative data on North Carolina public school students to corroborate earlier surveys that document broad racial and socioeconomic gaps in home computer access and use. Using within-student variation in home computer access, and across-ZIP code variation in the timing of the introduction of high-speed internet service, we also demonstrate that the introduction of home computer technology is associated with modest but statistically significant and persistent negative impacts on student math and reading test scores. Further evidence suggests that providing universal access to home computers and high-speed internet access would broaden, rather than narrow, math and reading achievement gaps.

Jacob L. Vigdor
Sanford School of Public Policy
Box 90312 Duke University
Durham, NC 27708
and NBER
jacob.vigdor@duke.edu

Helen F. Ladd
Sanford School of Public Policy
Box 90245 Duke University
Durham, NC 27708
hladd@duke.edu

1. Introduction

In recent years, policy makers and philanthropists have undertaken many initiatives to close the so-called "digital divide" in computer access for youth. Thanks in part to these efforts, racial and socioeconomic disparities in computer access at school were largely eliminated by 2003.[1] Recent evidence indicates, however, that differences in access to home computers persist.[2]

Partly motivated by these disparities in access to home computers, several states and school districts in the U.S. and abroad have experimented with programs granting laptops to middle or high school students.[3] As the typical American school has one computer for every four students, and laptop computers are more expensive and less durable than the desktop computers typically used in schools, these initiatives represent a significant increase in per-pupil spending on computer access. A laptop program extended to all public school secondary students in the U.S. would cost billions of dollars per year.[4]

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1 The FCC-administered E-Rate program, for example, allocates up to $2.25 billion each year to improve internet access at public schools and libraries (Goolsbee and Guryan, 2006). DeBell and Chapman (2006), analyzing data from the October 2003 computer use supplement to the Current Population Survey (CPS), report that among all students in nursery school through 12th grade, school computer use rates were 85% for whites and 82% for blacks; 80% for those living in families below the poverty line and 85% for those above. There may be differences in the frequency or type of computer use; Becker (2000) reports the results of a 1998 survey showing that schools serving higher-poverty students had fewer internet connections per computer, and if anything used computer technology more frequently for instructional purposes.

2 The October 2003 computer use supplement to the Current Population Survey found large disparities in home computer access and use by race and socioeconomic status. Among students in nursery school through 12th grade, rates of home computer use were 78% for whites and 46% for blacks; 88% for those with a postgraduate-educated parent and 35% for those with high school dropout parents (DeBell and Chapman, 2006).We document similar disparities in use patterns in North Carolina administrative public school data below.

3 The Maine Learning Technology Initiative, for example, spent $50 million in 2003 to provide Apple ibook laptops to each 6th grade student. The Texas Technology Immersion Project has provided laptops to students in 22 pilot middle schools since 2004. The Recovery School District in New Orleans recently issued laptops to all high school students, at the cost of $1.67 million for a single-year lease. In Australia, prime minister Kevin Rudd campaigned in 2007 on a pledge to issue laptops to all students in grades 9-12.

4 There are roughly 4.5 million students in each American public secondary school cohort. Given the typical laptop lifespan of 3 years, each would require two laptops for the six to seven years of secondary school. If purchased for $1,000 each, the annual cost would be $9 billion. For comparison purposes, the entire Federal

Is this a wise investment of public funds? Very little evidence exists to support a positive relationship between student computer access at home and academic outcomes. A separate literature studying the impact of instructional computer use in school settings, consisting largely of experimental or quasi-experimental studies, has found mixed results (Blanton et al. 2007; Angrist and Lavy 2002; Rouse and Krueger 2004; Goolsbee and Guryan 2006; Li, Atkins and Stanton 2006; Dynarski et al. 2007).[5] Studies of home computer access have revealed promising correlations, but generally have not employed reliable research designs (Attewell and Battle, 1999; Attewell, Suazo-Garcia, and Battle 2003; Borzekowski and Robinson, 2005; Judge 2005; Beltran, Das, and Fairlie, 2006; Jackson et al. 2006; Fiorini 2009).[6] Three quasi-experimental studies have found no significant positive evidence of home computer access on student outcomes. Malamud and Pop-Eleches (2008) analyze the impact of a Romanian policy granting home computers to low-income households, using a regression discontinuity design. Shapley et al. (2007) evaluate the group-randomized Texas Technology Immersion Program.[7] Fairlie and London (2009) report the results of a randomized experiment that gave computers to low-income community college students in northern California.[8]

The absence of significant positive effects in these more rigorous studies may reflect any

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budget for the Title I program in fiscal 2007 was just under $13 billion.

5 The two studies in this set reporting significant positive impacts are Li, Atkins, and Stanton (2006), which shows positive impacts of computer-assisted instruction on one of four test score outcomes in a randomized study of 122 Head Start participants in rural West Virginia, and Blanton et al. (1997), which finds significant benefits from computer use in a randomized trial administered in an after-school program for students in grades 3-6.

6 The dangers of inferring the impact of computer use in nonexperimental settings are emphasized by DiNardo and Pischke (1997), in their critical examination of Krueger's (1993) study of the return to using computers in the workplace.

7 Evaluation of the Texas TIP program is complicated by the fact that the intervention involved more than providing laptops to students. Schools were also given access to software, online instructional and assessment resources, teacher professional development, and initial and ongoing technical support (Shapley et al., 2007).

8 Fairlie and London report a number of positive point estimates, but the only significant result is an interacted effect showing a positive treatment effect for minority students. Importantly, the average age of students in the Fairlie and London experiment is 25. As will be discussed below, there are strong neurological reasons to expect students in their mid-20s to utilize computers more effectively than students in their teenage years.

of several hypothesized mechanisms associating home computer use with worsened student outcomes, including the displacement of social activities and attendant loneliness and depression, exposure to inappropriate violent, sexual, or commercial content, and physical problems, including increased obesity and injuries to the eyes, back, and wrist (Shields and Behrman, 2000; Bielefeldt, 2005).[9]

Do students' basic academic skills improve when they have access to a computer at home? Has the introduction of high-speed internet access, which in theory expands the set of productive tasks for which home computers can be used, caused further improvements? This paper addresses these questions by studying administrative data covering the population of North Carolina public school students between 2000 and 2005, a period when home computer access expanded noticeably, and home high-speed internet availability rose dramatically. This study focuses on students in grades 5-8, a population targeted by many existing laptop initiatives.

The larger sample size available with administrative data – over half a million student/year observations – addresses one common concern with existing studies of the impact of home computer use: low power associated with small sample sizes. The longitudinal nature of the data also permit us to address concerns that students with computer access are a non-random sample of the population by comparing the test scores of students before and after they report gaining access to a home computer, or before and after their local area receives high-speed internet service.

Our results substantiate concerns that simple OLS estimates, even when drawn from a relatively rich specification, falsely attribute positive effects to home computer access. Within-

9 The absence of significant positive effects in many experimental studies may also reflect low statistical power associated with small sample sizes. The Texas Technology Immersion Program, for example, is being evaluated using a school-level randomization with 22 schools in treatment and control groups (Shapley et al., 2007).

student estimates, by contrast, show modest but statistically significant negative impacts. In these models, we can trace the impact of home computer introduction for periods of up to three years; there is no indication that the negative effect of access diminishes over this time period. While the potential for selection bias persists in within-student estimates, the most reasonable mechanism – that family computer purchases coincide with general improvements in well-being – implies that our estimates understate the negative impact of home computer access.

The introduction of high-speed internet service is similarly associated with significantly lower math and reading test scores in the middle grades. Student fixed-effect specifications reveal that increased availability of high speed internet is actually associated with less frequent self-reported computer use for homework. On the margin, then, broadband internet access appears to crowd out studying effort, presumably by introducing new options for recreational use by students and other family members. Moreover, the introduction of broadband internet is associated with widening racial and socioeconomic achievement gaps. One interpretation of these findings is that home computer technology is put to more productive use in households with more effective parental monitoring, or in households where parents can serve as more effective instructors in the productive use of online resources. We find evidence consistent with this interpretation.

This study does not claim to measure all the potential impacts of home computer and internet access. While we find no evidence that this access improves math and reading scores, it is possible that computer and internet access improves important skills that are not directly measured by standardized tests in math or reading. These skills, ranging from the ability to use basic office software to advanced programming or hardware maintenance skills, may be of considerable value in the labor market.[10] While subsidies for home computer or internet access could still be advocated on the grounds that they improve these vocational skills, our results suggest that an additional consequence would be lower math and reading test scores, and wider test score gaps.

Section 2 presents basic information on the magnitude of the digital divide among North Carolina public schools students in grades 5-8, measured in terms of home computer access and the availability of broadband internet at the ZIP code level. Section 3 provides a brief conceptual discussion of the individual, family, and school-level determinants of home computer use and the potential impact of home computer technology on academic outcomes. Section 4 presents results relating internet availability and computer use for homework to standardized test scores in reading and math. Section 5 concludes.

2. Basic evidence on home computer use by North Carolina public school students

2.1 Access to home computers

When public school students in North Carolina take the state's required end-of-grade tests in math and reading, they fill out a brief questionnaire regarding their time use outside of school. The questionnaire asks about time spent on homework, time spent reading for leisure, time spent watching television, and the frequency of home computer use for schoolwork. It is this last question, asked of nearly one million students in 5^{th} through 8^{th} grade between 2000 and 2005, that serves as the basis for our analysis here.[11]

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[10] There is some debate in the literature regarding the labor market returns to computer skills; see Krueger (1993); DiNardo and Pischke (1997).

11 The survey question reads, "How often do you use a computer at home for schoolwork? Mark only *one* choice." The possible responses were: A: almost every day; B: once or twice a week; C: once or twice a month; D: hardly ever; E: Never, even though I have a computer at home; and F: I do not have computer at home. While we use this data item primarily to analyze the consequences of computer access, one could in theory also examine the

Figure 1 shows basic information on the self-reported rate of home computer ownership overall and by race and socioeconomic indicators. Across all observations in all years, nearly 85% of students reported having access to a computer at home.[12] This access rate differs by race and socioeconomic status. Almost 90% of white students have a computer at home, compared to 75% of black students. The disparities across free or reduced price lunch participation categories are larger; 71% of recipients have access to a home computer, versus 92% of non-participants. Disparities between the extreme categories of parental education, students with high school dropout parents and those whose parents have postgraduate education, are strongest: 98% of students in the highest parent education category have access to a home computer, versus 63% of students in the lowest parent education category.[13]

Figure 2 shows basic information on trends in computer ownership between 2000 and 2005, as reported by public school students in our sample. Ownership rates rose over this time period, from just under 80% of all students in 2000 to just over 90% in 2005. This increase in ownership over time is likely driven by continual improvements in technology, accompanied by decreases in prices for personal computers. The Bureau of Labor Statistics estimates that the

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consequences of more frequent use. There are several concerns, however, with such a research design. Concerns regarding the accuracy of self-reported use data have been downplayed in the literature (Hunley et al. 2005); a greater concern is that the frequency of use for schoolwork is jointly determined by the decisions of teachers, parents, and students, and thus might reflect time-varying unobservable characteristics of any of these actors. We make the argument below that the rise in computer access over time can be explained largely as the result of exogenous (to the individual) rapid declines in the cost of constant-quality computers.

12 All results in this paper are derived from a longitudinal sample consisting of three consecutive cohorts of public school students who progress from 5th to 8th grade in four years in North Carolina, finishing in 2002/03, 2003/04, and 2004/05. In some cases the sample is reduced because of missing data for individual students in individual years; restricting the sample to those students with no missing data across the four-year span does not materially influence the results. The sample excludes any student who exits the data before 8th grade, enters after 5th grade, or repeats a grade.

13 There also exist strong socioeconomic and racial gradients in the frequency of computer use for schoolwork, conditional on ownership. More advantaged children use their computers for schoolwork more frequently, possibly because their teachers give more computer-oriented assignments, because parents in these households are more able to instruct their children in ways of effectively using computers to complete assignments, or because the computers in more affluent households are of higher quality.

price of a constant-quality personal computer fell by more than two-thirds between April 2000 and April 2005. In our analysis below, we exploit this increase in computer ownership to identify the effect of ownership on test scores. Identification rests on the existence of idiosyncratic differences in the timing of computer purchases across families. We discuss this identifying assumption in more detail below.

2.2 Access to broadband internet service

In the absence of any direct measure of students' home use of the internet in North Carolina, we use a proxy variable based on biannual reports compiled by the Federal Communication Commission. These reports provide information on the number of firms with at least one broadband internet subscriber, by ZIP code. When the number of firms is more than zero but less than four, the actual number is redacted from the FCC report. In effect, then, we have information on whether a ZIP code had no service in a given year, between one and three service providers in a given year, or the actual number of providers if at least four. The FCC data do not reveal the number of actual subscribers per ZIP code; this information is available only for larger geographic areas.

As Table 1 illustrates, the time period covered by our study, 2000 to 2005, was a period of rapid expansion in household subscriptions to high speed internet service, in North Carolina and nationwide.[14] At the beginning of the time period, there were a grand total of 58,000

14 It is important to note that the period between 2000 and 2005 was not a period of rapid expansion in the number of *schools* with broadband internet access. Nationally, the period of rapid expansion in school access to broadband internet was between 1996, when only 14% of all instructional rooms had internet access and three-quarters of public schools with internet access utilized dial-up technology, and 2000, when 80% of public schools – and 77% of all classrooms – had high-speed internet access (Wells, Lewis, and Greene, 2006). This period coincides with the implementation of the Federal E-Rate program, which offered Federal subsidies for technology infrastructure in public schools (Goolsbee and Guryan 2006). Few public schools obtain internet

households and small business with broadband subscriptions.[15] By the end of the time period, 1.1 million households, or one in every three, were broadband subscribers.[16]

The rollout of broadband access was uneven across local areas. The two dominant modes of high-speed internet delivery are via phone lines (DSL) and coaxial cable; these portals are in turn controlled by local monopolies which have chosen to begin offering these services at different times. Moreover, availability of DSL internet service via phone line is also limited by the length of wire connecting a household to a "hub," usually located at a telephone company central office or switching station, introducing further localized variation in availability.[17]

Table 2 shows the impact across North Carolina ZIP codes of these variations in the timing of service introduction. Among the state's 738 ZIP code areas, 192, or just more than a quarter, had no broadband internet service providers (ISPs) in December of 1999. The majority of ZIP codes had at least one provider, but fewer than four. Only 33 ZIP codes had four or more ISPs at the end of 1999.

Over time, ZIP codes steadily transition to higher levels of service. The number without high-speed internet service declined, falling from 192 in 1999 to 66 two years later, then to 7 by December 2004. By the end of 2004, 62% of North Carolina ZIP codes were served by at least four broadband ISPs. These providers typically included the local cable company, the local phone company, and two or more other service providers, using either local phone lines or satellite delivery.

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access through the "facilities-based" internet service providers (primarily phone and cable companies) canvassed to produce the FCC reports.

15 At the beginning of the time period, FCC data do not distinguish between household and small business subscribers. Later data suggest that roughly one-third of these subscribers are small businesses.

16 Pegging the initial number of households with broadband subscriptions at 40,000 (two-thirds of 58,000), this works out to an annual growth rate of 67%.

17 DSL service is typically restricted to addresses within 3 wire-miles of a central telephone office. The bandwidth of DSL service declines with distance from the hub.

3. How home computer technology might influence academic achievement

Most previous studies of how student access to home computers affects achievement have started with the presumption that the relationship could be either positive or negative. On the one hand, computer technology can be used to complete schoolwork more efficiently and effectively, either through the use of dedicated educational software or by simplifying basic tasks such as editing written assignments, checking arithmetic, and so forth. On the other hand, computers can also be used for a host of non-productive activities. The 2003 computer use supplement to the CPS found that the most commonly reported computer activity among school-aged children was playing games, with work on school assignments a close second and browsing the internet (for a combination of schoolwork and other uses) third (DeBell and Chapman 2006). The use of computers for activities other than schoolwork could have detrimental impacts through a number of channels – by directly reducing the amount of time spent studying, by displacing social activities, or by introducing a number of health-related problems ranging from obesity to repetitive stress injuries. These mechanisms draw upon the insight of multiple disciplines across the social sciences. In the following section, we present basic theoretical arguments to put these insights in an economic perspective.

3.1 An adolescent's time allocation problem

A young adolescent's maximization problem is one of allocating time and money across competing uses. Suppose there exists a set of potential activities *P*. To engage in one units' worth of activity *i* within the set, adolescents must devote time $t_i>0$ and pay a monetary cost $p_i \geq 0$. Each activity contributes directly to the adolescent's utility. At least some activities also contribute indirectly to utility by contributing to human capital, which improves living standards later in life. Adolescents place at least some weight on future living standards in their computation of utility. Denoting the vector of activity consumption choices as *A* and the future living standard as *S*(*A*), utility can be written as:

(1) $U = U(A, S(A))$

We make the standard assumption that utility is increasing and concave in its arguments. It is not necessary to assume that all activities contribute positively to future living standards. The returns to future living standards may be increasing rather than diminishing for certain types of activity for certain individuals, but we do not focus on these cases.[18]

Adolescents maximize utility subject to both a time and budget constraint. Denoting the vector of time costs *T*, the vector of monetary costs *P*, available income *Y* and available time $\overline{T}$, these constraints can be written

(2) $PA \leq Y$

(3) $TA \leq \overline{T}$.

Solving this problem yields relatively straightforward first-order conditions equating the ratio of prices of any two activities *i* and *j* to the ratio of marginal utilities:

(4), $$\frac{p_i}{p_i} + \omega \frac{t_i}{t_j} - \frac{\frac{\partial U}{\partial A_i} + \frac{\partial U}{\partial S}\frac{\partial S}{\partial A_i}}{\frac{\partial U}{\partial A_j} + \frac{\partial U}{\partial S}\frac{\partial S}{\partial A_j}},$$

where ω, the ratio of shadow prices of time to income, determines the relative weight placed on time costs relative to monetary costs, and marginal utility incorporates both the instantaneous

18 The argument for increasing returns is basically a "superstars" argument: the return to being the best tennis player or violinist in the world may be orders of magnitude higher than being the 100th best (Rosen, 1981). Individuals with an intrinsic aptitude for an activity may therefore gravitate to a corner solution where all their time is allocated to a specific activity. For individuals at this type of corner solution, a shock to the relative prices of activities introduced by computer or broadband access will likely induce no change in behavior.

enjoyment associated with an activity and the impact of that activity on future living standards.

In this framework, the introduction of home computers or broadband internet can be conceptualized as a shock to the prices and time costs associated with various activities. In general, technology reduces these prices and costs, implying an increase in the adolescent's utility. The impact on future living standards, however, is unclear.

Ignoring the exceptional case where the introduction of technology reduces all prices and time costs proportionately, the standard assumption about diminishing marginal utility predicts that adolescents will substitute into activities for which home computer or broadband access occasions the greatest relative decline in the weighted sum of prices and time costs, and away from other activities. The introduction of technology will thus lead to an improvement in future living standards if it primarily lowers the cost of activities with strong future returns.

Access to computer technology reduces the prices and time costs of a wide variety of activities. The cost of revising a term paper declines with access to word processing software; the cost of accessing articles or encyclopedia entries for the purpose of research declines with broadband access. Both of these activities presumably have a positive impact on expected future living standards. In addition, computer access also reduces the marginal cost of playing arcade-style games, and of engaging in multiparty conversations with friends. These activities could conceivably lead to either an increase or decrease in future living standards, but the case for a positive impact is more tenuous.[19] In any event, these activities may yield smaller returns to future living standards than the activities that they displace.

As a final note, we have treated the introduction of computer technology or broadband

19 For example, there may be professional competitions providing rewards to highly skilled game players; the honing of hand-eye coordination may also be beneficial in certain occupations. And in certain occupations, such as air traffic control, the ability to carry on simultaneous conversations may be valuable.

access as costless from the adolescent's perspective. While the individuals under empirical study here are not labor market participants, and hence unlikely to purchase computers with their own earnings, their family's purchase could reduce financial resources available for their own consumption, or could alter the set of other resources (e.g., books, tutoring services) governing their choices. This introduces yet more uncertainty into the predicted impact of home computer technology on future living standards.

3.2 Adapting the rational model to ten-year-olds

The maximization problem outlined above requires adolescents to make a decision with long-run consequences. Neurologically, these types of "executive" decisions are the realm of the prefrontal cortex, a portion of the brain that is not fully developed in adolescence (Sowell et al. 1999). An easy method of incorporating this concern into the model would be to endow adolescents with very weak preferences over future living standards. This implies that the impact of home computer technology on adolescents may differ greatly from the impact on adults.[20]

In many cases, adolescents' observed time allocation choices will be driven less by their own preferences and more by constraints imposed upon them by parents, teachers or other authority figures. Such constraints could easily be incorporated into the model alongside the more typical budget constraints; they imply that the impact of computer technology may differ for students operating under different parenting or instructional regimes.[21]

20 This prediction could explain the contrast between our results below and Fairlie and London (2009), who find positive (though generally not significant) estimates in their study of community college students, whose average age is 25.

21 They also imply that across-student variation in time use decisions may reflect differences in regulatory regimes.

3.3 Estimation Strategy

The basic empirical exercise in this paper is to analyze the impact of home computer access and home broadband internet availability on standardized test scores in math and reading. These short-term measures serve as indicators of likely future living standards.[22] Our longitudinal sample consists of students enrolled in grades 5 through 8 in public schools in North Carolina between the years 2000 and 2005. We include only those cohorts who both begin 5th grade no earlier than 2000 and complete 8th grade no later than 2005.[23]

When analyzing the impact of access to home computers, we address concerns of non-random selection by employing a within-student estimator. The assumption underlying the analysis is that the main confounding factors, unobserved resources and constraints on behavior, do not vary much from year to year, while home computer access can. To assess the importance of these confounding factors, we also report the results of simpler repeat-cross-section models identified primarily by across-student variation.

Several threats challenge the validity of our within-student strategy. Computer purchases may correlate with broader changes in family circumstances, or may be directly responsive to revealed information about student performance. If families tend to buy computers following positive shocks to income, we run the risk of overstating any benefit (or understating any cost)

Efforts to use cross-sectional variation in behaviors to infer the impact of time use patterns on indicators of future living standards may confound uncontrolled or unobserved consequences of these differences in external regulation. Even longitudinal variation may be subject to this concern, as adolescents may switch regulatory regimes as they progress through school, or because of various alterations to their home life. For these reasons, our empirical analysis below focuses exclusively on indicators of access to technology, rather than use patterns.

[22] These are clearly imperfect indicators of future living standards; we discuss the possibility of home computer access contributing to future living standards through other mechanisms below.

[23] We begin the sample in 2000 because the FCC broadband access data begin in December 1999. We end the sample in 2005 because the aggregate computer ownership rate reaches a plateau, visible in Figure 2, implying that there are few non-ownership to ownership transitions in later years.

associated with computer access. Families might also use a computer purchase as an incentive for strong performance. If families evaluate performance on the basis of test scores, and test scores are noisy signals, then we may observe a tendency for computer purchases to be preceded by an upward spike and followed by mean reversion. Given the short duration of our panel, this will lead us to falsely attribute a negative impact to the computer purchase. Conversely, if families use computer purchases as part of a strategy to improve performance, we might expect the opposite pattern. We investigate these concerns in section 4.2 below.

The within-student estimator yields a treatment effect, under certain assumptions, that is local to the subpopulation that actually transitions between the states of having and not having computer access at home. Given that nearly 80% of students report having access to a home computer at the beginning of our sample period, this subpopulation is a relatively disadvantaged group. From a policy perspective, this group is of highest relevance for purposes of predicting the likely impact of efforts to universalize access to home computers.

In the case of broadband access, we lack direct information on home internet subscription status for each student. We instead use a more basic measure of service availability at the ZIP code-by-year level. As Table 2 noted, broadband service was introduced at different points in time across the state; students in different age cohorts are also exposed to the "treatment" of broadband access in different grades. Because our broadband access measure is not directly determined by household decision, we have less reason to expect significant bias in models identified with across-student data.[24] Nevertheless, our preferred regression models below will

24 To make this case, one would have to argue that broadband availability is uncorrelated with other determinants of student performance. The first argument in favor of this exclusion restriction is that the introduction of broadband access affects children born in different years at different ages. This argument is vulnerable, however, to concerns regarding other cohort-specific shocks. The second argument, related to the information

continue to incorporate student fixed-effects which constrain identification to within-student variation.

Equation 5 represents the basic econometric model to be estimated:

(5) $A_{ijzt} = a_{ij} + X_{it} + C_{it} + H_{zt} + e_{ijzt}$

where A_{ijzt} is the achievement of student *i* in subject *j* (math or reading) in a school in ZIP code *z* at time *t*. In practice, our models are estimated separately by subject. The a_{ij} term is a student-level fixed effect; X_{it} is a set of time-varying student characteristics, including time use variables and free or reduced price lunch participation; C_{it} is a binary variable measuring access to a home computer; H_{zt} is a set of variables indicating the availability of high speed internet in ZIP code *z* at time *t*, and e_{ijzt} is an idiosyncratic error term.[25] To verify the nature of selection bias, we also estimate versions of equation (3) that omit student fixed effects, adding a set of time-invariant student characteristics, including race, gender, parental education, as well as a lagged value of the dependent variable.[26]

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revealed in Table 2 above, is that the timing of broadband introduction varied across local areas. Variation in the introduction of service appears surprisingly idiosyncratic; ZIP codes receiving initial service in 2000 had an average median household income of $45,924, versus $44,200 for ZIP codes receiving initial service in 2004. Percent white in these two sets of ZIP codes were 75.5% and 74.5%, respectively.

25 To estimate the impact of internet access on academic outcomes, we match students to ZIP codes based on the address of the school they attend in a given year. Although student-level address data exists for many districts in many years, the gaps in address availability are pervasive enough to render address-level matching infeasible in the longitudinal data. In particular, the state's four largest school districts have no student address data in the statewide database in the years analyzed here. The typical ZIP code has a population of slightly more than 10,000, with larger population sizes in urban areas. Hence it is reasonable to think that most students attend schools in their ZIP code of residence. There is also a relatively high degree of spatial autocorrelation in the ZIP code ISP data.

26 We do not include lagged test scores as a predictor in within-student models, even though they are time varying. The typical rationale for incorporating lagged dependent variables is that they represent the quality of education inputs received at earlier points in a student career. This addresses concerns that serial correlation in the quality of inputs would lead to omitted variable bias when estimating the relationship between current inputs and educational outcomes. The presence of a lagged dependent variable, however, introduces econometric problems when the idiosyncratic component of the outcome (e.g., measurement error) is serially correlated. In a fixed-effect model, any time-invariant effects of educational inputs applied prior to the point of initial observation are subsumed into the fixed-effect itself. Thus it is harder to make the case that the introduction of a lagged dependent variable adds value sufficient to outweigh the potential econometric costs.

4. The impact of home computer technology on test scores

4.1 Comparing across- and within-student estimates

Table 3 presents estimates of the relationship between home computer ownership, high-speed internet availability, other student characteristics, and standardized test scores, in two sets of models. The first permits across-student variation to identify the relationship of interest. These models are problematic to the extent that student-level unobserved variables correlate with both computer access and test scores. The second set uses student fixed-effects to purge the estimates of any bias associated with time-invariant unobservables. The dependent variable in each specification has been normalized to have mean zero and standard deviation one, using the entire population of students for whom we have test scores in a given grade, year, and subject. The across-student specifications also include a control for a prior year's test score, as is common in "value-added" models of educational production.[27]

The across-student models show that students with access to home computers tend to score about 2% of a standard deviation higher on both reading and math test scores, conditional on a range of covariates.[28] This effect is about one-fifth the magnitude of the test score differential between students with high-school versus college-educated parents. The estimated coefficients on high-speed internet availability are generally small and in most cases statistically

27 Value-added specifications presume that learning is cumulative, but that the stock of knowledge depreciates at a constant rate. Coefficients on the lagged test score will be biased to the extent that test scores measure an underlying construct with classical measurement error. Instrumental variable methods, using the twice-lagged test score as an instrument for the once-lagged test score, produce results comparable to the ones reported here. For more complete discussions of the modeling assumptions associated with the education production process, see Boardman and Murnane (1979).

28 In additional specifications examining variation in frequency of computer use for schoolwork, students who report using their computer at a moderate frequency score significantly better than those who do not own a computer, own one but never use it for schoolwork, or own a computer and use it for schoolwork almost daily. This coincides with earlier estimates in the literature (e.g., Attewell and Battle, 1999), but it is not clear whether this reflects a causal mechanism or pure selection.

insignificant. The largest point estimate suggests that reading test scores are just under 2% of a standard deviation worse in ZIP codes with 4 or more ISPs, relative to ZIP codes without broadband access. These models include ZIP code fixed effects, implying that the broadband effects are identified through longitudinal comparisons of ZIP codes that transition from one category to another.

Within-student estimates present a direct contrast to the across-student results in Table 4.[29] Here, there is no evidence that home computer access improves test scores. Students who obtain access to a home computer sometime between 5th and 8th grade tend to score between 1% and 1.3% of a standard deviation lower on their subsequent math and reading tests.[30] The positive cross-sectional association between home computer ownership and test scores thus reflects the digital divide: those who own computers are in general a positively selected group. Some degree of selection bias may persist in the within-student specification, to the extent that families purchase computers in years with positive income shocks or other beneficial developments. If that selection mechanism operates in a manner similar to the one influencing our cross-sectional estimates, the estimated negative effects are understated.[31]

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29 The increase in sample size in Table 4 relative to Table 3 can be attributed to the inclusion of students with missing data for one or more time-varying characteristics. Results are not materially affected if the sample is restricted to those students with no missing data over the four-year span from 5th grade to 8th grade.

30 In theory, students who lose access to a home computer also contribute to the identification of this effect. Below we show that within this group, the loss of a home computer is associated with significant declines in math scores. Home computer loss may be associated with marital breakup, negative income shocks, or other stressful events that exert an independent effect on test scores.

31 In additional specifications that examine variation in reported home computer use for schoolwork, computer-owning students tend to post the best test scores in years when they indicate using their computers for schoolwork at a moderate frequency. Even moderate use, however, puts students at a significant disadvantage relative to years when they report having no computer at home. Once again, the mechanism underlying this pattern is unclear. One possible explanation for the non-monotonic relationship between self-reported computer use and test scores is the reverse-coded nature of the question. In this survey item, the most frequent use category was the first response alternative, the opposite of other time use questions on the survey. The most frequent use category, which is relatively uncommon, may consist of a disproportionate number of students who failed to follow directions, or were confused by the question. This underlying state of confusion, or inattention

Students in ZIP codes that transition from no broadband service to limited service from three or fewer providers post a statistically significant decline in math test scores. The estimated decline is a relatively strong 2.6% of a standard deviation. The impact on reading test scores is more modest and statistically insignificant. Students in ZIP codes that move beyond the four ISP threshold also exhibit modest declines in test scores. The effects are statistically significant, equivalent to 1.4% of a standard deviation in math and 1.6% of a standard deviation in reading.

Other time-varying student characteristics, included in Table 3, as well as time-invariant characteristics listed in Appendix Table 1, show associations in line with existing literature. Coefficients on lagged test scores, when included, are in the usual 0.7 to 0.8 range. Indicators of student disadvantage, including free/reduced lunch participation and parent education are sizable and significant in across-student models. Within-student variation in subsidized lunch receipt correlates much more weakly with test scores. Relative to non-Hispanic whites, black and Native American students perform worse on standardized tests. Hispanic and Asian students perform better, conditional on observables, a finding consistent with Clotfelter, Ladd and Vigdor (2009).

Coefficients on time use variables show both signs of self-selection as well as some robustness to the inclusion of student fixed effects. In three of four specifications, students who read between one and two hours for pleasure each day post the highest test scores. Students who report spending more time on homework each week attain higher test scores. Modest amounts of television viewing are associated with higher test scores, while students who report watching more than six hours per day score consistently below those who watch none. Each of these

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to (or perhaps even willful disregard of) instructions may also have caused students to perform poorly on the standardized test.

associations becomes smaller in magnitude when student fixed-effects are incorporated in the specification. Students unobservably predisposed to higher test scores tend to read for pleasure, spend more time on homework, and watch modest amounts of television. Consistent with existing evidence, students predisposed to poor test scores are more likely to spend at least six hours per day watching television (Gentzkow and Shapiro, 2008). Even restricting identification to within-student variation, however, there appear to be important differences in test score performance associated with year-to-year variation in student time use. Students who switch from no leisure reading to a small amount each day post gains of 5% of a standard deviation in reading and 3.3% of a standard deviation in math. Students who switch from spending no time on homework to a small amount show improvements of 6% of a standard deviation in reading and 8% in math. Students who cut their television watching down from six hours to four hours each day improve by 3% of a standard deviation in each subject.

These time use results are important because alterations in time allocation are the principal hypothesized mechanism for the relationship between home computer or internet access and test scores. It should be noted, however, that causal attribution is not necessarily warranted even in the within-student specifications. It could be that student time allocation decisions are driven by parent or teacher actions, and these actions also drive changes in unobserved determinants of performance. The main results of interest are unchanged if we omit time use variables from the model.

4.2 Extensions and robustness checks

Families' computer purchase decisions may respond directly or indirectly to student performance. Whereas a simple correlation with positive income shocks would impart a positive bias on our estimates, the potential bias associated with this type of endogenous response is uncertain. Figure 3 presents summary statistics that assess whether families tend to purchase computers following a transitory shock to achievement. The panels divide students into four categories: those who obtain a home computer between 6th and 7th grade, between 7th and 8th grade, prior to 5th grade, or never. The question to be addressed here is whether the computer purchase appears to coincide with a substantial positive or negative mean-reverting shock to student performance.[32]

The panels in Figure 3 reveal several important patterns. The most obvious pattern is a stark, monotonic relationship between initial performance in 5th grade and the timing of computer acquisition. Students who already have computers at home as of 5th grade score significantly above the statewide mean; those who acquire a computer after 6th grade, 7th grade, or never have 5th grade scores 0.375, 0.45, and 0.475 standard deviations below the mean, respectively. This underscores the nature of the digital divide and the selected sample of late adopters to which our estimated effects apply.

For students who always own a computer, or never own a computer, test score performance (normalized at the grade-by-year level) tends to improve slightly over time. The net improvement is modest for both groups, on the order of two percent of a standard deviation. The improvement appears monotonic for always-owners, though a bit noisier for never-owners.

By contrast, the test scores of students who acquire computers at intermediate points show declines in their standardized test scores up to the point of acquisition. These declines are

32 We need more than one year of prior performance to make this inference, which is why students who obtained computers in 6th grade are omitted from this analysis.

moderated or reversed in the years after purchase. This pattern suggests that some parents invest in a computer in response to poor performance signals from their children. The apparent reversal of fortune after the computer purchase could be a sign of a positive treatment effect, or of mean reversion following a negative shock.

The clear differences in starting points, and possibility of endogenous computer purchases in the wake of mean-reverting shocks, raise the concern that any differential patterns in test score performance among students at varying points in the initial test score distribution threatens to confound our estimates of the impact of computer acquisition. To the extent that these differential trends cause a general compression or expansion in the test score distribution, our grade-by-year normalization eliminates them as a source of concern. More complex transformations of the distribution, however, could lead us to spuriously attribute effects to computer ownership.

As a check for this possibility, Table 4 reports the results of additional estimates that interact a measure of ability – a student's 5th grade test score – with indicator variables for grade level. The results indicate that the dominant trend is mean reversion: students whose 5th grade math score is one standard deviation below the mean, for example, improve to 0.8 standard deviations below the mean, on average, by the time they are in 8th grade. Correcting for this mean reversion actually increases the magnitude of the computer ownership effect in both the reading and math specifications, relative to the equivalent specifications in Table 3. The negative effect of computer ownership on outcomes is partly obscured, then, because those who acquire them later than their 5th grade year tend to have low initial scores, and students with low initial scores tend to mean-revert.

4.3 Testing for effect heterogeneity

For many reasons, the effect of home computer access may not be equal for all students at all points in time. One readily testable form of effect heterogeneity involves the duration of access. Home computer use may become more beneficial over time, if for example non-productive computer uses such as gaming can be enjoyed instantaneously but productivity-enhancing uses must be learned over time. Alternatively, if non-productive computer uses have an addictive quality, implying that users habituate and require increasing doses to maintain utility, the effects could also become more negative over time.

Table 5 reports the results of specifications that control for duration of computer ownership, to test these competing hypotheses. We observe duration of ownership for those students who report having no computer at home in 5th grade. In our panel we can thus definitively identify some students in their first, second, and third years of an ownership spell. We do not observe duration for students who had an ownership spell underway in 5th grade. There is some within-student variation in ownership for this group, however, generated by the loss of access to a home computer. We can thus estimate the impact of losing home computer access with this group. The effect of losing access need not be the opposite of the effect of gaining access for two basic reasons. First, the effect of gaining access is estimated using a sample of late-adopters, for whom the effect of computer access may be quite different relative to early adopters. Second, the effect of losing access may be confounded with other negative family shocks that occur simultaneously – such as a downturn in financial circumstances or divorce.

Results for both reading and math indicate that the negative effect of computer ownership on both math and reading holds fairly steady over the first three years. There is slight evidence of moderating effects on reading test scores over time, but no trend in the negative impact on math scores. Any positive effects of learning to use a computer productively over time appear to be offset by negative effects, such as those associated with learning to use a computer for recreational purposes.

The loss of a home computer among students who had one in 5th grade is associated with a slight decrease in math test scores and a slight increase in reading test scores. Both changes are statistically significant, and may reflect either of the mechanisms described above.

In section 3.2 above, we suggest that the effect of home computer access may vary according to the constraints placed on adolescent behavior by parents or other adults. Students operating in a regime with few parental constraints may use computers for recreation more frequently. Parental constraints, in turn, may be less stringent in single parent households, or households where both parents work outside the home. This introduces the possibility that home computer technology exacerbates achievement gaps. While we have no direct measure of parent monitoring in the dataset, we have multiple indicators of student disadvantage. Table 6 presents the results of student fixed-effect specifications that interact the broadband internet availability variables with three student-level factors: race, gender, and subsidized lunch participation.[33]

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33 Note that race and gender are time invariant student characteristics subsumed by the student fixed effects.
At first glance, one might suspect that an interaction between internet availability and computer ownership would yield clearly differentiated effects, as there are few reasons to think that the availability of home internet would matter for those without computers at home. In fact, such an interaction does not produce this pattern. Rather, the estimated effect of internet access is more negative for those without computers at home. This seemingly anomalous result can be explained by internet-induced selection into computer ownership. In unreported specifications, we find that the introduction of ISP service increases the probability of computer ownership significantly in a ZIP code, implying that the set of non-computer owning households in ZIP codes with internet service are a more negatively selected group. The interactions reported here involve predetermined

In specifications with race interactions, three of four interaction terms indicate that the impact of increased broadband access is significantly more negative for black students than for others. The negative effect of initial high-speed service on math test scores appears to be independent of race; however initial introduction has a concentrated negative impact on black students' reading scores while having no significant impact on others. Expansion of service to four or more providers is associated with a much stronger test score reduction for black students, between 3 and 4 percent of a standard deviation in both reading and math. There is no significant impact of this wider access measure on math scores of non-black students, and the impact on non-black students' reading scores is less than one-third the estimated magnitude of the effect on blacks.

The sole significant interaction between gender and ISP access indicates that widespread adoption of high-speed internet is associated with a reduction in male reading test scores of 3% of a standard deviation, while female reading test scores are not significantly affected. This pattern is consistent with October 2003 CPS evidence indicating that girls are more likely to use the internet for completing school assignments and less likely to use it for playing games, to check up on news, weather or sports, or to find information on products relative to boys (DeBell and Chapman, 2006, Table 8A).

Further evidence of heterogeneity in the effect of internet availability appears when students are stratified by participation in the free or reduced price lunch program. In the math specification, initial introduction is associated with a negative but insignificant main effect and

student characteristics and not potentially endogenous factors.

The impact of ISP service introduction on computer ownership, coupled with the idiosyncratic nature of the timing of ISP service, could inspire one to consider ISP service as an instrument for ownership. This is unadvisable, however, because the exclusion restriction – that ISP service have no impact on student achievement except through the propensity to own a computer – is almost certainly violated, as ISP service could also have impacts on inframarginal computer owners.

interaction term. Broader expansion of high-speed internet service has no association with test scores among students not participating in the subsidized lunch program, but the interaction term shows a reduction of nearly 3% of a standard deviation in the scores of program participants. In specifications examining reading test scores, coefficients indicate that the impact of initial introduction and broader expansion of high-speed internet is more negative among free and reduced lunch participants, though the interaction on initial introduction is significant at only the 10% level. Initial introduction is estimated to have no impact on non-participants, while broader expansion is associated with a reading test score reduction of 1.2% of a standard deviation among non-participants and 2.5% of a standard deviation among participants.

This quasi-experimental evidence is consistent with evidence uncovered in the sole existing randomized study of home computer access by secondary school students. A recent evaluation of the Texas Technology Immersion Project shows that the treatment effect of being assigned a personal laptop computer is significantly greater for students with high initial test scores, although the mean impact is not distinguishable from zero (Shapley et al., 2007). Thus, reliable evidence points to the conclusion that broadening student access to home computers or home internet service would widen, not narrow, achievement gaps. As discussed in section 3 above, this may occur because student computer use is more effectively monitored and channeled toward productive ends in more affluent homes.

4.4 Examining the mechanism: broadband access and homework effort

The results presented to this point indicate that student performance on tests of fundamental skills declines when computers are introduced into the household. The presumed mechanism for this negative effect is that home computers and broadband crowd out productive study activity. Since we have self-reported measures of time spent studying, in principle one could check to see whether the data are consistent with the operation of this mechanism.

One complication with this strategy, however, is that a negative relationship between computer or internet access and homework time could reflect a beneficial mechanism, as both technologies could potentially permit students to work more efficiently at home. Homework time could decline, for example, because students can look up sources for reports online instead of in books, or because they can revise compositions using word processing software.

An alternative way to test the mechanism is to examine the impact of broadband internet activity on the frequency, rather than duration, of computer use for schoolwork. Broadband access might reduce total homework time, but should presumably offer students more opportunities to use home computers for schoolwork. Only if access to the internet severely crowds out productive study efforts should we expect a negative effect.

Table 8 presents results of models estimating the impact broadband internet access on students' self-reports of the frequency of home computer use for schoolwork. The first reported specification is an ordered probit model, where the dependent variable is the categorical response to the computer use question, with more intense use levels coded as greater. Coefficients indicate that computer use for schoolwork is significantly lower in ZIP codes with one to three broadband ISPs, and significantly greater in ZIP codes with four or more broadband ISPs, compared to ZIP codes with no ISPs. At face value, this is a confusing pattern, perhaps reflecting a tendency for early adopters of broadband internet to use it for nonproductive purposes, while later adopters use the internet more frequently for schoolwork. Extensive analysis of this pattern is not worthwhile, however, as it turns out not to be robust to the introduction of student fixed effects.

Focusing for a moment on the student-level correlates of home computer use for schoolwork, disadvantaged students identified either by participation in the free and reduced price lunch program or by low parental education use computers less frequently. Interestingly, black students use computers for homework more frequently than whites after conditioning on these other variables. Asian students also use computers more frequently than whites, Hispanic and Native American students less frequently. Computer use increases monotonically as students progress from grade 5 to grade 8; there is also evidence that younger cohorts are using home computers for schoolwork slightly less than their predecessors did – possibly because unproductive computer use is crowding out schoolwork of all kinds. Finally, note that reported home computer use is greater among students who report reading for pleasure each day, among those who report spending more time on homework, and among those who watch modest amounts of television.

The second specification is a simpler logit model predicting whether students report using their home computers for schoolwork at least once per week. It serves as a bridge between the ordered probit specification and the fixed-effects logit model in the third column. While results of the logit are not directly comparable to the ordered probit, the patterns are virtually identical. In particular, students in ZIP codes with one to three ISPs report significantly less home computer use for schoolwork than those in ZIP codes with no ISPs, while students in ZIP codes with four or more ISPs report significantly more.

The third column reports the results of fixed-effect logit models, which identify the impact of covariates from within-student variation. We note that a significant proportion of students – roughly half – are dropped from the sample here because they either always report computer use at the weekly level or higher, or never report computer use at that level. We also note that it is impossible to estimate the impact of time-invariant student characteristics in this model. Among those whose computer use crossed the weekly threshold in either direction (or both), changes in broadband internet service are *negatively* associated with computer use for schoolwork. Thus although the use of computers for school work tends to be highest in areas with the most ISPs, increases in broadband service over time lead students to use computers for school work less frequently, not more frequently. This pattern supports the hypothesis that broadband access crowds out homework effort.

5. Conclusions

Previous studies of home computer use among young adolescents have documented significant disparities in access and use, and have frequently ascribed clear educational benefits to home computer use. Together, these patterns suggest that a policy of broadening home computer access through programs of subsidy or direct provision would narrow achievement gaps. This paper corroborates the existence of sizable socioeconomic gaps in home computer access and use conditional on access, but comes to the opposite conclusion regarding the potential impact of broader access on achievement gaps. The very existence of a “digital divide” implies that simple attempts to infer the impact of home computer use on achievement in nonexperimental settings are threatened by omitted variable bias. Our paper replicates some existing results in documenting a positive association between home computer access and achievement in across-student comparisons, but shows that these results do not hold for within-student comparisons. Students who gain access to a home computer between 5th and 8th grade tend to witness a persistent decline in reading and math test scores.

Using local variation in the timing of introduction of broadband internet service, as well as the within-student analysis employed in the case of computer ownership, we find support for the hypothesis that access is in practice more detrimental for some students than others. The evidence is consistent with the view that internet service, and technology more broadly, is put to more productive use in households with more effective parental monitoring of child behavior.

For school administrators interested in maximizing achievement test scores, or reducing racial and socioeconomic disparities in test scores, all evidence suggests that a program of broadening home computer access would be counterproductive. Of course, administrators may have other goals aside from improving math and reading test scores. Computer literate students may enjoy improved job opportunities later in life, or may be poised to take better advantage of online resources once their internal mechanisms for behavioral regulation have fully developed. Evaluations of the Texas Technology Immersion Project have shown some positive impacts on student behavior and on measures of student proficiency with computers (Shapley et al., 2007).[34] It is not clear, however, whether computer literacy actually leads to better employment outcomes (Krueger, 1993; DiNardo and Pischke 1997), and also not clear whether access to home computers in the early secondary school years is critical to later computer literacy. Further research may be very valuable in addressing these concerns.

34 It is unclear whether these improvements should be attributed to student laptops, or the other components of the TIP program.

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Table 1: Total residential high speed internet subscribers by June 30 each year

Year	USA (millions)	North Carolina (thousands)
2000	3.1*	58**
2001	7.8*	164*
2002	14.0*	406*
2003	20.7*	596*
2004	30.1*	870*
2005	38.6	1,124

* Includes both residential and small business subscribers.
**Includes all subscribers. Nationwide, about two-thirds of all subscribers were residential or small business in 2000.
Source: FCC reports, available online at http://www.fcc.gov/wcb/iatd/comp.html

Table 2: The introduction of Broadband Internet in North Carolina

Year	Number of ZIP Codes			
	No ISPs	1-3 ISPs	4 or more ISPs	Total
1999	192	513	33	738
2000	135	485	118	738
2001	66	420	252	738
2002	31	326	381	738
2003	21	314	403	738
2004	7	274	457	738

Note: Number of ISPs is enumerated in December of each calendar year. Source: FCC reports, available online at http://www.fcc.gov/wcb/iatd/comp.html

Table 3: Estimates of the impact of home computer ownership and internet availability

Independent Variables	Across-student estimators		Within-student estimators	
	Reading	Math	Reading	Math
Own a computer at home	0.0187**	0.0185**	-0.0105**	-0.0132**
	(0.0025)	(0.0018)	(0.0020)	(0.0018)
No. of ISPs in ZIP code (0 omitted):				
4+	-0.0172**	-0.0089	-0.0163**	-0.0135**
	(0.0038)	(0.0059)	(0.0030)	(0.0049)
1-3	-0.0100	0.0213	-0.0083	-0.0256**
	(0.0143)	(0.0179)	(0.0097)	(0.0130)
Lagged Test Score	0.7365**	0.7928**	---	---
	(0.0013)	(0.0014)		
Free/Reduced Lunch	-0.0662**	-0.0501**	-0.0037*	0.0042**
	(0.0018)	(0.0018)	(0.0021)	(0.0021)
Grade (8 omitted):				
Grade 5	0.0040	0.0148**	0.0242**	0.0462**
	(0.0040)	(0.0062)	(0.0030)	(0.0051)
Grade 6	0.0165**	0.0180**	0.0293**	0.0414**
	(0.0034)	(0.0055)	(0.0025)	(0.0043)
Grade 7	0.0008	-0.0033	0.0145**	0.0175**
	(0.0032)	(0.0051)	(0.0023)	(0.0037)
Free Reading time (zero omitted):				
< 30 m/day	0.0573**	0.0306**	0.0505**	0.0334**
	(0.0024)	(0.0021)	(0.0020)	(0.0020)
30 minutes - 1 hour/day	0.0981**	0.0539**	0.0654**	0.0399**
	(0.0026)	(0.0024)	(0.0023)	(0.0023)
1-2 hours/day	0.1339**	0.0745**	0.0728**	0.0438**
	(0.0030)	(0.0027)	(0.0025)	(0.0026)
More than 2 hours/day	0.1576**	0.0684**	0.0707**	0.0308**
	(0.0035)	(0.0031)	(0.0032)	(0.0030)
Homework time (zero omitted):				
<1hr/wk	0.0905**	0.0901**	0.0642**	0.0816**
	(0.0054)	(0.0051)	(0.0044)	(0.0041)
1 to 3 hours/week	0.1342**	0.1330**	0.0865**	0.1060**
	(0.0055)	(0.0050)	(0.0045)	(0.0041)
3 to 5 hours/week	0.1729**	0.1808**	0.0981**	0.1240**
	(0.0057)	(0.0052)	(0.0047)	(0.0042)
5 to 10 hours/week	0.1943**	0.2156**	0.1048**	0.1437**
	(0.0058)	(0.0054)	(0.0048)	(0.0045)

Table 3: Estimates of the impact of home computer ownership and internet availability

Independent Variables	Across-student estimators		Within-student estimators	
More than 10 hrs/week	0.1812**	0.2079**	0.1050**	0.1503**
	(0.0074)	(0.0067)	(0.0061)	(0.0057)
Television (zero omitted):				
1 hour/day	0.0188**	0.0059	0.0198**	0.0104**
	(0.0039)	(0.0037)	(0.0033)	(0.0031)
2 hours/day	0.0309**	0.0132**	0.0219**	0.0140**
	(0.0039)	(0.0038)	(0.0034)	(0.0031)
3 hours/day	0.0210**	-0.0008	0.0154**	0.0073**
	(0.0041)	(0.0039)	(0.0035)	(0.0032)
4 to 5 hours/day	0.0191**	-0.0092**	0.0100**	0.0007
	(0.0042)	(0.0040)	(0.0036)	(0.0033)
More than 6 hours/day	-0.0274**	-0.0436**	-0.0146**	-0.0202**
	(0.0046)	(0.0042)	(0.0040)	(0.0037)
Number of Observations	731,392	731,251	745,977	745,867

Note: standard errors in parentheses, corrected for clustering at the ZIP code/year level where appropriate. Dependent variables are normalized to have mean zero, standard deviation one. Across-student specifications include controls for race, parental education, cohort, gender, and ZIP code fixed effects. Coefficients for these additional variables can be found in Appendix Table A1.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 4: Allowing for differential trends by initial test score

Independent variables	Math	Reading
Own a computer at home	-0.020**	-0.017**
	(0.002)	(0.002)
Number of ISPs in ZIP code (0 omitted):		
4+	-0.042**	-0.032**
	(0.013)	(0.010)
1-3	-0.011**	-0.017**
	(0.005)	(0.003)
5^{th} grade test score*grade 6	-0.140**	-0.173**
	(0.002)	(0.002)
5^{th} grade test score*grade 7	-0.170**	-0.215**
	(0.003)	(0.002)
5^{th} grade test score*grade 8	-0.200**	-0.245**
	(0.002)	(0.002)
Number of Observations	745,867	745,977

Note: Standard errors in parentheses, corrected for clustering at the ZIP/year level. Both models include student fixed effects, as well as all additional covariates reflected in Table 3.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 5: Duration of Computer Ownership and Test Scores

Independent Variable	Math	Reading
First year of computer ownership	-0.026**	-0.015**
	(0.002)	(0.002)
Second year of computer ownership	-0.022**	-0.012**
	(0.003)	(0.003)
Third year of computer ownership	-0.026**	-0.010**
	(0.004)	(0.004)
Loss of ownership (among those who have a home computer at the beginning of the panel)	-0.010**	0.006*
	(0.003)	(0.003)
Number of Observations	745,867	745,977

Note: Standard errors in parentheses, corrected for clustering at the ZIP/year level.
Specifications include all Table 3 covariates, including student fixed effects.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 6: Heterogeneity in the impact of internet access

Independent Variables	Dependent Variable: Math			Reading		
Main effects:						
Four or more ISPs	-0.0039	-0.0123**	-0.0033	-0.0107**	-0.0284**	-0.0118**
	(0.0050)	(0.0051)	(0.0052)	(0.0030)	(0.0035)	(0.0030)
One-Three ISPs	-0.0280**	-0.0282**	-0.0192	0.0018	-0.0111	0.0030
	(0.0127)	(0.0129)	(0.0126)	(0.0076)	(0.0102)	(0.0075)
Interaction terms:						
Four or more ISPs *	-0.0380**			-0.0237**		
Black	(0.0066)	---	---	(0.0050)	---	---
One-Three ISPs * Black	0.0043			-0.0398**		
	(0.0138)	---	---	(0.0171)	---	---
Four or more ISPs *		-0.0025			0.0228**	
Female	---	(0.0026)	---	---	(0.0025)	---
One-Three ISPs * Female		0.0046			0.0049	
	---	(0.0079)	---	---	(0.0084)	---
Four or more ISPs *			-0.0281**			-0.0135**
Free/Reduced Lunch	---	---	(0.0046)	---	---	(0.0036)
One-Three ISPs *			-0.0173			-0.0287*
Free/Reduced Lunch	---	---	(0.0131)	---	---	(0.0151)
Number of Observations	766,259	766,269	766,278	766,341	766,351	766,359

Note: Standard errors in parentheses, corrected for clustering at the ZIP/year level. Specifications include all Table 3 covariates, including student fixed effects, plus a complete set of home computer use for schoolwork indicators.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 7: The impact of internet access on the frequency of home computer use for schoolwork

Independent Variables	Dependent Variable: Ordinal computer use	Computer Use at Least Weekly	
	Ordered Probit	Logit	Student Fixed Effects Logit
Number of ISPs in ZIP code (0 omitted):			
4+	0.0621**	0.0826**	-0.0273**
	(0.0090)	(0.0191)	(0.0110)
1-3	-0.0407**	-0.1488*	-0.0875**
	(0.0174)	(0.0799)	(0.0215)
Free/Reduced Lunch	-0.3349**	-0.2479**	-0.0167
	(0.0043)	(0.0086)	(0.0152)
Grade (8 omitted): Grade 5	-0.4323**	-0.5972**	-0.7936**
	(0.0092)	(0.0225)	(0.0105)
Grade 6	-0.2700**	-0.4069**	-0.5314**
	(0.0086)	(0.0212)	(0.0092)
Grade 7	-0.1240**	-0.1889**	-0.2424**
	(0.0068)	(0.0172)	(0.0085)
Free Reading time (zero omitted): < 30 m/day	0.2012**	0.3706**	0.2526**
	(0.0051)	(0.0122)	(0.0159)
30 minutes - 1 hour/day	0.3027**	0.5874**	0.3964**
	(0.0056)	(0.0131)	(0.0174)
1-2 hours/day	0.3201**	0.6239**	0.4268**
	(0.0064)	(0.0144)	(0.0193)
More than 2 hours/day	0.2852**	0.6043**	0.4948**
	(0.0078)	(0.0171)	(0.0234)
Homework time (zero omitted): <1hr/wk	0.1388**	0.0689**	0.0886**
	(0.0106)	(0.0255)	(0.0314)
1 to 3 hours/week	0.2812**	0.3255**	0.2990**
	(0.0109)	(0.0255)	(0.0313)
3 to 5 hours/week	0.3430**	0.4852**	0.4335**
	(0.0115)	(0.0268)	(0.0322)
5 to 10 hours/week	0.4054**	0.6616**	0.5746**
	(0.0126)	(0.0288)	(0.0331)
More than 10 hrs/week	0.4609**	0.8747**	0.7738**
	(0.0170)	(0.0355)	(0.0408)
Television watching (zero omitted): 1hr/day	0.0791**	0.1060**	0.0842**
	(0.0079)	(0.0169)	(0.0234)
2 hours/day	0.0649**	0.0243	0.0613**
	(0.0081)	(0.0181)	(0.0241)
3 hours/day	0.0030	-0.0985**	0.0079
	(0.0085)	(0.0191)	(0.0248)
Television (cont'd): 4 to 5 hours/day	-0.0539**	-0.1960**	-0.0537**
	(0.0089)	(0.0197)	(0.0261)

Table 7: The impact of internet access on the frequency of home computer use for schoolwork

Independent Variables	Dependent Variable:		
More than 6hrs/day	-0.0596**	-0.1199**	-0.0095
	(0.0092)	(0.0209)	(0.0285)
Race (white omitted): Asian	0.2487**	0.5105**	---
	(0.0135)	(0.0269)	
Black	0.0211**	0.2058**	---
	(0.0053)	(0.0108)	
Hispanic	-0.1697**	0.0074	---
	(0.0119)	(0.0214)	
Native American	-0.1184**	-0.0155	---
	(0.0133)	(0.0290)	
Mixed	-0.0448**	-0.0044	---
	(0.0121)	(0.0281)	
Other	0.1356	0.8581**	---
	(0.1461)	(0.2767)	
Parent Ed (postgraduate omitted): < HS	-0.7291**	-0.7766**	---
	(0.0117)	(0.0278)	
High School	-0.4627**	-0.5883**	---
	(0.0101)	(0.0253)	
Trade/Business School	-0.3167**	-0.4791**	---
	(0.0108)	(0.0276)	
Community/Technical College	-0.2994**	-0.4816**	---
or Some College, No Degree	(0.0102)	(0.0254)	
College	-0.1209**	-0.2339**	---
	(0.0078)	(0.0201)	
Cohort 1 (8th grade in 2002/03)	0.0391**	0.2263**	---
	(0.0074)	(0.0182)	
Cohort 2 (8th grade in 2003/04)	0.0154**	0.0966**	---
	(0.0056)	(0.0151)	
Male	-0.0843**	-0.1767**	---
	(0.0027)	(0.0063)	
Number of Observations	768,363	747,998	382,041

Note: Standard errors in parentheses, corrected for clustering at the ZIP code/year level where appropriate. Fixed-effects logit omits students who always or never use a home computer for schoolwork at least weekly. In the ordered probit specification, higher values of the dependent variable are associated with more frequent use.
** denotes a coefficient significant at the 5% level; * the 10% level.

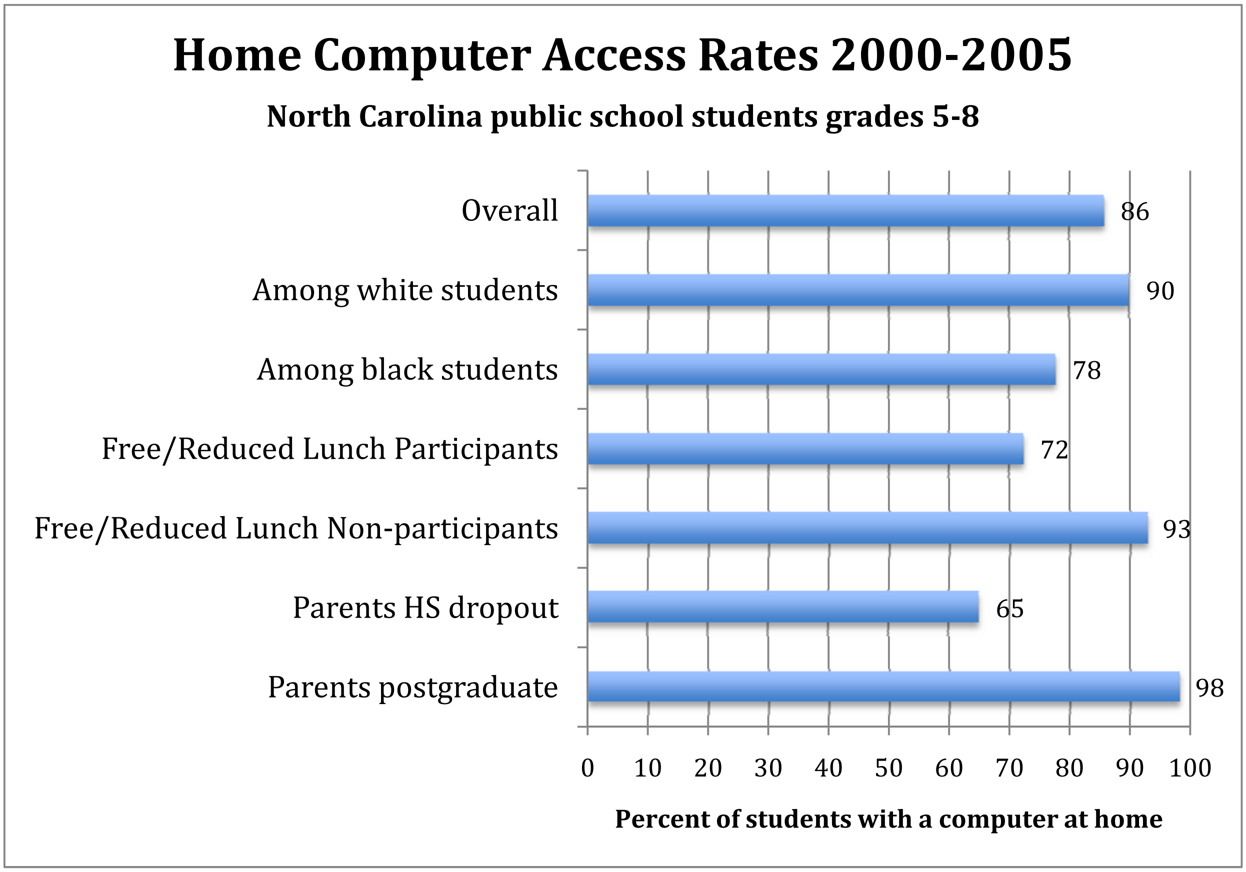
Home Computer Access Rates 2000-2005
North Carolina public school students grades 5-8
Overall
Among white students
Among black students
Free/Reduced Lunch Participants
Free/Reduced Lunch Non-participants
Parents HS dropout
Parents postgraduate
86
90
78
72
93
65
98
0
10
20
30
40
50
60
70
80
90
100
Percent of students with a computer at home

Figure 1

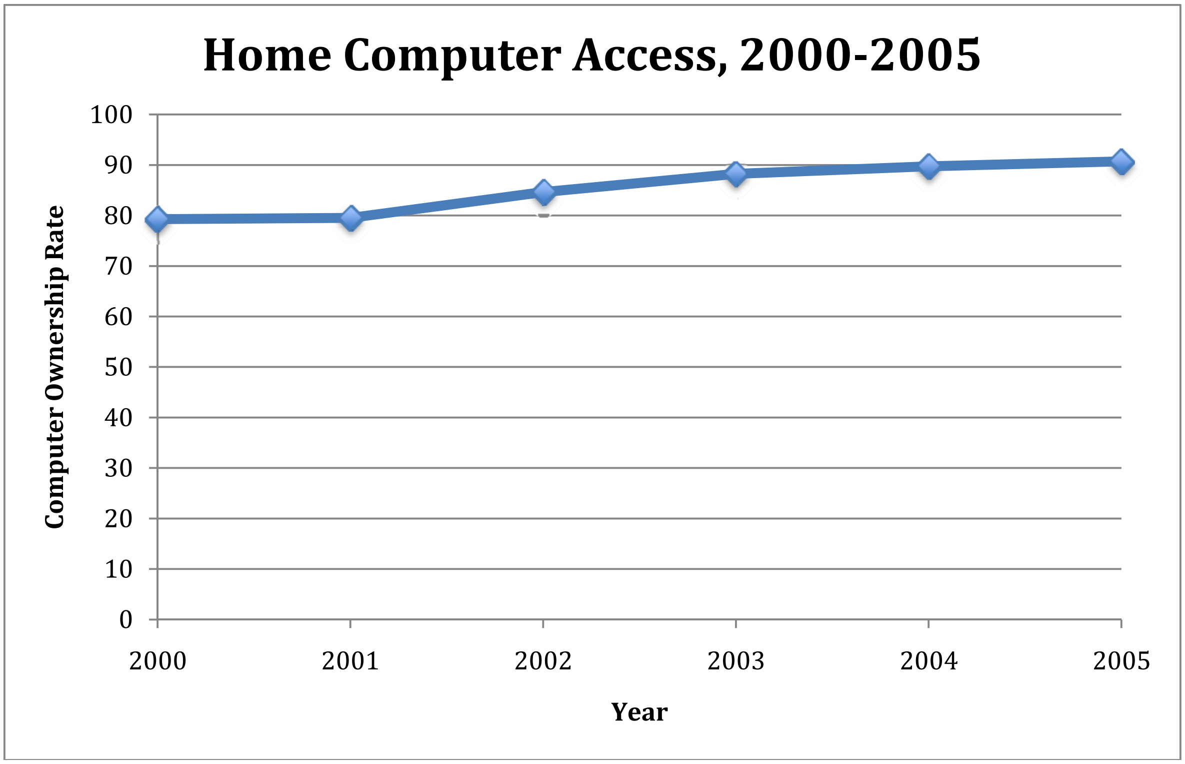
Home Computer Access, 2000-2005
Computer Ownership Rate
100
90
80
70
60
50
40
30
20
10
0
2000
2001
2002
2003
2004
2005
Year

Figure 2

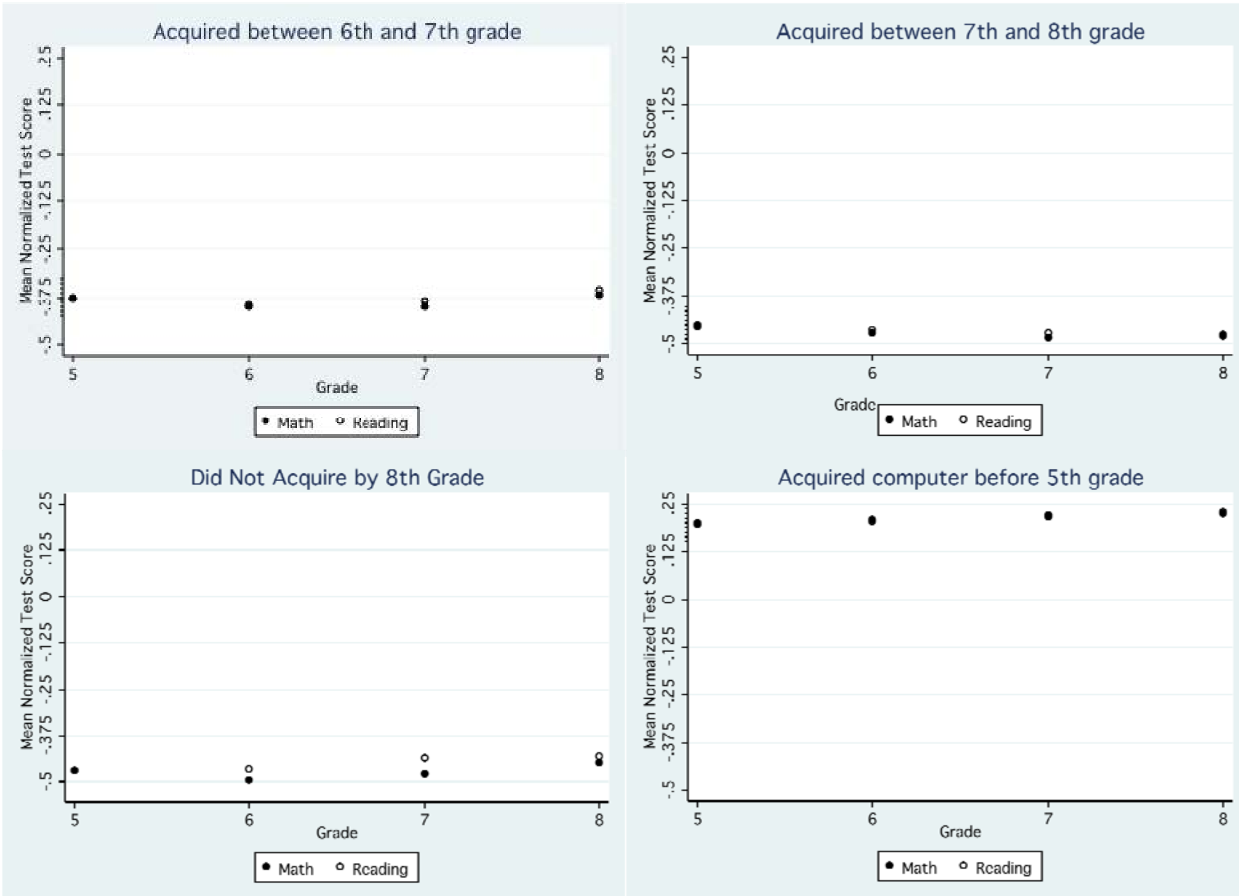

Figure 3: Test score patterns for students by point at which they report obtaining a computer.

Race (white omitted): Asian	0.0204**	0.0914**
	(0.0048)	(0.0053)
Black	-0.1049**	-0.0704**
	(0.0023)	(0.0022)
Hispanic	0.0102**	0.0269**
	(0.0044)	(0.0042)
Native American	-0.0432**	-0.0441**
	(0.0083)	(0.0087)
Mixed	-0.0131**	-0.0144**
	(0.0059)	(0.0054)
Other	-0.1813**	-0.0296
	(0.0772)	(0.0703)
Parent Ed (postgraduate omitted): < HS	-0.2391**	-0.2255**
	(0.0044)	(0.0046)
High School	-0.1626**	-0.1705**
	(0.0033)	(0.0038)
Trade/Business School	-0.1134**	-0.1231**
	(0.0037)	(0.0043)
Community/Technical College or Some College, No Degree	-0.1063**	-0.1311**
	(0.0035)	(0.0039)
College	-0.0501**	-0.0629**
	(0.0029)	(0.0033)
Cohort 1 (8^{th} grade in 2002/03)	-0.0194**	-0.0101**
	(0.0031)	(0.0049)
Cohort 2 (8^{th} grade in 2003/04)	-0.0048	-0.0010
	(0.0030)	(0.0047)
Male	-0.0162**	0.0072**
	(0.0013)	(0.0013)