Scaling the Digital Divide: Home Computer Technology and Student Achievement

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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 secondary students reduce these disparities? We use administrative data on North Carolina public school students to corroborate earlier surveys which 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.

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1. Introduction

In recent years, policy makers and philanthropists have undertaken many initiatives to increase disadvantaged children's access to computers and related technology. Some of these initiatives have focused on schools.[1] Partly as a result of these investments, by 2003 over 90% of middle and high school students reported using a computer at school (DeBell and Chapman, 2006). Reported rates of school-based computer use vary little by race or socioeconomic status.[2]

The so-called "digital divide" in computer access for youth is much more evident at home. 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.

Partly motivated by these disparities in access to home computers, several states and school districts have experimented with programs granting laptops to middle or high school students. The Maine Learning Technology Initiative 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

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).

2 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.

single-year lease. These initiatives represent a significant increase in per-pupil spending on computer access. The typical American school has one computer for every four students; moreover, laptop computers are more expensive than desktop models typically used in schools, and generally have lower usable lifespans. A laptop program extended to all public school secondary students would cost billions of dollars per year.[3]

These considerable investments have been made even though very little evidence exists to support a positive relationship between student computer access and academic outcomes. Peer-reviewed experimental or quasi-experimental studies of the impact of the instructional use of computers have found very 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).[4] Studies of home computer use have revealed promising correlations, but generally have not employed experimental 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).[5] Two quasi-experimental studies have found no significant 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

3 There are roughly 4.5 million students in each 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 budget for the Title I program in fiscal 2007 was just under $13 billion.

4 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.

5 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.

Technology Immersion Program.[6] The absence of positive effects in these more rigorous studies may reflect any 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).[7]

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.

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. Identification of the effect of internet service is also aided by the uneven timing of service introduction across local areas, determined in part by the idiosyncratic actions of

6 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).

7 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).

monopolistic local telecommunication service providers.

Results show that there is a "digital divide" among North Carolina public school students comparable in magnitude to national statistics derived from the CPS. The very existence of a digital divide means that simple estimates of the relationship between computer use and academic outcomes could be biased, since access to home computer technology is likely correlated with unobserved determinants of test scores. Our results show that these concerns are valid. Simple OLS estimates suggest that students who have access to home computers and use them for homework a few times each month score significantly higher on standardized math and reading tests than those with no computer access. Student fixed-effect results, by contrast, show modest but statistically significant negative impacts of home computer access, and little impact of use conditional on access. 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.

Student fixed-effect specifications reveal that increased availability of high speed internet is actually associated with less frequent self-reported computer use for homework as compared to no availability. On the margin, then, broadband internet access appears to crowd out productive computer use, and possibly other forms of homework, presumably by introducing new options for recreational use by students and other family members. Consistent with this effect, the introduction of high-speed internet service is associated with significantly lower math and reading test scores. Moreover, broadband internet is associated with wider 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.

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 the ability to use basic office software to advanced programming or hardware maintenance skills, may be of considerable value in the labor market. 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 lower math and reading test scores, and wider test score gaps, would be an additional consequence. From the perspective of traditional academic skills, the digital divide proves to be of little practical concern.

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 reviews basic information on patterns of home computer use, including the impact of internet access on computer use. Section 5 presents results relating internet availability and computer use for homework to standardized test scores in reading and math. Section 6 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 5th through 8th grade between 2000 and 2005, that serves as the basis for our analysis here.[8]

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.[9] 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.

Figure 2 shows basic information on trends in computer ownership between 2000 and 2005, as reported by public school students in our sample. Access rates rose over this time period, from just under 80% of all students in 2000 to just over 90% in 2005. This increase in

8 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. There is some concern regarding whether students can be relied upon to accurately report their home computer use. Hunley et al. (2005) compare daily time use logs to students' self-reported estimates of use in a sample of public school students and find a high degree of correlation. Thus there is reason to believe that these data are accurate.

9 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.

access 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 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. To the extent that late adopters of computer technology are different from early adopters, we may estimate coefficients that are not representative of the population as a whole. Our effect estimates should be more representative, however, of the population that would be influenced by policies to subsidize home computer ownership.

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.

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.[10] At the beginning of the time period, somewhere on the order of 40,000

10 It is important to note that the period between 2000 and 2005 was not a period of rapid expansion in the number

households in North Carolina – one in every eighty – had high speed internet service. By the end of the time period, 1.16 million households, or one in every three, were broadband subscribers. This works out to an annual growth rate of roughly 67%.

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.[11]

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, the number of ZIP codes without high-speed internet service diminishes, falling from 192 in 1999 to 66 two years later, then to 7 by December 2004. Meanwhile, the number of ZIP codes with one to three ISPs declined continuously, and the number with four or more increased. By the end of 2004, 62% of North Carolina ZIP codes were served by at least

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

11 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.

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.

We believe the gradual rollout that resulted from these largely uncoordinated introductions of broadband internet service amounts to a supply-driven technology shock, exogenous to individual households. Gentzkow (2006) takes a similar viewpoint when using the staged introduction of broadcast television as a proxy for television viewing behavior; Gentzkow and Shapiro (2007) use the staged introduction of broadcast television to study the impact of television viewing on academic outcomes.[12] Such a strategy is most appropriate when the introduction of the new technology – broadband internet, in this case – is truly driven by idiosyncratic supply-side factors, rather than by demand. However, the introduction of broadband service may be influenced by demand as well, and that demand is likely to be correlated with household characteristics that may also have an independent impact on academic outcomes. This correlation opens up the possibility of bias when one estimates the effect of broadband service on student achievement.

Even if variation in the timing of high-speed internet access is demand-driven, our primary identification strategy should address most concerns that unobserved family or neighborhood characteristics correlate with internet availability. By using student fixed effects, we restrict our analysis to cases where we observe students in ZIP codes that transition from one

12 One might think that the availability of high-speed internet could be used in this analysis as an instrument for a student's self-reported computer use. Recall, however, that the observed variable measures a student's computer use for schoolwork. Hence the exclusion restriction – that internet access have no link to student academic outcomes except through the excluded endogenous variable – is violated in the event that internet access increases computer use for non-academic purposes, and non-productive computer use in turn influences academic outcomes. We also show evidence below that the first stage for this potential IV model is problematic. High-speed internet availability actually decreases students' self-reported computer use for schoolwork, in models with student fixed effects.

level of access to another, and determine whether student performance improves or worsens afterward. Our strategy does not require the availability of high-speed internet access to be idiosyncratic, rather it requires that the introduction be uncorrelated with any other community-level shocks that simultaneously affect student performance. Nonetheless, for descriptive purposes we present some additional analysis of the correlates of high-speed internet introduction.

Table 3 presents basic summary statistics for ZIP codes, categorized by the year in which they first received any ISP service, and the year in which they first obtained service from four or more ISPs. The table's top panel shows the average median income, percent college educated, and percent white for ZIP codes categorized by year of initial access to high-speed internet service. There is some evidence of a gradient: areas receiving internet access earlier tend to have residents with higher income and more education, and the small number of ZIP codes without any broadband service at the end of 2004 are the most disadvantaged. There is no real evidence of a trend in ZIP code racial composition.[13] Moreover, the gradients in income and education are modest. The difference between ZIP codes receiving service by the end of 1999 and those receiving it in 2004 is only about $1,700 – less than 5%. The share college educated is 19.6% in the ZIP codes with earliest access, compared to 17.7% in the ZIP codes with latest access. While these differences suggest that initial access to broadband service may have been influenced by demand, the preponderant similarity between areas receiving early versus late access suggests that supply-side factors played a strong role.

13 Given economies of scale in providing service, one would expect urban areas to receive broadband internet access first, followed by rural areas. In North Carolina, rural areas tend to be predominantly black in the Eastern part of the state, and predominantly white in the Western part. The mountainous topography of the Western portion makes land-based broadband delivery – whether by coaxial cable or telephone line – difficult relative to the flat Eastern portion. This explains the disproportionate number of predominantly white areas in the set without broadband access as of 2004.

The lower panel of Table 3 shows similar statistics for ZIP codes categorized by the year in which they first received service from four or more different ISPs. Here, the evidence in favor of a demand-driven process is stronger. The ZIP codes that crossed this threshold by the end of 1999 have an average median income of $58,150, and are 33% college educated. By contrast, the areas crossing the threshold in 2004 had median incomes more than $10,000 lower and rates of college education almost 13 percentage points lower. The ZIP codes that remained below the 4 ISP threshold at the end of 2004 are substantially worse off socioeconomically than those that had reached the threshold. Interestingly, there is once again no clear trend in ZIP code racial composition. The areas with the highest minority representation are as likely to be in the earliest as the latest adopting groups.

3. How home computer technology might influence academic achievement

Most previous studies of computers and student achievement have started with the presumption that student access to home computers could have either positive or negative effects on academic outcomes. 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. As an illustration, the 2003 computer use supplement to the CPS found that school-aged children were most likely to report using a computer to play games, with work on school assignments a close second and browsing the internet third. The three most common uses of the internet were for schoolwork, to use email or instant messaging, and to play games (DeBell and

Chapman 2006). Activities such as these could detract from schoolwork through a number of channels – by directly reducing the amount of time spent studying, or by introducing physical or social impediments to successful progress in school. 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 perspective.

3.1 An economic view of home computer technology

Simple economic models of behavior posit that individuals allocate scarce resources to maximize an objective subject to various constraints. The young adolescent's problem is one of allocating time across competing uses. The adolescent is constrained by the number of hours available in a day, beyond those devoted to school and the basic necessities of life. For simplicity, suppose that the adolescent allocates free time between two activities, schoolwork and leisure. We assume that an hour spent on schoolwork provides the adolescent with less direct satisfaction than an hour spent in leisure, but schoolwork offers a long-term reward in terms of increased human capital, which leads to higher living standards in adulthood.

This basic formulation can be represented with an equation. Adolescents have a lifetime utility U, which is influenced both by the proportion of current available time spent in leisure, L, and future living standards S. Future living standards are a function of time spent studying in the current period, $(1-L)$.

(1) $U = U(L, S(1-L))$

The adolescent chooses a value of L between zero and one to maximize this expression. The first-order condition for such a maximization is:

$$(2)\quad \frac{\partial U}{\partial L} = -\frac{\partial U}{\partial S}\frac{\partial S}{\partial L}\ .$$

In words, the adolescent maximizes lifetime utility at the point where switching a minute from schoolwork to leisure generates a gain in current satisfaction that is exactly offset by a loss to future living standards associated with reduced future human capital.

Figure3 illustrates this tradeoff between current leisure and future living standards. The concave line is a production possibility frontier, illustrating the possible combinations of leisure and future living standards that an adolescent can obtain if all her time is used productively. Devoting all time to schoolwork will put the adolescent at the vertical intercept; devoting all time to leisure will put the adolescent at the horizontal intercept. The concave shape of the production possibility frontier reflects an assumption of diminishing marginal returns to schoolwork; at some point, adolescents gain very little from spending additional free time studying.

Overlaid on this production possibility frontier are indifference curves, which link the set of leisure/future living standard combinations that generate equivalent utility. The slope of an indifference curve indicates the degree to which future living standards must rise to compensate an adolescent for a unit loss in current leisure. Curves further away from the origin represent higher levels of utility. The adolescent maximizes utility by locating the point on the production frontier that reaches the furthest indifference curve. This point is labeled A in the figure.

Introducing access to home computers or the internet does two things to this picture. First, the production possibility frontier expands. Because both technologies allow schoolwork to be accomplished more efficiently – that is, with less time investment – adolescents can now attain a higher future living standard for any given investment of time. This expanded frontier is represented as a dashed line in Figure 3.

The second consequence is a potential change in the adolescent's valuation of leisure. Home computers and the internet introduce new possibilities for leisure activities, some of which may be more enjoyable than the set of alternatives present prior to their introduction. In this simple model, the new leisure activities can be thought of as introducing stronger preferences for leisure.[14] Indifference curves become steeper: adolescents must now be compensated with an even larger increase in future living standards to compensate for a loss in current leisure.

In isolation, the first effect should lead to an increase in future living standards – as well as test scores, which are the first indication of the amount of schoolwork accomplished. The effect on leisure time is ambiguous – income effects should lead the adolescent to demand more of it, so long as it is a normal good, but substitution effects – the greater marginal productivity of time spent studying – point the other direction. The second effect, in isolation, should lead to a reduction in future living standards and an increase in leisure. When the two effects occur simultaneously, it is unclear which effect dominates – that is, it is not clear whether future living standards, and their short-run proxy, should increase or decrease. Likewise, it is unclear whether time spent in leisure – and conversely, time spent studying – should increase or decrease.

3.2 Beyond economics

The maximization problem in equation (1) 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 which is not fully developed in adolescence (Sowell et al. 1999). Left to their own devices, then, we might expect adolescents to make systematically

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14 In a slightly more complicated model, leisure activities could be divided into two categories: one which requires a home computer, and a second which does not. In such a model, the introduction of a home computer unambiguously leads adolescents to spend more time on leisure activities which require a home computer, and has ambiguous effects on future living standards. This is the same as the prediction made in the simple model.

short-sighted decisions, choosing to devote their time to leisure activities unless presented with an overwhelming opportunity to improve their human capital and future living standards.

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 in their lives. Teachers may assign extra homework either to lower-performing or higher-performing students; teacher decisions may particularly reflect a desire to help at-risk students pass the state's mandatory test in computer skills, offered to students beginning in 8th grade.[15] Of course, the decision to complete the homework still resides with the adolescent, but patterns of computer use for homework could reflect variation in teacher strategies as much as variation in student preferences. Teachers who assign disproportionate amounts of computer-oriented homework may be more or less effective than others in unobserved ways.[16] This introduces the potential for omitted variable bias in correlational estimates of the link between home computer and internet use and academic outcomes. Importantly for our study, this bias is not cured by employing student fixed effects, since any within-student variation in computer use may be driven by variation in teacher practices. This bias is presumably less of a factor, however, when analyzing the impact of computer and internet access, rather than use, since teachers in general do not make access decisions for their students.

Parents influence an adolescent's computer use decision by deciding whether to purchase a computer or internet service in the first place, and potentially by regulating the adolescent's use. Parents' decisions to impose constraints on their children reflect a number of factors,

15 The computer skills test is first administered in 8th grade; students have additional opportunities to pass the test in subsequent years. Students must pass the test prior to receiving a high school diploma. State reports indicate that about 81% of students overall, but only 63% of Hispanic students and 69% of black students, pass the test on the first try (Public Schools of North Carolina, 2005).

16 In North Carolina data on middle school students, we have no direct means of linking students to teachers, thus all teacher attributes, credentials, and behaviors are unobserved for purposes of this study.

including parents' capacity to oversee and sanction behavior, social and cultural norms, and the parent's own family background. The factors determining parents' choice of constraint may also contribute to parental decisions to purchase a home computer. Adolescents with computers available may also have access to other parentally-provided educational resources, or may have received computer access as a reward for prior performance. Even conditional on availability, the adolescent's choice of how much to use the computer for productive purposes may correlate with parental monitoring, which in turn correlates with numerous other determinants of achievement.

Even in the absence of issues related to teacher and parent determination of computer access and use, estimation of the relationship between computer access and academic outcomes raises more basic concerns of ability bias. Students who choose to use computers more frequently may be different from others along unobserved dimensions, and these unobserved differences may in turn have a strong influence on the outcome of interest. Students who use computers more frequently for homework may also be using them more frequently for leisure, to the point where they crowd out offline studying. In this case, estimates of the relationship between intensity and use may not reflect the true impact of more frequent productive computer use when unproductive use is held constant.

As a final note, this model leads to a prediction that the impact of computer use and availability may depend on the degree of parental monitoring available. Left to their own devices, adolescents may be more likely to use computers for non-productive purposes, to the potential detriment of their academic performance. Adolescents who are more forward-looking, either because they are neurologically advanced or more closely monitored by parents, may show greater benefits from computer access and use. We present some estimates below that test for such a pattern, but this prediction should also be kept in mind when interpreting our basic estimates, since they are based to some extent on variation within the subset of families who are late adopters of computer technology.

3.3 Estimation Strategy

Our strategy for overcoming at least some of these confounding relationships hinges on the availability of longitudinal data on computer and internet availability, use, and student outcomes. The assumption underlying the analysis is that the main confounding factors, innate ability and parental resources, do not vary much from year to year, while computer and internet availability can. In such a scenario, within-student variation in availability and use can be used to identify the impact of these factors on achievement. Given that nearly 80% of students report having access to a home computer at the beginning of our sample period, our estimates should be interpreted as measuring the impact of computer access on late-adopting families.

To identify the impact of high-speed internet access, we use variation that is driven in some part by supply-side decisions. If we had information on home internet access at the student level, we could use the supply-side measure as an instrument for it. As we do not, the analysis can be thought of as a reduced-form "intent-to-treat"-type analysis of potential internet access on student outcomes.

Equation 3 represents the basic econometric model to be estimated:

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

where A_{izt} 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 set of variables measuring access to and use of home computers; 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. 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.

Our basic identification strategy is suspect if families invest in computer technology in response to short-run changes in achievement. This implies that some component of e_{ijst} is correlated with C_{it}. Given the broad increases in computer access observed in Figure 2, which are in turn likely driven by the continual reduction in price of constant-quality home computers, and the rapid deployment of broadband internet evident in Table 1, this would appear to be a secondary concern. If, however, our strategy fails to purge the impact of unmeasured confounding variables, we may still be able to bound the impact of computer or internet availability, under a weaker assumption that the impact of factors confounding within-student estimates is of the same sign as the impact of factors confounding across-student estimates. For example, if across-student estimates are confounded by the fact that wealthier families purchase both computers and other educational resources, then within-student estimates are confounded, presumably to a lesser extent, by the tendency for families to purchase more of both kinds of resources when their incomes increase. If within-student estimates are smaller than across-student estimates, this assumption points to the conclusion that our ultimate estimates are biased upwards. This is our primary rationale for reporting the results of models without student fixed effects, in spite of the fact that they are not our preferred model.

Because within-student variation in computer use, conditional on ownership, may be driven by variation in teacher practices, our strategy of using within-student variation is less reassuring when applied to the study of use rather than availability. To help understand whether the frequency of computer use is driven by teacher action rather than student choice, we will pay close attention below to analysis of the relationship between self-reported homework time and achievement. If teachers assign more homework to struggling students, and these students correspondingly spend more time on homework, we would expect coefficients on homework time to exhibit a more pronounced downward bias in models without student fixed effects.

4. The correlates of computer use

Before reporting the results of models estimating the relationship between home computer technology access and test scores, we present more basic information on correlations between student characteristics and reported levels of home computer access and use. There are several reasons to examine computer use patterns. We can further examine the digital divide, to see whether racial and socioeconomic differences in computer access are compounded by differences in use conditional on access, or potentially offset by use patterns. We can study the relationship between internet availability and home computer use for schoolwork. Finally, and most importantly for subsequent analysis, we can make inferences regarding the likely direction of omitted variable bias in non-experimental studies of the impact of computer use on achievement.

Figures 4 through 6 are bar charts showing patterns of home computer use for schoolwork across racial or socioeconomic categories, conditional on ownership. Even among students who own computers, more advantaged students tend to report greater use. Figure 4 shows that black, Hispanic, and Native American students with access to a computer at home report using it for schoolwork no more than once a month nearly half the time. White and Asian students in computer-owning households fall into this use category only 30% of the time. While socioeconomic groups with low average socioeconomic status are clearly under-represented in the monthly and weekly use categories, a noteworthy number report almost daily computer use for homework. Black students, in particular, report rates of daily use, conditional on ownership, that exceed those of white students.

Similar patterns appear in Figure 5, which looks across free or reduced price lunch participation categories, and Figure 6, which compares students across parent education categories. Disadvantaged students are more likely to report never using a computer for school work, or using it less than once per month – more than half of subsidized lunch recipients with computer access at home fall into these categories. At the same time, disadvantaged students are proportionately represented, or even over-represented, in the highest category of computer users, conditional on ownership.

Why are disadvantaged students more likely to report extremely low or extremely high levels of computer use? At the high end, teacher practices may be responsible for some of the pattern. Especially in light of the state's computer skills test, a graduation requirement for students in the cohorts analyzed here, some teachers may be giving extra computer-based assignments to students with home computer access, to ready them for the examination. Students may also be substituting electronic resources for parental resources in the completion of homework. Whether linked to the internet or not, computers offer students resources for checking spelling, grammar, and arithmetic calculations – functions that can also be performed by parents. At the low end of the use distribution, students in households with computers may be less likely to use them because those computers are functionally obsolete, or inoperative. Disadvantaged students may also receive less instruction in how to use a computer, either because their schools have poorer resources, because their parents have less technical expertise, or because their parents are simply less available. Regardless of cause, the observed tendency for disadvantaged students to be over-represented in the extreme categories of computer use raises concerns of omitted variable bias in models estimating the impact of use on achievement test scores.

This basic information on computer use is relatively consistent with statistics from the October 2003 CPS supplement on computer use, as reported by DeBell and Chapman (2006). That study reported an overall rate of home computer usage among 6th-8th grade students of 72%; 71.5% of 5th through 8th grade students in the North Carolina data using home computers for schoolwork at least occasionally. The rates of computer use reported by disadvantaged groups in the CPS are somewhat lower than those reported in the North Carolina data. This may reflect differences in data collection procedures between the two surveys. The CPS collects information from a household member at least 15 years of age; this restriction implies that virtually none of the information on 6th through 8th graders is self-reported in the CPS. Parents of disadvantaged children may under-report their children's computer use because it is more likely to occur outside their direct supervision.

Table 4 presents results of multivariate models estimating the impact of student characteristics, as well as ZIP code-level broadband internet access measures, on students' selfreports of home computer use. 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.[17]

The first reported specification in Table 4 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. Many results in this specification corroborate the basic graphical information presented above. Students participating in the free and reduced price lunch program use computers less frequently, as do students whose parents have less education. Interestingly, the black-white computer use gap disappears, and in fact reverses, after conditioning on these other variables. Asian students 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. These time use variables are jointly determined; it is not necessarily appropriate to think of these correlations as reflecting causality in any one direction.

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,

17 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.

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 necessarily advisable, however, as it turns out not to be robust to the introduction of student fixed effects.

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 from the two models are not directly comparable, 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. It should be noted 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. It should also be noted 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, an increase in the number of providers leads students to use computers for school work less frequently, not more frequently.

It is comforting to note that the positive coefficients in earlier specifications are confined to the four-or-more ISP variable, which in Table 3 was shown to have a more obvious connection with local demographic characteristics. This furthers our argument that the timing of initial ISP service was determined largely by idiosyncratic supply-side factors, and not demand. It is also comforting to note that student fixed-effect models reveal the expected sign of bias in the four-or-more ISP variable.

Finally, note that the within-student estimates of the partial correlation between computer use and both time use patterns and other time-varying student characteristics and computer use are generally quite comparable to the estimates in the second column. This increases our confidence that students provide reasonably accurate reports of their time use.

5. The impact of home computer technology on test scores

5.1 Across-student estimates

Table 5 presents estimates of the relationship between home computer ownership, high-speed internet availability, other student characteristics, and standardized test scores, in models that allow across-student variation to identify coefficients. As discussed, these models will be problematic to the extent that student-level unobserved variables correlate both with the covariates of interest and the outcome. They are provided here primarily as a benchmark, to gauge the direction of bias in comparison to more reliable student fixed effect models presented below. The dependent variable in each specification has been normalized to have mean zero and standard deviation one. Each specification also includes a control for a prior year's test score, as is common in "value-added" models of educational production.[18]

18 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.

The models uniformly associate home computer ownership with significantly higher math and reading test scores. In models with and without ZIP code fixed effects, studying either reading or math test scores, students with access to a home computer attain scores between 1.7% and 1.9% of a standard deviation higher than those with no home computer access. This effect is about one-fifth the magnitude of the test score differential between students with high-school versus college-educated parents. This effect should not be assigned a causal interpretation, however.

The estimated impact of high-speed internet availability is generally small and in most cases statistically insignificant. Test scores in ZIP code/years with between one and three ISPs are indistinguishable from those in ZIP code/years with no service, with or without ZIP code fixed effects. In ZIP code/years with four or more ISPs, point estimates suggest that both reading and math test scores are worse than in ZIP codes with no service, though the effects are significant only in the case of reading. The largest point estimate suggests that reading test scores are just under 2% of a standard deviation worse in ZIP codes that transition into 4+ ISP service. While causal interpretation is generally not advised in these specifications, this pattern is striking in light of the general tendency for ZIP codes with four or more ISPs to be more affluent, as shown in Table 3 above.

The remainder of the estimates in Table 5 corroborate general findings in the literature. Coefficients on lagged test scores are in the usual 0.7 to 0.8 range. Students receiving subsidized lunch tend to perform worse on standardized tests, as do students with less educated parents. Relative to non-Hispanic whites, black and Native American students perform worse on

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For more complete discussions of the modeling assumptions associated with the education production process, see Boardman and Murnane (1979).

standardized tests. Hispanic and Asian students perform better, conditional on observables, a finding consistent with Clotfelter, Ladd and Vigdor (forthcoming). Leisure reading is monotonically associated with better reading test scores; there is however an interior maximum in the relationship between leisure reading and math test scores. Test scores improve with self-reported time spent on homework, up to the ten hour per week threshold. This suggests that any tendency for teachers to assign extra homework to struggling students is offset, either by the positive treatment effects of doing homework, or by struggling students' failure to complete the additional assignments. Modest amounts of television viewing are associated with higher test scores; a significant negative relationship appears beyond the four-hour-per-day threshold in math, and beyond the six-hour-per-day threshold in reading. Each of these time use results should be interpreted cautiously, as they involve across-student comparisons and unobserved student or family characteristics may determine both time use and independently influence test scores. This concern will be addressed to a large extent in student fixed-effect models.

Table 6 expands these results by analyzing how test scores vary among students who report varying amounts of home computer use for schoolwork. The regressions underlying the reported coefficients here are identical to those in Table 5, with the exception that the single binary control for home computer ownership has been replaced with five categorical controls representing the self-reported frequency of use for schoolwork responses.

As discussed above, the results of these specifications must be interpreted cautiously, as the variation in frequency of computer use for schoolwork is driven by a combination of teacher, parent, and child decisions. Selection into frequency of use categories is a particular concern in these models, which rely largely on between-student comparisons to identify effects. With these caveats in mind, Table 5 shows a pattern consistent with much of the existing non-experimental literature: moderate levels of home computer use for schoolwork are associated with higher test scores. Relative to students with no computer at home, those who use a home computer for schoolwork once or twice per month score between 4 and 5 percent of a standard deviation higher on both reading and math tests. This is a substantial difference, equal to roughly half the observed difference between students with high school versus college educated parents. Students who own a computer but never use it for schoolwork have math test scores nearly indistinguishable from those without a home computer, while scoring slightly better than reading. Students reporting almost daily use of their home computer for schoolwork score significantly worse than students with no computer at home.

To repeat, the results shown in Tables 5 and 6 do not represent our preferred estimates, as they may in part reflect unobservable disparities between students with access to home computer technology and those without it. They are presented primarily for purposes of contrast with our preferred within-student estimates, to provide information on the direction and magnitude of selection bias.

5.2 Within-student estimates

Table 7 presents our preferred within-student estimates of the relationship between home computer ownership, internet availability, and test scores.[19] These results present a direct contrast to the across-student results in Table 5. Here, there is no evidence that home computer access improves test scores. Students who obtain access to a home computer sometime between

19 The increase in sample size in Table 6 relative to Table 5 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.

5th and 8th grade tend to score between 1% and 1.3% of a standard deviation lower on their subsequent math and reading tests.[20] 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 this 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, these negative effects are understated.

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.

Note that the remainder of our estimates are mostly consistent with the across-student models, with a few notable exceptions. Within-student estimates of the impact of leisure reading are roughly half the magnitude of across-student estimates, indicating that unobservably more able students prefer to read more. The negative association between high doses of television and test scores is considerably smaller in within-student estimates, consistent with the notion that students predisposed to poor test scores tend to spend more time watching television (Gentzkow and Shapiro, forthcoming).

The impact of time spent on homework is also reduced; in cross-sectional models,

20 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.

students in the highest homework time category score 18-21% of a standard deviation higher than their counterparts spending no time on homework. The within-student estimates reduce the magnitude of these effects to the 11-15% range. As discussed above, we would have expected the addition of student fixed effects to increase, rather than decrease, these estimates if the dominant determinant of variation in homework time were teachers' efforts to assign struggling students more homework. In practice, unobservably better students spend more time on homework. This could imply that teachers do not actually assign more homework to struggling students, or that struggling students are more likely to ignore homework assignments. In either event, they lessen the concern that variation in self-reported computer use for schoolwork is driven by teachers' assignments of more work to struggling students.

With this result in mind, Table 8 presents within-student estimates of the relationship between frequency of computer use for homework and standardized test scores. The coefficients shown here are drawn from models identical to those in Table 7, replacing the single binary indicator of ownership with a set of indicators for frequency of use for schoolwork. In general, and in contrast to the relevant across-student estimates in Table 6, there is little variation among students in four of the five use categories. While transitioning from no home computer access to any of these use categories is associated with a statistically significant decline in both reading and math test scores, the point estimates for all categories except "almost daily" range narrowly from 0.8% to 1.3% of a standard deviation in reading, and from 0.5% to 1.6% of a standard deviation in reading. Evidence continues to suggest that intermediate levels of computer use for schoolwork are the least harmful, but the amplitude of the relationship is relatively weak.

The exception to this modest pattern is students who report using their computer for schoolwork almost daily. These estimates suggest that students who transition from having no home computer to having one and using it for schoolwork almost every day post relative test score declines on the order of 4% of a standard deviation in both reading and math. While this could hypothetically reflect teacher or parent decisions to give more computer assignments to students who both have access to a home computer and are struggling with their work, the absence of such a selection pattern into homework in general suggests that the likelihood of such a pattern is quite remote here. Instead, the most plausible explanation is that students who transition into the highest computer use category are using their computers for much more than just schoolwork, and these non-productive uses are actually crowding out productive study time.

5.3 Do the effects of home computer access moderate over time?

There are many reasons to think that the effect of home computer access are not 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, the effects could also become more negative over time.

Table 9 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 (and possibly more years after that). In our panel we can thus identify 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, divorce, and so forth.

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 are in some cases offset by negative effects, possibly by negative effects of learning to use a computer non-productively.

The loss of a home computer among students who have had one since 5th grade is associated with a slight decrease in math test scores and a slight increase in reading test scores. This could indicate that long-term owners are more likely to use computers productively for math-related tasks, or alternatively that the loss of a home computer is associated with other events that are disproportionately detrimental to math performance, such as the loss of a father figure in the home due to divorce or separation.

5.4 Heterogeneity in the effect of internet access

Does home computer technology widen achievement gaps? Is parental monitoring a critical moderator of the impact of technology access on student test scores? While we have no direct measure of parent monitoring in the dataset, we have multiple indicators of student disadvantage. Table 10 presents the results of student fixed-effect specifications that interact the arguably idiosyncratic-conditional-on-observables internet availability variables with three student-level factors: race, gender, and subsidized lunch participation.[21] These specifications ask the basic question of whether the introduction of high-speed internet service tends to widen or narrow achievement gaps.

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

21 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 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.

impact on non-black students' reading scores is less than one-third the estimated magnitude of the effect on blacks.

There is comparatively little evidence that the introduction of broadband internet had differential impacts on boys and girls. 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 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.

6. 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 moderate computer use 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 5^{th} and 8^{th} grade tend to witness a persistent decline in reading and math test scores. There is little evidence that more intensive computer use for schoolwork offsets these negative effects.

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. Survey behavior indicates that students very commonly use the internet, and computers more generally, both to work on school-related projects and for personal entertainment. In households with insufficient monitoring, unproductive uses may not only crowd out productive computer time, but may also crowd out offline studying.

Our preferred specifications indicate that 5^{th} through 8^{th} grade students generally perform best on math and reading tests when they do not have access to a computer at home. Conditional on owning a computer, the "optimal" rate of use is infrequent, twice a month or less. For the average student, introducing home internet service does not produce additional benefits. 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 improvements in student proficiency with technology and student discipline (Shapley et al., 2007).[22] 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.

Given the evidence of negative impacts of computer technology access and use on achievement, school administrators and parents may benefit more clearly from policies and initiatives designed to inhibit unproductive uses. Promoting the productive use of computers may in itself be counterproductive, as students with more excuses to use the computer may have greater difficulty in avoiding unproductive uses. Put to appropriate use, information technology has always offered the promise of increasing the productivity of teaching and learning. The challenge is to ensure that young students use information technology appropriately.

22 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: Which ZIP codes received broadband internet first?

	Average Zip Code Characteristics		
Year of initial ISP service	Median Income	% with College Degree	% White
1999	45,935	19.6	74.8
2000	45,924	19.4	75.5
2001	45,019	18.3	75.5
2002	44,528	17.9	75.7
2003	44,412	17.8	74.9
2004	44,200	17.7	74.5
No Broadband service by 2004	41,302	16.6	81.0
First year with 4 or more ISPs			
1999	58,150	33.5	70.6
2000	55,995	32.5	72.9
2001	51,003	26.1	73.9
2002	48,919	22.7	75.9
2003	48,385	21.7	76.6
2004	47,623	20.7	76.8
Fewer than 4 ISPs in 2004	38,848	13.2	72.1

Note: ZIP codes with initial ISP service before 1999 are coded as receiving service in 1999; ZIP codes with 4 or more ISPs prior to 1999 are coded as receiving 4 or more ISPs in 1999. Data source: 2000 Census, merged to FCC reports on broadband internet access.

Table 4: 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)

Table 4: The impact of internet access on the frequency of home computer use for schoolwork

Independent Variables		Dependent Variable: Ordinal computer use — Ordered Probit	Computer Use at Least Weekly — Logit	Computer Use at Least Weekly — Student Fixed Effects Logit
Television (cont'd):	4 to 5 hours/day	-0.0539**	-0.1960**	-0.0537**
		(0.0089)	(0.0197)	(0.0261)
	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 (8^{th} grade in 2002/03)		0.0391**	0.2263**	---
		(0.0074)	(0.0182)	
Cohort 2 (8^{th} 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.

Table 5: Across-student estimates of the impact of home computer ownership and internet availability

Independent Variables	Math test score		Reading test score	
Own a computer at home	0.0177**	0.0185**	0.0196**	0.0187**
	(0.0019)	(0.0018)	(0.0020)	(0.0025)
No. of ISPs in ZIP code (0 omitted): 4+	-0.0073	-0.0089	-0.0139**	-0.0172**
	(0.0054)	(0.0059)	(0.0034)	(0.0038)
1-3	0.0075	0.0213	-0.0006	-0.0100
	(0.0156)	(0.0179)	(0.0108)	(0.0143)
Lagged Test Score	0.7984**	0.7928**	0.7408**	0.7365**
	(0.0014)	(0.0014)	(0.0013)	(0.0013)
Free/Reduced Lunch	-0.0513**	-0.0501**	-0.0667**	-0.0662**
	(0.0020)	(0.0018)	(0.0018)	(0.0018)
Grade (8 omitted): Grade 5	0.0175**	0.0148**	0.0073**	0.0040
	(0.0059)	(0.0062)	(0.0037)	(0.0040)
Grade 6	0.0192**	0.0180**	0.0184**	0.0165**
	(0.0060)	(0.0055)	(0.0036)	(0.0034)
Grade 7	-0.0032	-0.0033	0.0016	0.0008
	(0.0053)	(0.0051)	(0.0034)	(0.0032)
Free Reading time (zero omitted): < 30 m/day	0.0325**	0.0306**	0.0578**	0.0573**
	(0.0022)	(0.0021)	(0.0024)	(0.0024)
30 minutes - 1 hour/day	0.0554**	0.0539**	0.0987**	0.0981**
	(0.0025)	(0.0024)	(0.0026)	(0.0026)
1-2 hours/day	0.0757**	0.0745**	0.1344**	0.1339**
	(0.0028)	(0.0027)	(0.0030)	(0.0030)
More than 2 hours/day	0.0676**	0.0684**	0.1573**	0.1576**
	(0.0032)	(0.0031)	(0.0035)	(0.0035)
Homework time (zero omitted): <1hr/wk	0.0936**	0.0901**	0.0923**	0.0905**
	(0.0051)	(0.0051)	(0.0054)	(0.0054)
1 to 3 hours/week	0.1371**	0.1330**	0.1373**	0.1342**
	(0.0051)	(0.0050)	(0.0055)	(0.0055)
3 to 5 hours/week	0.1852**	0.1808**	0.1759**	0.1729**
	(0.0052)	(0.0052)	(0.0057)	(0.0057)
5 to 10 hours/week	0.2204**	0.2156**	0.1982**	0.1943**
	(0.0055)	(0.0054)	(0.0058)	(0.0058)
More than 10 hrs/week	0.2123**	0.2079**	0.1855**	0.1812**
	(0.0069)	(0.0067)	(0.0075)	(0.0074)
Television (zero omitted): 1hr/day	0.0065*	0.0059	0.0171**	0.0188**
	(0.0038)	(0.0037)	(0.0039)	(0.0039)
2 hours/day	0.0123**	0.0132**	0.0278**	0.0309**
	(0.0039)	(0.0038)	(0.0039)	(0.0039)
3 hours/day	-0.0035	-0.0008	0.0164**	0.0210**
	(0.0040)	(0.0039)	(0.0041)	(0.0041)
4 to 5 hours/day	-0.0129**	-0.0092**	0.0139**	0.0191**
	(0.0042)	(0.0040)	(0.0042)	(0.0042)
More than 6hrs/day	-0.0478**	-0.0436**	-0.0331**	-0.0274**
	(0.0044)	(0.0042)	(0.0046)	(0.0046)

Table 5: Across-student estimates of the impact of home computer ownership and internet availability

Independent Variables	Math test score		Reading test score	
Race (white omitted): Asian	0.0861**	0.0914**	0.0213**	0.0204**
	(0.0063)	(0.0053)	(0.0049)	(0.0048)
Black	-0.0842**	-0.0704**	-0.1094**	-0.1049**
	(0.0031)	(0.0022)	(0.0027)	(0.0023)
Hispanic	0.0203**	0.0269**	0.0087*	0.0102**
	(0.0050)	(0.0042)	(0.0046)	(0.0044)
Native American	-0.0581**	-0.0441**	-0.0818**	-0.0432**
	(0.0123)	(0.0087)	(0.0112)	(0.0083)
Mixed	-0.0187**	-0.0144**	-0.0099	-0.0131**
	(0.0058)	(0.0054)	(0.0060)	(0.0059)
Other	-0.0344	-0.0296	-0.1779**	-0.1813**
	(0.0703)	(0.0703)	(0.0779)	(0.0772)
Parent Ed (postgraduate omitted): < HS	-0.2171**	-0.2255**	-0.2440**	-0.2391**
	(0.0053)	(0.0046)	(0.0045)	(0.0044)
High School	-0.1680**	-0.1705**	-0.1689**	-0.1626**
	(0.0045)	(0.0038)	(0.0034)	(0.0033)
Trade/Business School	-0.1204**	-0.1231**	-0.1191**	-0.1134**
	(0.0050)	(0.0043)	(0.0038)	(0.0037)
Community/Technical College	-0.1289**	-0.1311**	-0.1125**	-0.1063**
or Some College, No Degree	(0.0047)	(0.0039)	(0.0035)	(0.0035)
College	-0.0634**	-0.0629**	-0.0546**	-0.0501**
	(0.0038)	(0.0033)	(0.0029)	(0.0029)
Cohort 1 (8th grade in 2002/03)	-0.0094*	-0.0101**	-0.0174**	-0.0194**
	(0.0050)	(0.0049)	(0.0032)	(0.0031)
Cohort 2 (8th grade in 2003/04)	0.0002	-0.0010	-0.0039	-0.0048
	(0.0048)	(0.0047)	(0.0031)	(0.0030)
Male	0.0077**	0.0072**	-0.0154**	-0.0162**
	(0.0014)	(0.0013)	(0.0014)	(0.0013)
ZIP code fixed effects	No	Yes	No	Yes
Number of Observations	731,251	731,251	731,392	731,392

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.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 6: Across-student estimates of the effects of home computer use for schoolwork

Independent Variable	Math test score		Reading test score	
Frequency of Home Computer Use for schoolwork (no access omitted):				
Never	-0.0030	-0.0037	0.0088**	0.0080**
	(0.0024)	(0.0024)	(0.0025)	(0.0025)
Hardly Ever	0.0254**	0.0257**	0.0254**	0.0248**
	(0.0021)	(0.0020)	(0.0022)	(0.0022)
Once/Twice a Month	0.0452**	0.0479**	0.0458**	0.0457**
	(0.0023)	(0.0021)	(0.0023)	(0.0023)
Once/Twice a Week	0.0234**	0.0252**	0.0196**	0.0178**
	(0.0025)	(0.0024)	(0.0025)	(0.0024)
Almost Daily	-0.0356**	-0.0332**	-0.0377**	-0.0393**
	(0.0030)	(0.0028)	(0.0031)	(0.0030)

Note: coefficients are drawn from models identical to those in Table 5, substituting these computer use categories for the single computer ownership indicator. 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.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 7: Within-student estimates of the impact of home computer ownership and internet availability

Independent Variables	Math	Reading
Own a computer at home	-0.0132**	-0.0105**
	(0.0018)	(0.0020)
Number of ISPs in ZIP code (0 omitted): 4+	-0.0135**	-0.0163**
	(0.0049)	(0.0030)
1-3	-0.0256**	-0.0083
	(0.0130)	(0.0097)
Free/Reduced Lunch	0.0042**	-0.0037*
	(0.0021)	(0.0021)
Grade (8 omitted): Grade 5	0.0462**	0.0242**
	(0.0051)	(0.0030)
Grade 6	0.0414**	0.0293**
	(0.0043)	(0.0025)
Grade 7	0.0175**	0.0145**
	(0.0037)	(0.0023)
Free Reading time (zero omitted): < 30 m/day	0.0334**	0.0505**
	(0.0020)	(0.0020)
30 minutes - 1 hour/day	0.0399**	0.0654**
	(0.0023)	(0.0023)
1-2 hours/day	0.0438**	0.0728**
	(0.0026)	(0.0025)
More than 2 hours/day	0.0308**	0.0707**
	(0.0030)	(0.0032)
Homework time (zero omitted): <1hr/wk	0.0816**	0.0642**
	(0.0041)	(0.0044)
1 to 3 hours/week	0.1060**	0.0865**
	(0.0041)	(0.0045)
3 to 5 hours/week	0.1240**	0.0981**
	(0.0042)	(0.0047)
5 to 10 hours/week	0.1437**	0.1048**
	(0.0045)	(0.0048)
More than 10 hrs/week	0.1503**	0.1050**
	(0.0057)	(0.0061)
Television (zero omitted): 1hr/day	0.0104**	0.0198**
	(0.0031)	(0.0033)
2 hours/day	0.0140**	0.0219**
	(0.0031)	(0.0034)
3 hours/day	0.0073**	0.0154**
	(0.0032)	(0.0035)
4 to 5 hours/day	0.0007	0.0100**
	(0.0033)	(0.0036)
More than 6 hrs/day	-0.0202**	-0.0146**
	(0.0037)	(0.0040)
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.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 8: Within-student estimates of the effects of home computer use for schoolwork

Independent variable	Math	Reading
Frequency of Home Computer Use for Schoolwork(no access omitted):		
Never	-0.0135**	-0.0095**
	(0.0022)	(0.0024)
Hardly Ever	-0.0086**	-0.0054**
	(0.0021)	(0.0022)
Once/Twice a Month	-0.0079**	-0.0050**
	(0.0021)	(0.0022)
Once/Twice a Week	-0.0134**	-0.0167**
	(0.0022)	(0.0023)
Almost Daily	-0.0426**	-0.0354**
	(0.0027)	(0.0028)

Note: coefficients are drawn from models identical to those in Table 7, substituting these computer use categories for the single computer ownership indicator. 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.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 9: 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)
Effect of ownership for those who own a computer from 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 7 covariates, including student fixed effects.
** denotes a coefficient significant at the 5% level; * the 10% level.

Table 10: Heterogeneity in the impact of internet access

Independent Variables	Math			Reading		
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)
Four or more ISPs * Black	-0.0380**	---	---	-0.0237**	---	---
	(0.0066)			(0.0050)		
One-Three ISPs * Black	0.0043	---	---	-0.0398**	---	---
	(0.0138)			(0.0171)		
Four or more ISPs * Female	---	-0.0025	---	---	0.0228**	---
		(0.0026)			(0.0025)	
One-Three ISPs * Female	---	0.0046	---	---	0.0049	---
		(0.0079)			(0.0084)	
Four or more ISPs * Free/Reduced Lunch	---	---	-0.0281**	---	---	-0.0135**
			(0.0046)			(0.0036)
One-Three ISPs * Free/ Reduced Lunch	---	---	-0.0173	---	---	-0.0287*
			(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 7 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.

Figure 1: Computer ownership rates

North Carolina 5-8 grade students, 2000-2005

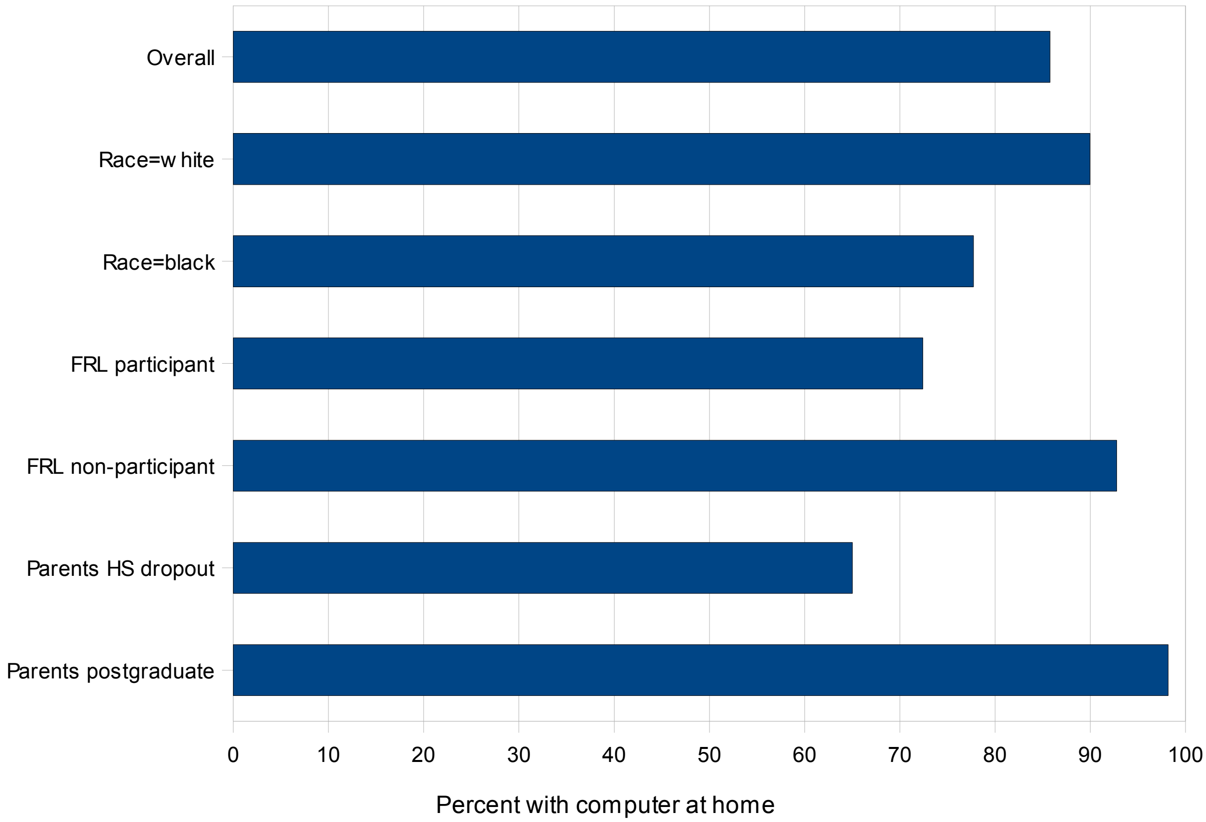
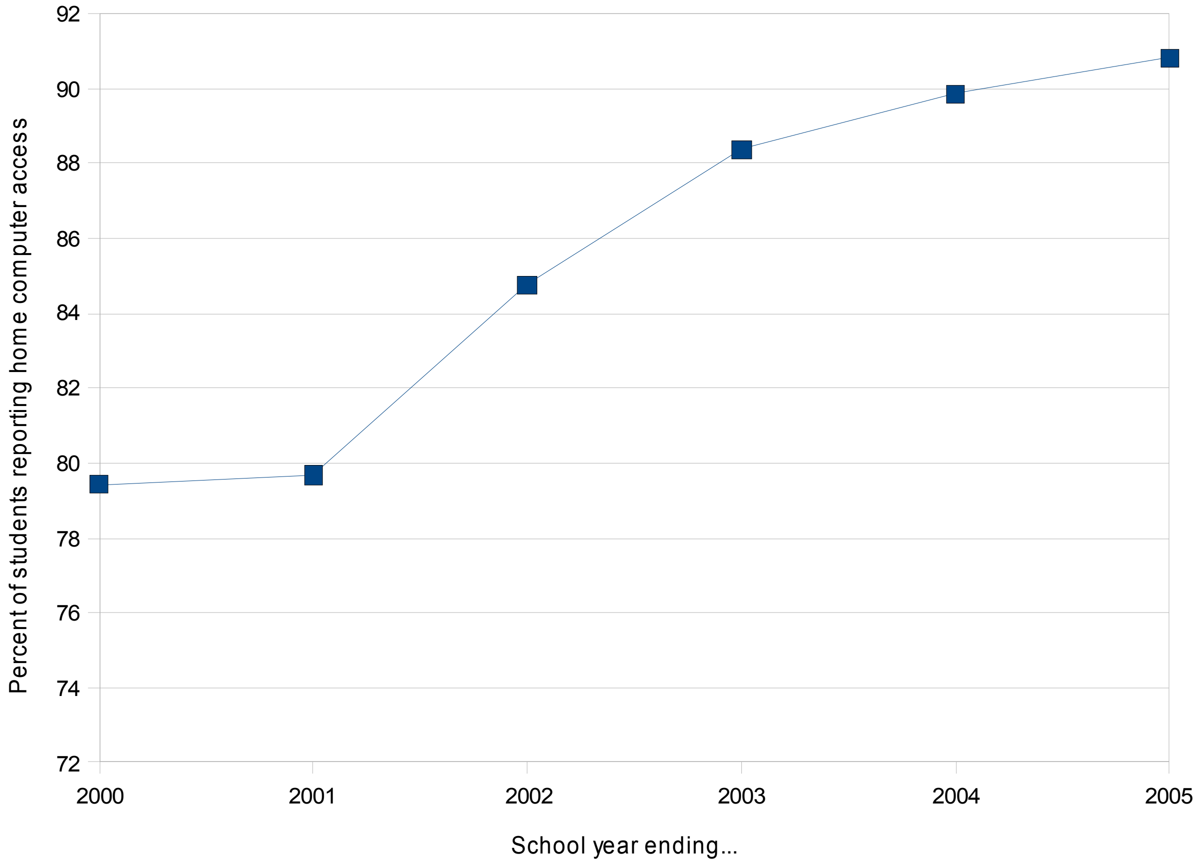


Figure 2: The expansion of home computer access over time



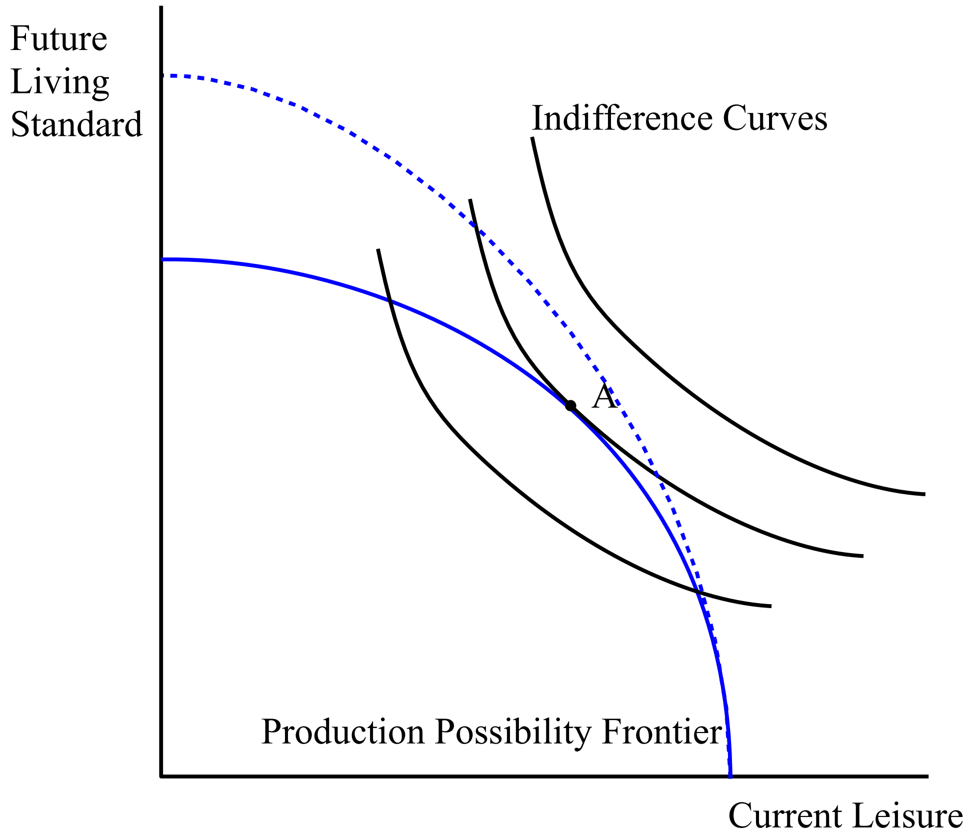


Figure 3: An economic model of an adolescent's time allocation problem.

Figure 4: Use conditional on ownership by race

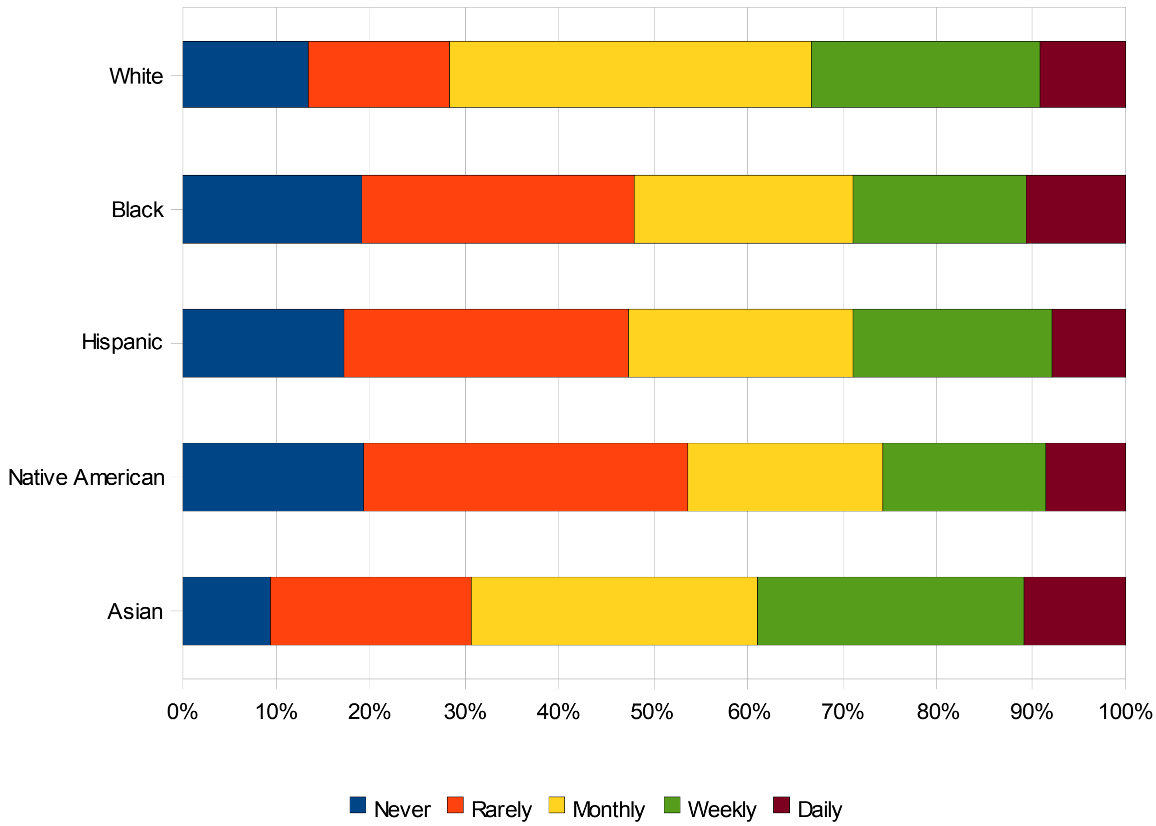


Figure 5: Use conditional on ownership by free/reduced lunch participation

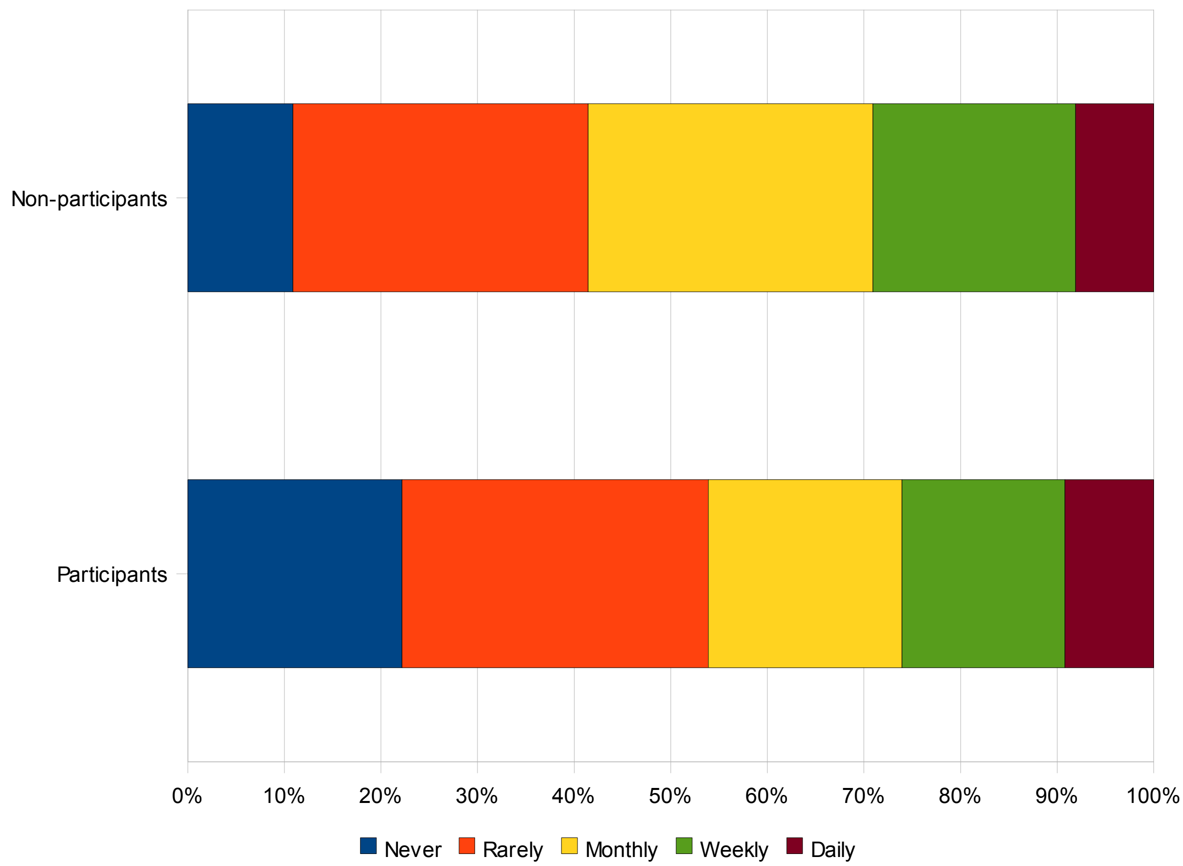


Figure 6: Use conditional on ownership by parental education