College Openings, Mobility, and the Incidence of COVID-19 Cases — Source link

Martin Andersen, Ana I. Bento, Anirban Basu, Christopher R. Marsicano ...+1 more authors

Institutions: University of North Carolina at Greensboro, Indiana University, University of Washington, Davidson College

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College Openings in the United States Increased Mobility and COVID-19 Incidence

Martin S. Andersen[1,*,+], **Ana I. Bento**[2,*,+], **Anirban Basu**[3], **Christopher R. Marsicano**[4,5], **and Kosali Simon**[6]

[1]Department of Economics, University of North Carolina at Greensboro, Greensboro, NC 27412
[2]Department of Epidemiology and Biostatistics, School of Public Health, Indiana University-Bloomington, Bloomington, IN 47405
[3]The Comparative Health Outcomes, Policy, and Economics (CHOICE) Institute, Departments of Pharmacy, Health Services, and Economics, University of Washington, Seattle, Seattle, WA 98195
[4]The College Crisis Initiative at Davidson College, Davidson College, Davidson, NC 28035
[5]Educational Studies Department, Davidson College, Davidson, NC 28035
[6]O'Neill School of Public and Environmental Affairs, Indiana University, Bloomington, IN 47405
[*]msander4@uncg.edu or abento@iu.edu
[+]these authors contributed equally to this work

ABSTRACT

School and college reopening-closure policies are considered one of the most promising non-pharmaceutical interventions for mitigating infectious diseases. Nonetheless, the effectiveness of these policies is still debated, largely due to the lack of empirical evidence on behavior during implementation. We examined U.S. college reopenings' association with changes in human mobility within campuses and in COVID-19 incidence in the counties of the campuses over a ten-week period around college reopenings in the Fall of 2020. We used an integrative framework, with a difference-in-differences design comparing areas with a college campus, before and after reopening, to areas without a campus and a Bayesian approach to estimate the daily reproductive number (R_t). We found that college reopenings were associated with increased campus mobility, and increased COVID-19 incidence by 1.9 cases per 100,000 (95% confidence interval [CI]: 0.9 – 2.9). This reflected our estimate of increased transmission locally after reopening. A greater increase in county COVID-19 incidence resulted from campuses that opened for in-person teaching and with greater exposure to students from counties with high COVID-19-incidence in the weeks before reopening. As we approach Fall of 2021, and many people are still not vaccinated, our study sheds light on movement and social mixing patterns during the closure-reopening of colleges and offers strategic instruments for benefit-cost analyses of school reopening/closure policies.

Main

One of the key lessons learned from the COVID-19 pandemic has been the pivotal role of human behavior, specifically mobility and mixing in spreading infection, and the role of young adults. In the United States and globally, these phenomena are acutely important in congregate and communal living settings that are common in colleges, prisons but also in older adults in nursing homes[1–4]. However, the role of communal living, and its interaction with mobility and mixing, is difficult to identify empirically since people enter communal living settings non-randomly. The resumption of teaching on a college campus provides a sudden change in a community's exposure to communal living and differences across college campuses lead to variation in the extent to which campus reopenings induce mixing with higher and lower incidence areas.

The susceptibility of children and college-age individuals to COVID-19 and their role in transmission has been heavily debated and remains hard to quantify[5–9]. Following the first wave of school closures in the United States in the spring of 2020, COVID-19 incidence fell across the country, leading many public health officials to view closing schools as a viable strategy to mitigate the spread of the pandemic[10,11]. However, closing schools, while potentially reducing the spread of COVID-19, may adversely affect children and college students. As a result, it is important to understand what role college reopenings play, if any, in the COVID-19 pandemic to design efficient mitigation strategies now and in the future.

During late Summer 2020, colleges and universities across the United States reopened and welcomed hundreds of thousands of students back to campus in the United States[12]. Over half of these institutions reopened for in-person teaching, although many institutions switched to online instruction after rapid increases in reported COVID-19 cases on campuses and in the community[13,14]. A few studies have sought to formally test the hypothesis that reopening college campuses increased COVID-19 incidence[4,15–18]. However, the institutions in these studies represent a small proportion of the 11 million undergraduates enrolled in public and non-profit four-year institutions across the country[12]. A phylogenetic study from western Wisconsin[3] identified two clusters of SARS-CoV-2 strains on college campuses that may have subsequently infected nursing home residents, demonstrating transmission between college campuses and the surrounding community. Nonetheless, the effectiveness of college reopening policies as non-pharmaceutical interventions for mitigating the burden of COVID-19 is still disputed. Simulation-based studies have been unable to provide public health officials with conclusive recommendations, despite detailed COVID-19 transmission datasets[19,20]). The lack of a clear direction is mostly due to insufficient data about the college-specific details and how to harness movement as proxies for behavior and mixing patterns of the population while such strategies are in place. As we approach Fall 2021, with expected mass movement events in the US, millions of college and university students will return to residential instruction. This leaves little time to achieve high levels of full vaccination necessary to prevent outbreaks. Furthermore, due to new variants now circulating, there is an increased risk of breakthrough infections[21]. Thus, it is more important than ever to understand school reopenings' effects and mass mobility events on COVID-19 incidence.

We harnessed comprehensive, national data covering the start date and instructional method of most four-year U.S. colleges and universities together with a highly resolved dataset (both spatially and by age) from the CDC,[22] which provided detailed demographic information on COVID-19 cases around the country. This gave us the ability to directly measure the variation in human movement patterns caused by the policy and, in addition, allowed us to identify college-age cases and assign cases based on symptom onset. We hypothesized that reopening colleges would increase COVID-19 transmission within the college community with potential spillover effects onto the neighboring populations. We also hypothesized that increases in incidence would be greater on campuses that attract students from areas with a higher incidence of COVID-19 and that these effects would be concentrated among campuses providing face-to-face instruction. While there is some compelling research around testing[23,24] and limiting student mobility[9] as COVID-19 mitigation strategies, it is outside of the scope of our study to understand the impact of specific actions colleges may have taken in response to rising rates.

We use an integrative framework, with a difference-in-differences design comparing areas with a college campus, before and after reopening, to areas without a campus and a Bayesian approach to estimate the daily reproductive number (R_t). We unequivocally demonstrate that there was a marked increase in COVID-19 incidence among college-age students following the reopening of campuses. Finally, while COVID-19 case counts have been a focus of several studies, our data also allowed us to examine other public health outcomes, such as hospitalizations or deaths. Our results provide evidence of the COVID-19 impact of colleges-reopening policies locally and in neighboring and undoubtedly informs future events in these settings.

Results

Our study period ran from July 5th 2020 to November 1st 2020, which spanned the four weeks before the first campus reopening and four weeks after the last campus reopened. Of the 3,142 counties of the United States, 784 contained a college campus from our universe of 1,360 colleges. However, over 238.0 million people live in counties with a college campus. Figure 1 of the Supplementary Information maps the campuses in our sample by teaching modality.

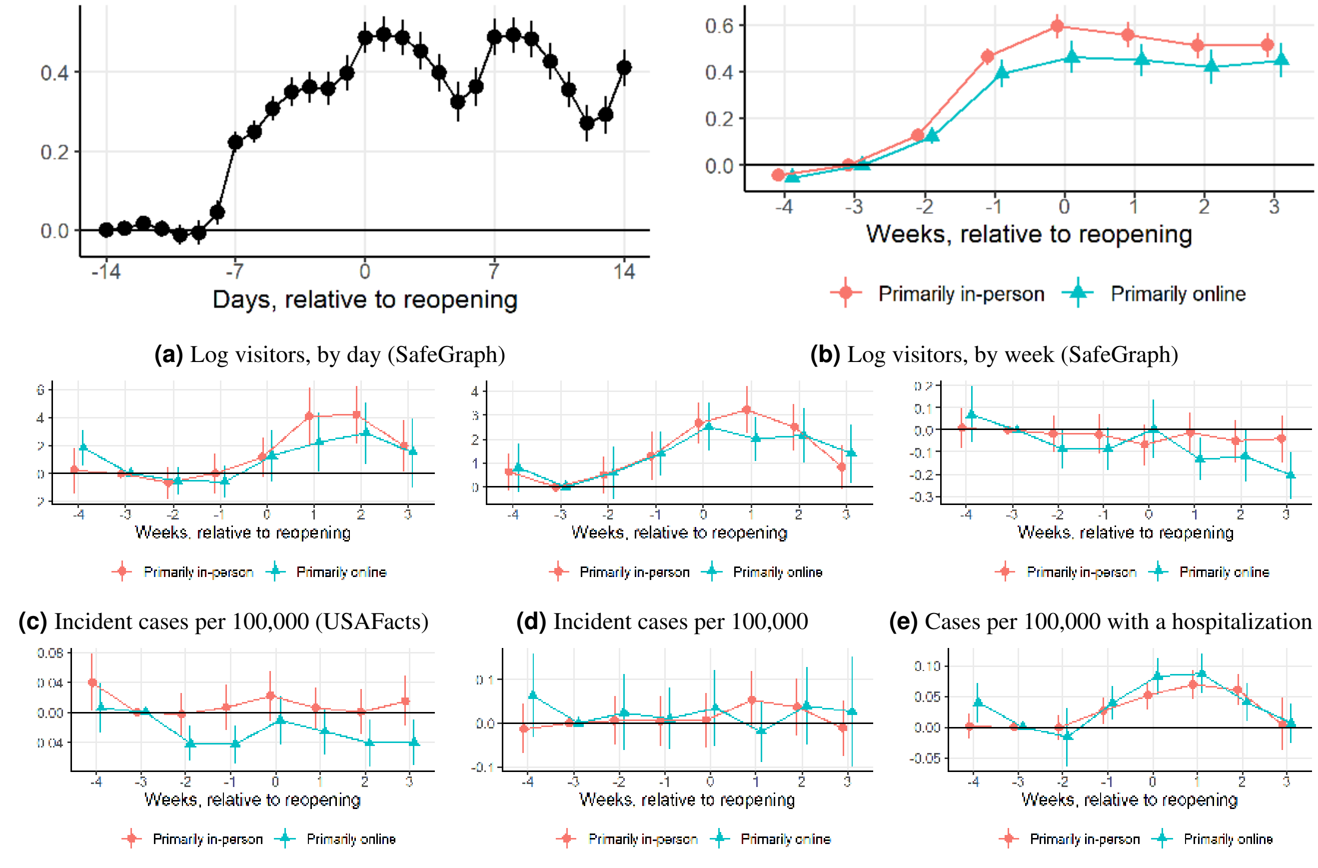
Our identification strategy made comparisons between counties with and without a college campus around the time that a campus reopened in a "difference-in-differences" design[25]. Since several counties contained more than one college campus, we assigned county status based on the status of the first, and largest, campus to reopen in each county. We explore the sensitivity of our results to the assignment of reopening dates in the Supplementary Information. Based on preliminary results on mobility, which indicated that on-campus mobility increased significantly the week before the resumption of classes, we defined our "post" period as beginning one week before classes resumed.

Event studies

The reopening of a college affected mixing patterns not only of the students but also the members of the surrounding communities where these students live. The number of devices on campus increased significantly in the week before campuses reopened and remained high for at least the first 14 days following reopening (Figure 1a). Aggregating by week, which smooths out day of the week fluctuations in movement, and separating the sample by teaching modality demonstrated that there were significant increases in movement to census block groups containing college campuses after those campuses reopened regardless of the teaching modality (Figure 1b), although the increase was larger for in-person reopenings. The increase in mobility was accompanied by a rise in COVID-19 incidence (Figure 1c and Figure 1d). The increase in COVID-19 cases was not accompanied by increases in cases requiring hospitalization and that resulted in death, particularly among campuses that opened for primarily online teaching(Figure 1, panels e and g). R_t increased regardless of the teaching modality chosen by the college (Figure 1h).

Difference-in-differences estimates

The reopenings lead to a cascade of indirect effects at the population level. To show this, we estimated a series of difference-in-difference models to estimate the effect of reopening a college campus on mobility and COVID-19 outcomes. We present the



(a) Log visitors, by day (SafeGraph)
(b) Log visitors, by week (SafeGraph)
(c) Incident cases per 100,000 (USAFacts)
(d) Incident cases per 100,000
(e) Cases per 100,000 with a hospitalization
(f) Cases per 100,000 with an ICU admission
(g) Cases per 100,000 resulting in death
(h) R_t

Figure 1. Event study estimates of reopening college campuses, relative to counties without a college campus. Colors refer to teaching modality, where red is primarily in person and blue is primarily online. a Reopening college campuses significantly increased the number of devices on college campuses, with evidence of a steady increase in the ten days before the start of classes. These increases persisted on college campuses for at least four weeks after reopening b and was larger for campuses that reopened for primarily in-person teaching. Reopening college campuses also increased the incidence of COVID-19 in the county, regardless of teaching modality or data source c and d. Estimates for the effects on new cases resulting in hospitalization e, ICU admissions f, or mortality g were decreasing over time and, for the most part, non-significant or less than zero. Local transmission, measured by R_t, increased after reopening a college, regardless of teaching modality h. COVID-19 related data are from the CDC unless otherwise specified.

detailed results in the Supplementary Information (Table 2), but describe the results below.

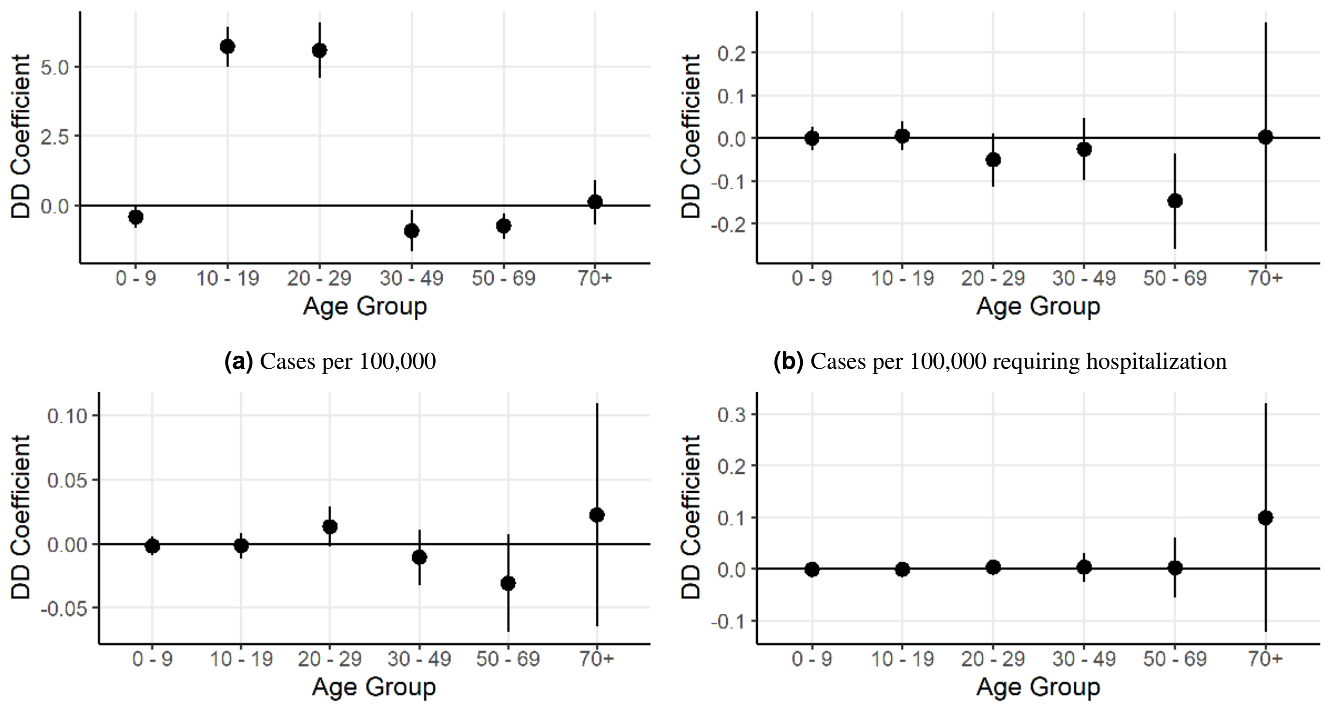
Reopening a college campus was associated with a 46.9 log point increase in the number of devices on campus, or approximately a 59.8% increase in movement on campus, from the week prior to the start of classes (Table 2, column (1)). The increase in movement was larger in schools that reopened for primarily in-person, as opposed to primarily online, instruction (49.9 vs. 41.1 log points or 64.7% vs. 50.8%, $p < 0.001$) and began increasing the week before reopening. The increase in mobility was larger for colleges that had greater exposure to students from areas with high levels of COVID-19 incidence.

Using our difference-in-difference framework, we found that reopening a college was associated with a statistically significant increase of 1.9 cases per 100,000 people (Table 2, column (2)) using case data from USAFacts. The estimate was similar, although slightly smaller, using data from the CDC sample of counties (1.6 cases per 100,000 Table 2, column (3)). The increase in COVID-19 incidence was larger for counties that were classified as “Primarily in-person” as opposed to “Primarily online”, although the observed differences were not statistically different from one another, and grew in magnitude following the the resumption of classes (column 2). The increase in COVID-19 incidence was also substantially larger in counties with a campus that attracted students from areas with a higher incidence rate two weeks before reopening; specifically, for every ten thousand devices migrating from areas with an incidence rate of one case per 100,000 increased the incidence rate in the county by an additional 1.2 cases per 100,000 per day.

Using data from the CDC, we found that reopening a college campus was also associated with a statistically significant decrease of 0.054 cases per 100,000 that ultimately require hospitalization (column 4), which primarily arises from campuses that reopened primarily online. Having a campus that attracted students from areas with a higher incidence of COVID-19, however, was associated with higher rates of cases requiring hospitalization (column 4) and resulting in death (column 6).

The central epidemiological parameter governing a disease system's dynamics is the effective reproduction number (R_t). We estimated a significant increase in daily (R_t) around the time of reopening, consistent with an uptick in transmission. On average there was an increase in R_t of 0.042 (CI: 0.028 - 0.056). We note that R_t did not significantly differ by the teaching method chosen for the campus (Table 2) but was larger in counties that were exposed to students from counties with a greater incidence of COVID-19 prior to reopening.

Age-specific incidence



(a) Cases per 100,000

(b) Cases per 100,000 requiring hospitalization

(c) Cases per 100,000 requiring ICU admission

(d) Cases per 100,000 resulting in death

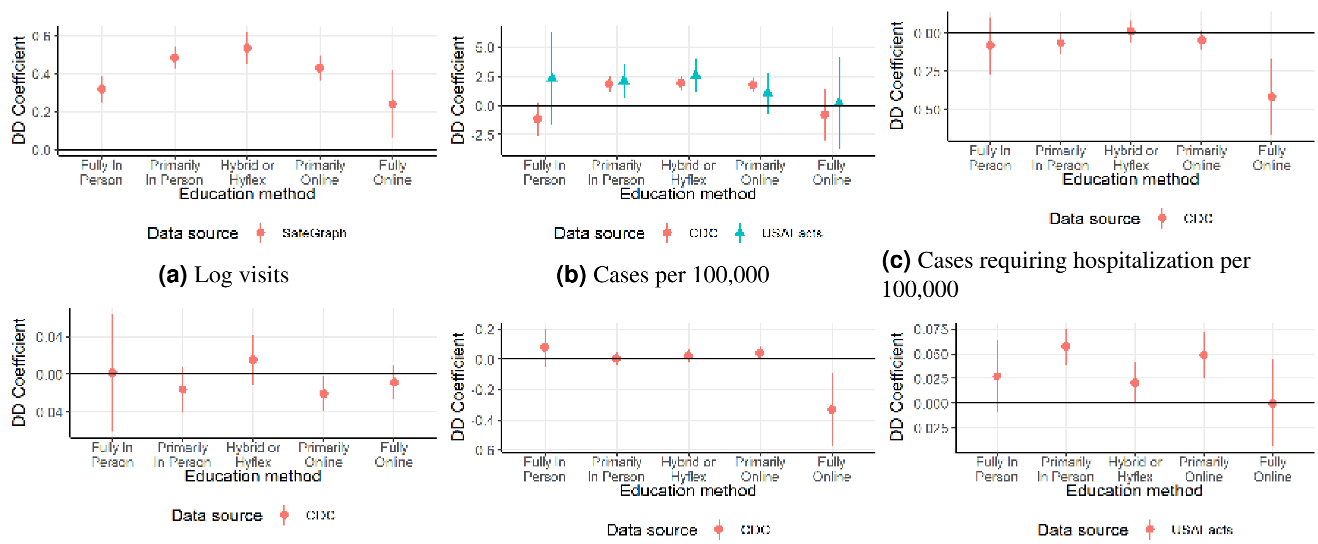
Figure 2. Age-specific effects of college reopenings. a demonstrates that the increase in the incidence of COVID-19 was isolated to people between 10 and 29 years of age, which encompasses most college-age individuals. There were no statistically significant and age-specific changes in the incidence of cases resulting in hospitalization among college-age students b. Nevertheless, the incidence of cases resulting in an ICU admission rose by almost one additional case per million people between 20 and 29 years of age c. We did not find any age-specific increases in mortality due to COVID-19, although these results were imprecisely estimated d. Figure plots point esitmates and 95% confidence intervals. Point estimates and standard errors are available in Table 3 of the Supplementary Information.

To observe the age-stratified dynamics, we explored age-specific incidence. Our analyses supported the conclusion that the shifts in age dynamics overtime likely resulted from college reopenings in Figure 2. The top panel (Figure 2a) demonstrates a clear shift, where we observe an increase in COVID-19 incidence in people ages 10 - 29, while incidence did not increase appreciably in any other age group and appears to have fallen among 30-49 and 50-69 year old age groups. However, the increase in these college-aged students was dramatic, with incidence increasing by almost six additional cases per 100,000 people between 10 and 29 years of age. The second panel indicates that our estimates of the effect of reopening on hospitalizations by age group are too noisy to draw any inferences, although there is a reduction in the incidence of cases requiring hospitalization among 50-69 year olds. In the third panel, we demonstrate that reopening a college campus increases the number of incident COVID-19 cases that result in an ICU admission by the end of 2020 among 20-29 year olds, although the effect is only marginally significant. The fourth panel demonstrates that there was no statistically significant age-specific increase (or decrease) in COVID-19 related mortality.

While the data appear to paint a clear picture, it is possible that several mechanisms may yield a similar age-specific profile of cases. Thus, in the SI, we test these observations. We show age-specific event studies (Figure 3) for our four age-specific outcomes. These event studies clearly demonstrate that COVID-19 incidence rose beginning in the weeks immediately before campuses reopened and remained elevated subsequently, with statistically significant increases after 3 weeks for 10-19 and 20-29 year olds. The event studies for hospitalization, ICU admissions, and death typically present little evidence of a time trend in advance of the campus reopening, although we also find few other statistically significant changes in our outcomes.

Differential effects by teaching modality

We separated teaching modality into more detailed categories to further explore our finding that in-person teaching was more strongly associated with increases in COVID-19 cases than online teaching. Our results demonstrate that campuses that reopened with a greater emphasis on in-person teaching were associated with larger increases in mobility and incident COVID-19 cases (Figure 3).



(a) Log visits

(b) Cases per 100,000

(c) Cases requiring hospitalization per 100,000

(d) Cases requiring ICU admission per 100,000

(e) Cases resulting in death per 100,000

(f) R_t

Figure 3. Differential effects of reopening college campuses by expanded teaching modality. a Campuses that reopened for "Primarily in-person" and "Hybrid" teaching had the largest increase in devices on campus following reopening, while the increase in visitors was significantly smaller for fully online reopenings. All reopenings except "Fully Online" were associated with a significant increase in COVID-19 cases after reopening b. There were no statistically significant adverse effects of reopening a college campus by teaching modality for hospitalizations c, ICU admissions d, or mortality following a reopening e. Except at the extremes, for which we had relatively few colleges, there were uniform increases in R_t, regardless of the teaching modality f.

Robustness and alternative specifications

We considered a number of alternative models, which we report fully in the Supplementary Information (section 2). Our results for mobility were robust to using a balanced, as opposed to a trimmed panel, although using the balanced panel increases the bias in two-way fixed effects models[25,26]. Our results were, for the most part, stronger when we adjusted for timing-group specific time trends in our outcome variables and, except for R_t and ICU admissions, indicated that reopening a college increased COVID-19 incidence, cases resulting in a hospitalization, and cases resulting in death. Weighting by population had no effect on our CDC-derived outcome measures, but rendered our USAFacts based estimates non-significant. Restricting to counties with a college left our mobility and some COVID-19 disease outcomes unaffected. Including all colleges, rather than just the first and largest college, in a county left our main results on cases and R_t unaffected, although our estimates for CDC-derived variables were no longer statistically significant. Finally, allowing for different effects for each starting date and aggregating these estimates by the share of colleges with a given starting date[26], yields estimates for our USAFacts-derived variables that are consistent with our baseline estimates.

Discussion

Schools and universities are gearing up to welcome millions of students back to campus for Fall 2021 while vaccine uptake has stagnated[27] and many remain vaccine hesitant. Therefore, it is crucial to revisit the effects of mass movement events into campuses and how they affect local and surrounding communities. Our results provide a quantitative evaluation of mobility patterns during periods of reactive college closure and reopening strategies and highlight their impact in shaping social interactions of the college and surrounding communities. We found that college policies induced marked changes in the overall number of daily mobility interactions. Our findings demonstrate that re-opening a college was associated with an increase in the number of cellular devices on campus (a dramatic increase in population size) leading up to the start of classes and after classes resumed for all teaching modalities, although the increase in mobility is larger for in-person as opposed to online teaching. We unequivocally showed that re-opening a college significantly increased the incidence of COVID-19 in the county as well as increased COVID-19 mortality, with marginally significant increases in hospitalizations and ICU admissions. In general, these increases were larger or only present for counties that contain more universities that reopened for in-person, as opposed to online, education, and persisted after reopening. We also demonstrated that counties containing colleges that drew students from areas with higher COVID-19 incidence experienced significantly larger increases in COVID-19 incidence following campus reopening. This is likely induced by the dramatic increase in the number of contacts of students with each other on the campuses and with the surrounding communities.

To contextualize our findings, there are 238.0 million Americans in the 784 counties that contain a college campus in our sample. Our results demonstrate that reopening college campuses resulted in an additional 4,500 (4546 [95% CI: 2204 – 6888]) cases of COVID-19 per day. This estimate is consistent with the aggregate number of cases reported on the New York Times case tracker which reported more than 397,000 cases as of December 11 2020[28], which would correspond to thirteen weeks of additional cases using our main estimate.

However, because of the nature of the cases reports data, we were unable to disentangle how many of the cases we measure as our outcome are "imported" (student arrivals) and how many are local transmissions from the students. Further, asymptomatic cases were only identified if testing was done on campus regardless of symptoms. Nevertheless, our results are inconsistent with large numbers of "imported" cases since an imported case would lead to an increase in COVID-19 cases contemporaneously with any increase in mobility, while we observed a one-week lag between peak mobility and the peak change in COVID-19 incidence, when cases are assigned based on symptom onset.

We did not quantify potential spillovers to the communities surrounding campuses, as these effects would require college-level incidence data, which are not consistently collected. However, using age-specific data, we were able to demonstrate that most of the increase in COVID-19 incidence arose among college-aged students (ages 10-29).

Additional work is necessary to identify the optimal reopening- closure policies (e.g., lengths) and under which circumstances specific policies are cost-effective. However, evaluating the effectiveness of specific mitigation measures taken by colleges, especially the ways in which colleges have reacted to the initial increases in cases with strong countermeasures, was beyond the scope of this initial study and remain priorities for future studies. Similarly, we were unable to test what has occurred once colleges change decisions, such as changing instructional modes temporarily or encouraging students to return home[9] since these changes were reactions to rapidly increasing case counts[29].

While we only directly demonstrate that college campuses that were more heavily exposed to COVID-19 lead to larger increases in incidence, our results also indicate that sending students home from colleges due to high COVID-19 incidence is likely to lead to increased COVID-19 incidence in students' home communities since the same exposure mechanism would run in reverse. Public health officials have also raised these concerns, some of whom have publicly opposed closing dormitories, even after a college or university transitioned to online education[30]. Further research on the effects of sending students home is needed to understand the risks and benefits of closing residence halls.

The nature of our data limits our results. Our mobility analysis relies on observing cellular GPS signals and these devices may not always report their location. In addition, it is unlikely that devices correspond in a one-to-one manner with people since college students may have more than one device (a phone and a cell-enabled tablet) that provide data under distinct identifiers. Second, we are unable to measure cases among college students vs. others in the county community, beyond using the age of the individual. Third, our mobility measure does not take account of students who may live in off-campus housing and take classes online.

Our results demonstrate the essential role that mixing and mobility play in seeding COVID-19 in the community and the role that congregate living settings play in providing a fertile ground for COVID-19 to expand. For example, these results highlight the role that nursing homes and prisons play in the COVID-19 pandemic and complement existing research on cross-nursing home linkages and COVID-19 incidence[1]. While we expect that continued testing on college campuses and current vaccination efforts will mitigate some of the effects we observed, the rate of vaccination remains low, particularly among college-age individuals[31], and the majority of colleges did not engage in high-quality testing regimes in the 2020-2021 academic year[32]. Combined with the continued emergence of new variants and rising incidence in several states[33], by the time of school start in the fall of 2021, we expect to observe similar dynamics, should no other strategies be implemented.

Our analysis is a good step towards building a framework to map mobility to contacts (as COVID-19 era contact matrices become available[34]), in the analysis of airborne infectious diseases. As such, our framework has a much wider scope than the study of COVID-19 related college policies in one specific region. Our findings are critical in the context of adapting public health management strategies, as they consider additional strategies to mitigate disease burden and decrease transmission. The effects of college reopenings are also informative for outbreak management in other communal settings, including nursing homes and prisons, both of which have been particularly hard hit by the COVID-19 pandemic.

Despite all data limitations, our study, provides (i) empirical evidence about changes in “behavior" (mobility surges) of the population during the implementation of the school-reopening strategies, (ii) a multi pronged approach to estimate mobility patterns and evaluate effects on the spread of infectious diseases with an unique degree of detail and (iii) tools for evidence-based decision-making beyond evaluating college reopening strategies.

Methods

Study Data

College characteristics

We collected data on opening dates and announced instructional methods from the College Crisis Initiative at Davidson College (C2i)[35] for 1,431 public and non-profit colleges and universities (“colleges”) in the United States. The College Crisis Initiative collects data on nearly all non-profit and public four-year degree-granting institutions with full-time undergraduates that receive Title IV aid. It excludes four-year for-profit institutions, specialty institutions like seminaries or stand-alone law schools, or institutions with graduate-only programs. This list comes from the Integrated Postsecondary Education Data System (IPEDS), which lists in total 6,527 institutions ranging from research universities to non-degree-granting institutions like local cosmetology schools. IPEDS indicates that of those, 2,009 are four-year public and non-profit degree-granting institutions with first-time, full-time undergraduates. Our sample, therefore, represents nearly 70 percent of these institutions. Further, this represents 70 percent of total undergraduate enrollment among all institutions of higher education in the United States (author calculations based on IPEDS administrative 2018 data).

We assigned college campuses to Census Block Groups (CBGs) using a college campus shapefile (geographic coordinates) prepared by the Department of Homeland Security[36]. We used a spatial join to assign each Census Block Group to the college campus that occupied the largest area in the block group, as a result, our assignment of campuses to block groups was unique. We then merged these data with college opening dates. Our final sample included 1360 schools in 786 counties. We assigned reopening strategies based on the mode of instruction reported on the date instruction began for Fall 2020. Campuses were classified as primarily in-person or primarily online based on the instructional modality in effect the day classes resumed for the Fall semester. Institutions that instituted primarily hybrid (379) or in-person (493) modes of instruction were classified as “primarily in person.” Institutions that offered only online classes, or for which the majority of the classes offered were online were classified as “primarily online” (499). We assigned instructional modalities to the 786 counties with a college in our sample based on the status of the first campus to reopen in each county and, if necessary, the largest campus of those that opened on the same day. We classified 343 counties primarily in-person, 209 as hybrid, and 234 as primarily online.

Mobility

We extracted cellular data from SafeGraph’s Social Distancing Metrics files. SafeGraph aggregates anonymized location data from numerous applications in order to provide insights about physical places, via the Placekey Community. To enhance privacy, SafeGraph excludes CBG information if fewer than five devices visited an establishment in a month from a given CBG. These data measure the number of devices that are detected each day in each CBG, from June 24th through November 9th. SafeGraph data have been used in several recent publications[37–42].

COVID-19 cases and sequelae

We used aggregate cumualtive case data at the county level from USAFacts and deidentified, case-level data from the Centers for Disease Control to estimate the incidence of COVID-19 in a county by age-group[22]. The University of North Carolina at Greensboro Institutional Review Board reviewed and approved our use of the CDC data. The CDC does not make any claims regarding the accuracy or validity of its data therefore we restricted our use of the CDC data to those counties in which the cumulative number of cases at the end of our study period was no less than 95% of the USAFacts estimate for that same county and the correlation in the rolling thirty day incidence of cases exceeded 0.95. Figure 2 in the Supplementary Information provides a map of the 1917counties that met our inclusion criteria for the CDC data. Using the CDC data we estimated the number of cases diagnosed in each county, age-group, date cell and the number of cases that were, by March 31, 2021, hospitalized, admitted to the ICU, or resulted in death. We converted these values into values per 100,000 people in a age-county cell using population data from the 5-year American Community Survey[43]. The CDC data identifies the ultimate outcome of cases by diagnosis date, so our data indicates the number of incident cases per 100,000 people and the number that resulted in death, hospitalization, or ICU admission.

In the Supplementary Information, we describe our estimation of the effective reproductive number ($R(t)$) (1.1) and how we constructed our index for college exposure to other counties (1.2).

Data availability

All data used can be requested from SafeGraph, the CDC, and the College Crisis Initiative or are publicly available at USAFacts.org.

Data availability

Code to replicate our results will be made available at github.com/andersen-hecon/Colleges_COVID_19.

Statistical Analysis

Our main analyses use a panel of counties and Census Block Groups (CBGs). In our county level analyses we identified the earliest and, if necessary, largest college or university in each county and assigned the county it's reopening modality. For our primary analyses we used a trimmed sample in which a college or university was included in the sample for the period four weeks prior to reopening and ending four weeks after reopening.

We used event-study and difference-in-difference methods to assess the relationship between college reopenings and our main outcomes: mobility to campuses, COVID-19 incidence, and COVID-19 cases resulting in a hospitalization, ICU admission, or death by March 31 2021.

Our event study assessed the changes in mobility and changes in COVID-19 cases, hospitalizations, ICU admissions, and deaths, relative to when a college has reopened, controlling for the geographic level of our analysis—either the CBG (for the mobility models) or county (for the COVID-19 models)—calendar date, and college (since a college can span more than one CBG or county).

Our regression models for the event studies, using i to denote the geographic unit (CBG or county), s the state containing that unit, c the college in that unit, and t to denote time can be written as:

$$O_{it} = \sum_{\tau=-14, \tau\neq -10}^{14} \beta_\tau 1[t - R_c = \tau] + \delta_i + \sigma_t + \chi_c + \eta_{st} + \varepsilon_{ict}$$

Where O_{it} the outcome, R_c is the reopening date for campus c, δ_i, σ_t, and χ_c are county, time, and college fixed effects, η_{st} is a set of state-by-date fixed effects to account for state-specific policies and ε_{ict} is an idiosyncratic error term. We also estimated our event study model using week indicators for the period beginning four weeks prior to reopening and ending four weeks after reopening (the third week before reopening is the omitted reference level) to smooth out daily fluctuations due to day-of-week effects and provide a longer horizon to visually detect pre-trends. For our difference-in-difference models we replaced the time relative to opening indicators with a single indicator for the post period (beginning one week before reopening to accommodate students returning to campus).

We assessed changes relative to the reopening date in all models, controlling for county (or CBG), college, and date effects. We also estimated models that included interactions with an indicator for a campus being primarily in-person, our student exposure index, and breaking up the post period into the week before the start of classes, weeks 0 and 1, and weeks 2 and 3. To incorporate variation across age groups, we also estimated age-specific event studies and difference-in-difference models.

Means and standard deviations of our dependent variables are presented in table 1 of the Supplementary Information.

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Author contributions:

M.A., A.I.B., A.B., C.M., and K.S. designed the research and wrote the paper. M.A. and A.I.B. performed the research and analyzed the data. C.M. contributed novel data.

Additional information

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