Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Socio-economic disparities in activity-travel behavior adaptation during the COVID-19 pandemic in North Carolina

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ABSTRACT

The COVID-19 pandemic significantly affected human mobility. This study examines the changes in people's activity-travel behavior over 23 months (from Jan 2020 to Nov 2021) and how these changes are associated with the socio-economic status (SES) at the block group level in North Carolina. We identified 5 pandemic stages with different restriction regimes: the pre-pandemic, lockdown, reopening stage, restriction, and complete opening stage. Using the block-group mobility data from SafeGraph, we quantify visits to 8 types of destinations during the 5 stages. We construct regression models with interaction terms between SES and stages and find that visit patterns during the pandemic vary for different types of destinations and SES areas. Specifically, we show that visits to retail stores have a slight decrease for low and medium SES areas, and visits to retail stores and restaurants and bars bounced back immediately after the lockdown for all SES areas. The results suggest that people in low SES areas continued traveling during the pandemic. Transportation planners and policymakers should carefully design the transportation system to satisfy travel needs of those residents. Furthermore, the results also highlight the importance of designing mitigation policies that recognize the immediate recovery of visits to retail locations, restaurants, and bars.

1. Introduction

The COVID-19 pandemic posed an unprecedented threat to public health, the economy, and society. National social distancing interventions to restrict human movement were widely adopted to contain the spread of the disease. In the United States, federal and local governments implemented stay-at-home orders to limit out-of-home activities and restrict non-essential travel. As the COVID-19 case numbers stabilized and decreased, many states gradually lifted policy restrictions, and travel began to bounce back (Washington Post, 2020). When the COVID-19 vaccine distribution began in December 2020, more people were expected to travel again. This study examines the changes in people's activity-travel behavior over 23 months (from Jan 2020 to Nov 2021) to improve the understanding of the impacts of the COVID-19 pandemic on activity-travel behavior.

Where did people travel during the lockdown, and how did it differ from travel before the pandemic? Were these impacts consistent for all social-economic groups (SES)? How did people's travel behavior-activity change during the reopening stage, and how did these changes differ among different social-economic groups? Answers to these questions are important for public health and planning policymakers. Understanding the impacts of the COVID-19 pandemic on the activity-travel behavior can provide useful insights for health policymakers into effectively designing public health and mitigation policies. It can also guide transportation planners and policymakers to develop more equitable, sustainable, and resilient transportation systems.

Many studies examined how the COVID-19 pandemic affects people's mobility and travel behavior and revealed significant disparities in mobility reduction among different socio-economic groups during the lockdown (De Vos, 2020; Gao et al., 2020a, Gao et al., 2020b; Huang et al., 2020; Irawan et al., 2021; Lee et al., 2020, Willberg et al., 2021; Shamshiripour et al., 2020). However, previous studies predominantly focused on mobility change, measured as the reduction in miles traveled or in home-dwelling time, at the early stage of COVID-19. Little is known about whether the reduction was consistent for all destinations and for all groups of people with different SES status. It is also unclear whether the reduction persisted through different stages of the pandemic.

In this study, we focus on trip generation to eight types of destinations during the different stages of the pandemic, including retail stores, restaurants and bars, offices, grocery stores, and recreational,

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educational, healthcare, and social assistance facilities. Specifically, we answer two research questions: (APTA, 2021) how did the pandemic affect the trip generation to eight types of destinations?? how did these impacts vary among neighborhoods with different SES? We answer these research questions by using the mobile device data from SafeGraph to derive trip generation to the eight types of destinations and then constructing linear mixed-effect models to examine the disparities in activity-travel behavior among neighborhoods with different SES at different stages of the pandemic.

2. Literature review

2.1. Mobility and socio-economic status (SES)

Measures of SES reflect people's ability and need to travel for activities. People with low SES usually have fewer modal options (e.g., Lucas, 2012) and fewer choices for both residence and employment locations to accommodate travel needs and preferences (e.g., Cao et al., 2007). Lower SES populations also tend to have lower accessibility to key destinations, such as workplaces, education institutions, healthcare facilities, and leisure places, and limited temporal flexibility (Ettema et al., 2010; Blumenberg, 2017). Consequently, people with low SES make fewer trips (e.g., Huntsinger and Rouphali, 2014), have barriers to access employment (e.g., Schleith et al., 2016), have lower healthcare visits (Syed et al., 2013; Wang et al., 2021); and are less likely to make trips for voluntary activities (e.g., Morency et al., 2011; Roorda, 2010).

Many studies used the number of trips to measure mobility and revealed the disparities among different SES groups (Giuliano, 2005; Martin et al., 2016; Banerjee, 2018). For example, Roorda, 2010 examined the trip frequency of low-income Canadians, and found they tend to make fewer trips than the average population because of their lower car ownership. Martin et al. (2016) revealed the number of personal trips increases as income increases by examining the US National Household Travel Survey 2019 data.

People with low SES are also less likely to make discretionary trips for social and recreational purposes (Lucas et al., 2016). People with low SES usually have limited travel options, giving them constrained spatial-temporal flexibility to schedule and participate in activities (Ettema et al., 2010). Furthermore, people living in neighborhoods with low SES have lower accessibility to recreation and social facilities (Moore et al., 2008; Park and Guldmann, 2020). As a result, they are less likely to make discretionary trips for recreational and social purposes.

People with access to Information and Communication Technology (ICT) could have virtual mobility and participate in activities without making trips. According to a Pew Research Center Survey of US adults, 24% of adults with household income below $30,000 reported no access to a smartphone, 43% reported no home broadband service, and 41% reported no access to a desktop or laptop computer. However, over 90% adults with household income over $100,000 reported access to each of these technologies (Vogel, 2021). The limited access to ICT of low SES people restricts their ability to make virtual activities to replace physical travel. Moreover, low SES people have fewer work-at-home opportunities and thus need to continue commuting during the pandemic. Dey et al. (2020) revealed that working at home is generally feasible in well-paid management, professional and administration jobs but not in service, transportation, construction, leisure, retail, and production jobs.

2.2. COVID-19 and travel

In response to stay-at-home orders and social distancing regulations, mobility decreased significantly in the early stage of the COVID-19 pandemic. (e.g., Huang et al., 2020; Lee et al., 2020; Echaniz et al., 2021). However, low SES groups exhibited less reduction (Huang et al., 2020; Lee et al., 2020; De Vos, 2020; Dasgupta et al., 2020; Pepe et al., 2020; McLaren, 2021). People with low income and low educational attainment tended to show less reduction in mobility because of their inability to work remotely (Dasgupta et al., 2020; Pepe et al., 2020; McLaren, 2021; Brough et al., 2020; Huang et al., 2020). Population density was positively associated with more mobility reduction because areas with higher population density tend to have more transit-dependent populations, who were also more likely to be severely affected during COVID-19 (Lee et al., 2020).

These previous studies provided significant insights on mobility changes during Covid-19, but most of them examined the change in general mobility level, such as home-dwelling time (e.g., Huang et al., 2020), travel distance traveled (e.g., Lee et al., 2020; Kim and Kwan, 2021). Fewer studies examined the trip generation to different activities at different pandemic stages. Irawan et al. (2021) examined the activity-travel behavior changes during the beginning of COVID-19 in Indonesia based on a self-administered survey. They found that many people increased their telework and e-learning and significantly reduced their out-of-home activities. They also found that higher-income earners were more likely to conduct telework and teleshopping. Shamshiripour et al. (2020) distributed a state-preference and reveal-preference survey in Chicago from April 25, 2020, to June 2, 2020, to examine people's perceptions and daily-activity travel behavior. They found an increasing number of people who used telework and on-line shopping during and even after the lockdown. Kar et al. (2021) examined the relationship between the social-economic status of travelers and frequently visited business activities in the Columbus region of Ohio. They found that low and moderate SES groups traveled mostly for long and medium-distance commuting trips. In contrast, high SES groups traveled primarily for recreational and non-work purposes with short-distance trips during the lockdown. However, these previous studies predominantly focused on the early stage of the COVID-19 pandemic (e.g., March to April 2020; March to Aug 2020). It is yet unclear whether these changes in mobility persisted through different stages of the pandemic or bounced back to pre-pandemic levels. Examining mobility change on a more comprehensive timeline would provide more insights on the impacts of COVID-19 on the activity-travel behavior.

3. Research approach and data

3.1. Study area and context

Our study area is the US state of North Carolina (NC). COVID-19 became a global pandemic in December 2019. The Governor of NC declared a state of emergency on March 10, 2020, and issued the stay-at-home orders on March 14, 2020, closing all K-12 public schools and banning gatherings of more than 100 people. Additional stay-at-home orders were signed during March to close non-essential businesses, enforce social distance measures, and prohibit gatherings of over 10 people. On May 8, 2020, the Governor started to ease certain COVID-19 restrictions, such as reopening retail businesses and childcare facilities. On May 22, 2020, NC's stay-at-home orders moved into phase 2, reopening restaurant dine-in services and allowing gatherings of up to 10 people. Entertainment facilities and bars remained closed during this phase. On September 1, 2020, NC moved to phase 2.5, reopening indoor exercise facilities and increasing mass gathering limits. On October 2, 2020, the Governor implemented phase 3 by allowing the reopening of bars, entertainment venues, and movie theaters, with capacity restrictions. Since then, most types of business re-opened with capacity limits. On Nov 23, 2020, the Governor issued COVID-19 safety measures to tighten mask requirement to control the rising COVID-19 cases in NC. On December 8, 2020, NC implemented modified stay-at-home orders, requiring people to stay at home between 10 p.m. and 5 a.m., restaurants, bars, entertainment venues, personal care businesses, and more to close at 10:00 p.m. because of a rapid increase in COVID-19 cases in NC. On Feb 25, 2021, NC lifted the modified staying-at-home orders, increasing the capacity limits of indoor facilities. The state has continually eased COVID-19 restrictions as the COVID-19 vaccine became increasingly available and the COVID-19 case numbers decreased. On

July 30, 2021, no further restrictions were imposed by executive orders. On April 6, 2021, anyone 16 years or older became eligible to get a COVID-19 vaccination. COVID-19 vaccinations were then available for those aged 5–15. At the end of the study period (Nov 15, 2021), 54% of the population in NC was fully vaccinated, and about 67% of the population received at least one dose of vaccine.

We identified five stages with different restriction regimes (severity of non-pharmacological interventions). Stage 1 is the pre-pandemic stage (from the week starting on 2020-01-06 to 2020-03-02); stage 2 is the lockdown stage (from the week starting on 2020-03-10 to 2020-05-04); stage 3 is the reopening stage (from the week starting on 2020-05-11 to 2020-12-08); stage 4 is the stage with the restrictions of modified stay-at-home orders (from the week starting on 2020-12-08 to 2021-02-25); stage 5 is the complete opening stage with some capacity restrictions (from the week starting on 2021-02-25 to 2021-11-15).

3.2. Data

We obtained data on visits to different destination types in NC from SafeGraph, a data company that tracks mobile devices' visits from their home Census Block Groups (CBGs) to 7 million points of interest (POI) across the United States and Canada via the global positioning system (GPS). It tracks devices that have opted in via navigation and social media mobile apps. SafeGraph defines each device's home CBG as the most common nighttime location over a six-week period. The proportion of population per week sampled in NC ranges from 4.5% to 8% across the pandemic. Like other mobile device data, the SafeGraph data has limited representativeness of people living in low-income neighborhoods in NC (Wang et al., 2021). However, an overall mobility trend at the county level in the US revealed by SafeGraph data is consistent with the mobility trend in Google mobility data (Chang et al., 2021).

We obtained visit information from SafeGraph's Core Places and Weekly Patterns datasets, which record the North American Industrial Classification System (NAICS) code for each POI, estimates of the number of visits and visitors to each POI, and the home CBG of each visitor. The study period is the week starting on January 6, 2020, through Nov 15, 2021.

We aggregated estimates of weekly visitors originating from each home CBG to eight types of destinations by NAICS code (Table 1). These eight types cover most travel destinations (over 90% of trips). We separated grocery stores from retail stores for a separate analysis because visit patterns to grocery stores and retail stores were different during COVID-19, and grocery store shopping is essential for human life (Chen et al., 2021).

We used several preprocessing techniques to clean the data. We removed CBGs with zero population since sampled devices in CBGs with zero population are likely to be misidentified. The number of devices in some CBGs dropped significantly across 2020 from thousands or hundreds to only a few. To address this, we only included CBGs where weekly counts of sampled devices were at least 2% of the CBG's population. The analysis results are not sensitive to the selection of the cut point (2% here). This preprocessing yielded 98 weeks (about 2 years) of data for 5211 of the 6155 North Carolina CBGs.

Table 1
Destination types and weekly trip counts in North Carolina.

NAICS code	Types	Weekly average counts of trips	Proportion of total trips
44-45 (except grocery stores 445)	Retail stores (Except Grocery Stores)	2,114,672	29.9%
7224–7225	Restaurants and bars	1,493,225	20.7%
51–54	Office	1,090,975	15.3%
71	Recreation	689,654	9.6%
61	Education	382,071	4.9%
621–623	Healthcare	365,742	5.1%
445	Grocery	355,609	5.1%
624	Social Assistance	104,695	1.4%
Total		6,596,643	92.1%

Note: the weekly average counts are an average of the number of trips per week during the study period; the proportion of trips to each type of destination is calculated for each week and then averaged to get the weekly average proportion.

Dependent Variables: The number of sampled devices decreased dramatically during the lockdown stage in 2020. Thus, we normalized the number of visitors by the number of sampled devices at the CBG and then took the average for each stage as the average number of visitors per week per device. We used the average number of visits per week per device as a proxy measure of trip generation. We measure this indicator for each type of destination (in Table 1) from each CBG.

Socioeconomic Status (SES): We used the 2018 Area Deprivation Index (ADI) developed by the University of Wisconsin School of Medicine and Public Health to measure the socioeconomics of CBGs. The 2018 ADI is a validated, factor-based neighborhood deprivation index based on 17 indicators of education, income, employment, and housing captured in the American Community Survey 2014–2018 data (Kind and Buckingham, 2018). ADI is a relative measure, which ranks CBGs within North Carolina by decile (American Public Transit Association (APTA), 2021; Banerjee, 2018; Bartik et al., 2020; Bloomberg, 2021; Blumenberg, 2017; Brough et al., 2020; Cao et al., 2007; Chang et al., 2021; Chen et al., 2021; Currie et al., 2010) with lower scores indicating most advantaged neighborhoods and higher scores indicating least advantaged neighborhoods. We further categorized state decile ADI rankings into three groups, high SES (ADI = 1–3), medium SES (ADI = 4–6), and low SES (ADI = 7–10) (see Fig. 1).

Covariates: We constructed variables of population density and employment density to measure the built environment and incorporated the percentage of white-collar workers to measure the occupation of residents at the CBG level. We used 2010 county level Rural-Urban Commuting Area (RUCA) from the US Department of Agriculture (USDA) as a measure of rurality and geographic context for the CBGs. We recategorized the RUCA codes into four groups: 1) metropolitan-core urban areas (RUCA = 1); 2) metropolitan-suburban areas (RUCA = 2,3); 3) micropolitan areas (RUCA = 4,5,6); 4) rural areas (RUCA = 7,8,9,10).

3.3. Methods

We developed a series of regression models to understand the cross-sectional SES differences and changes in activity-travel behavior. The study used linear mixed effect regression models, allowing us to capture variation across CBGs.

Level 1 (stages within a CBG):

$$y_{it} = \beta_{0i} + \beta_{1i} Stage_{it} + \varepsilon_{it}$$

Level 2 (CBG):

$$\beta_{0i} = \lambda_0 + \lambda_{01} SES_i + \lambda_{02} COV_i + \alpha_{0i}$$

$$\beta_{1i} = \lambda_1 + \lambda_{11} SES_i + \alpha_{1i}$$

where Y_{it} are the outcome variables, average number of visitors to each type of destination per week per device for CBG i at stage t. $Stage_{it}$ denotes five regulation stages: pre-pandemic, lockdown, reopening, restriction, and complete opening stage. SES_i is the categorical variable of neighborhood SES derived from the neighborhood deprivation measure (ADI). COV_i are the covariates, including % of white-collar workers, population density and job density. β_{0i} and β_{1i} are random quantities. α_{1i} and α_{0i} mean zero random variables. We incorporated the cross-level interaction terms between stage and SES to examine the differences in changes by the levels of SES.

4. Results

4.1. Descriptive analysis

To examine the association between neighborhood SES and visits to different types of destinations, we graphically examined the average number of visitors per week per device over time among three SES areas (Fig. 2).

The overall visit patterns to the eight types of destinations are similar in all three SES areas. Visits to seven types of destinations (except grocery stores) dropped at the start of the pandemic, started to recover when business was reopened, continued to increase, declined slightly when modified stay-at-home orders were implemented during the restriction stage, but bounced back to the pre-pandemic level when business was completely reopened. The visits to grocery stores increased slightly at the start of the pandemic, dropped afterward during the reopening stage, and started to recover during the complete opening stage.

The magnitude of changes in visits and the recovery patterns differ among the eight types of destinations during the pandemic. Specifically, visits to retail stores, restaurants, and bars decreased by 50% during the lockdown but bounced back immediately at the start of the reopening stage and recovered or even exceeded the pre-pandemic level during the complete opening stage. The visits to restaurants and bars did not decline during the restriction stage. The change in the visits to grocery stores was very small; the visits increased slightly during the lockdown, immediately dropped slightly, then bounced back, and exceeded the pre-pandemic level during the complete opening stage. Visits to healthcare, recreational facilities, and offices decreased by 50%, bounced back a little during the reopening stage. However, visits to offices recovered to the pre-pandemic level during the complete opening stage. In contrast, visits to healthcare and recreational facilities remained lower than the pre-pandemic level. Visits to social assistance, and educational facilities decreased significantly during the lockdown (~80%), had very small recovery during the reopening and restriction stage as most social and educational facilities remained partially opened, and did not recover to the pre-pandemic level during the complete reopening stage. Additionally, visits to social assistance and education facilities have striking seasonality.

Before the pandemic, people living in areas with high SES had a higher number of visits to all destinations (except retail stores). During the lockdown, when the statewide stay-at-home orders were enforced, travel decreased more for people in high SES areas, consistent with previous studies (e.g., Huang et al., 2020; Lee et al., 2020). Specifically, travel to all seven types of destinations (except grocery stores) decreased more for people in high SES areas. People in high SES areas experienced more decline while people in low and medium SES areas continued/maintained a higher number of trips to retail stores during the lockdown. Travel to grocery stores increased less for people in high SES areas than it did for people in low SES.

During the reopening stage, travel to retail stores and offices for people in low and medium SES areas almost bounced back to the pre-pandemic level. The differences in travel to healthcare facilities, recreational destinations, restaurants, and bars among people in CBGs with different SES status increased compared to the lockdown stage. Travel to those locations by people in high SES areas increased more than travel by people in low SES areas. The visits to grocery stores during the reopening stage declined for all three SES areas.

During the complete opening stage, all SES areas exhibited almost similar recovery patterns. Visits to retail stores, offices, restaurants, and bars, grocery stores rebounded during this stage. Visits to healthcare, education and social assistance facilities were still lower than pre-pandemic levels. The disparities in the visits to grocery stores among SES areas switched during the complete opening stage compared to the pre-pandemic stage; compared to people in high SES areas, people in lower and medium SES areas now have higher grocery visits than people in high SES areas.

4.2. Modeling results

The coefficients on the SES characteristics of neighborhoods (see Table 2) generally indicate a negative association between social-economic disadvantage and travel (except the travel to retail stores), which is consistent with previous studies (e.g., Currie et al., 2010; Lucas, 2012).

Travel to all types of destinations (except grocery stores) decreased during the lockdown compared to the pre-pandemic stage. During the reopening stage, visits to these types of destinations (except retail stores and grocery stores) started to increase but did not recover to pre-pandemic levels. During the restriction stage, no decline was observed for all destinations compared to the reopening stage. During the complete opening stage after February 2021, the visits to offices, retail stores, restaurants, and bars, and recreational facilities bounced back while the visits to healthcare, education, and social assistance were still below the pre-pandemic level.

Travel patterns to grocery stores during the study period were different from the other types of destinations. We observed a very slight change in average visits (0.02–0.03) per week per device to grocery

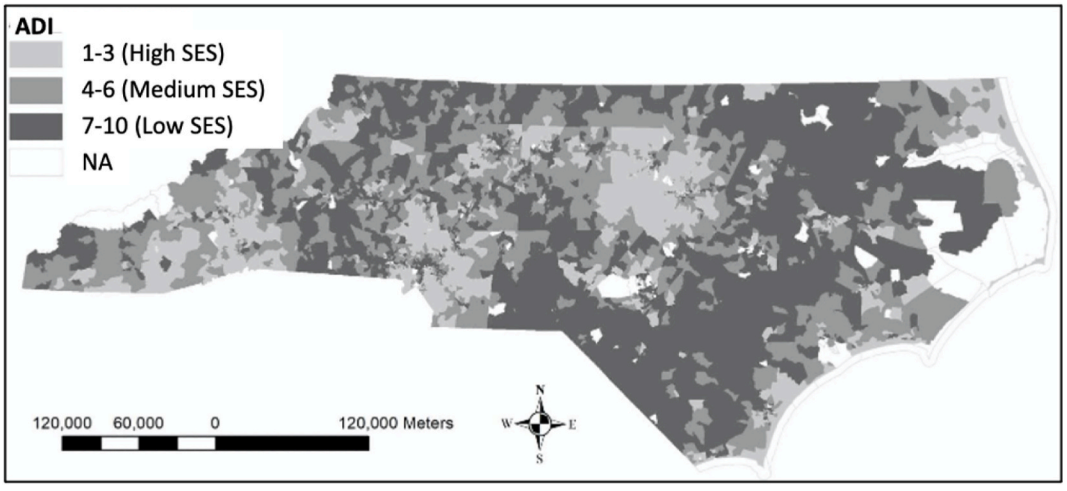

Fig. 1. Spatial distribution of the ADI in North Carolina
Note:NA represents that the index is not available because of low population, a high group quarter population, or missing variables for constructing the index.

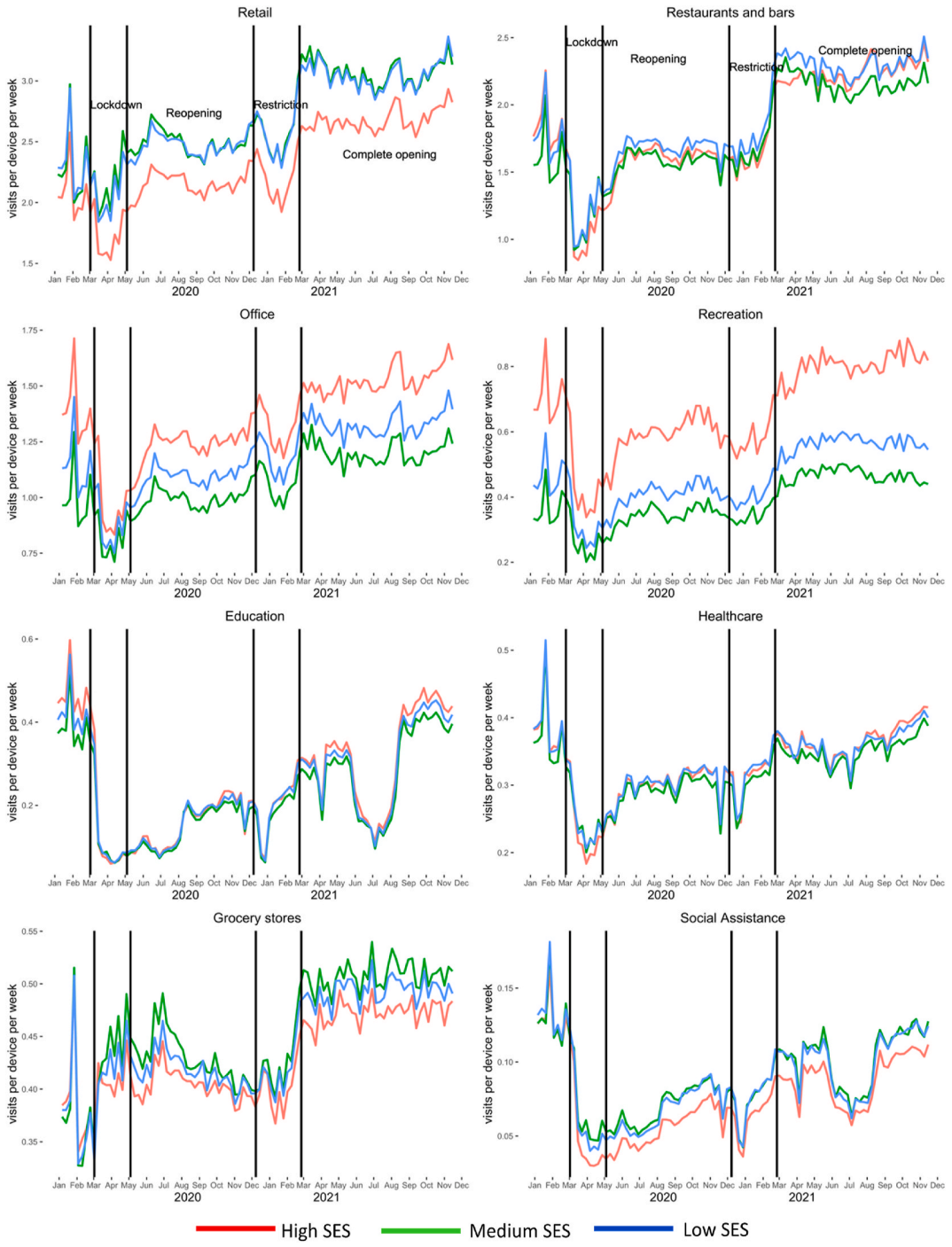

Fig. 2. Visits per week per device to eight types of destinations.

stores during the study period. During the complete opening stage, visits to grocery stores exceeded pre-pandemic levels by 0.09.

The positive coefficients on the interaction terms between the SES and the pandemic stages are statistically significant, suggesting the impacts of the COVID-19 restrictions on visit patterns to all destinations were moderated by the SES of CBGs. To better interpret interaction terms, we plotted the predicted visits per week per device for CBGs with different SES status (Fig. 3). The results are consistent with descriptive results. More reductions in the number of visitors per device per week to education, health, social assistance and recreation facilities, restaurants and bars were observed for CBGs with high SES status during the lockdown stage, and thus disparities among SES groups decreased. Visits to offices did not decrease much for people in low SES CBGs while visits to offices decreased by over 30% for people in CBGs with high SES during lockdown. Visits to retail stores were stable for low and medium SES CBGs during the lockdown compared to the pre-pandemic stage, and people in CBGs with high SES decreased their visits to retail stores by 15% during the lockdown. SES areas had similar visit frequency to grocery stores during lockdown, decreasing the disparities observed during the pre-pandemic period.

During the reopening stage, the recovery of visits to healthcare, social assistance facilities and education was very slight. However, the recovery for people in high SES areas was more rapid. Visits to retail stores for people in high SES areas recovered back to the pre-pandemic

Table 2
Model estimation results of visits per week per device to eight types of destinations.

	Retail stores		Restaurants and bars		Office		Recreation		Education		Healthcare		Grocery stores		Social assistance	
	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.	Coef.	Sig.
Stage (ref.=pre pandemic)																
Lockdown	−0.37	***	−0.75	***	−0.41	***	−0.28	***	−0.34	***	−0.16	***	0.03	***	−0.09	***
Reopening	0.07	***	−0.24	***	−0.12	***	−0.11	***	−0.29	***	−0.09	***	0.02	***	−0.07	***
Restriction	0.12	***	−0.18	***	−0.05	***	−0.13	***	−0.25	***	−0.07	***	0.02	***	−0.06	***
Complete opening	0.59	***	0.39	***	0.15	***	0.10	***	−0.13	***	−0.02	***	0.09	***	−0.04	***
SES (ref.=High SES)																
Medium SES	0.08	***	−0.07	***	−0.14	***	−0.17	***	−0.03	***	−0.00		−0.03	***	−0.00	
Low SES	−0.02		−0.23	***	−0.21	***	−0.23	***	−0.06	***	−0.01	**	−0.03	***	−0.005	**
Phase*SES																
Lockdown*Medium SES	0.14	***	0.18	***	0.15	***	0.12	***	0.03	***	0.01	***	0.02	***	0.01	***
Lockdown*Low SES	0.25	***	0.33	***	0.24	***	0.17	***	0.06	***	0.03	***	0.04	***	0.02	***
Reopening*Medium SES	0.11	***	0.14	***	0.10	***	0.06	***	0.03	***	0.003		0.02	***	0.01	***
Reopening*Low SES	0.16	***	0.23	***	0.14	***	0.09	***	0.05	***	0.007	**	0.03	***	0.01	***
Restriction*Medium SES	0.15	***	0.18	***	0.11	***	0.07	***	0.03	***	0.005		0.02	***	0.01	***
Restriction *Low SES	0.19	***	0.27	***	0.14	***	0.10	***	0.04	***	0.003		0.03	***	0.01	***
Complete opening*Medium SES	0.19	***	0.15	***	0.06	***	−0.00		0.02	***	0.002		0.03	***	0.01	***
Complete opening*Low SES	0.21	***	0.17	***	0.07	***	−0.00		0.03	***	0.000		0.04	***	0.01	***
% White-collar workers	−0.004	***	0.00		0.003	***	0.003	***	0.001	***	0.0002	*	−0.00		−0.00	***
Spatial Locations (ref.=Metropolitan-core urban)																
Metropolitan-suburban	0.15	***	0.06	**	−0.05	**	−0.06	***	0.02	***	−0.02		0.02	**	0.001	
Micropolitan	0.06	***	0.01		−0.17	***	−0.06	***	0.04	***	−0.01	**	0.04	***	0.002	
Rural/Small towns	−0.10	***	−0.19	***	−0.23	***	−0.09	***	0.04	***	−0.03	***	0.001		0.003	
Population density (ln)	−0.03	***	−0.001		0.04	***	0.03	***	−0.003		−0.01	***	−0.01	***	0.001	*
Job density(ln)	−0.08	***	−0.05	***	−0.03	***	0.001		−0.01	***	−0.01	***	−0.004	*	−0.002	***
Constant	2.99	***	2.05	***	1.02	***	0.31	***	0.46	***	0.46	***	0.49	***	0.15	***
Random effect																
CBG level variance	0.21	***	0.13	***	0.10	***	0.018	***	0.005	***	0.007	***	0.01	***	0.001	***
Error term	0.07	***	0.05	***	0.02	***	0.005	***	0.004	***	0.003	***	0.004	***	0.001	***
Intra class correlation	0.76		0.74		0.86		0.77		0.56		0.69		0.77		0.57	
NT (Sample Size)	25,840															
N (Number of CBG)	5168															
T (Number of Stages)	5															

Note: ***p < .001; **p < .01; *p < .05.

level. Visits to offices, restaurants and bars, and recreational facilities for people in high SES areas also recovered more than people in low and medium SES.

During the restriction stage with the modified stay-at-home orders, we did not see any decline for all types of destinations (except grocery shopping). The changes in visits compared to the reopening stage were not statistically significant.

During the complete opening stage, we see a more rapid and larger increase in visits to offices, recreational facilities, educational facilities, restaurants, and bars for people living in high SES areas. We also see reverse disparities in visits to grocery stores among SES compared to the pre-pandemic stage; people in low SES had high numbers of visits.

The visits to the eight types of destinations also varied by spatial locations. The disparities in visits to retail stores and restaurants and bars across four types of spatial locations were more striking. Compared to people in core urban areas, people in suburban areas had higher numbers of visits to those destinations.

After controlling the spatial locations, the population and job density still exhibit statistically significant associations with the visits to eight types of destinations. Population density has positive associations with visit rates to recreational and social assistance facilities but negative associations with the visits to other six types of destinations. People living in CBGs with higher employment density had a low visit frequency to all types of destinations (except recreation facilities). Besides, CBGs with a higher percentage of white-collar workers is positively associated with lower visits to retail stores and social assistance facilities but higher visits to offices, restaurants and bars and recreation, education, and healthcare facilities.

5. Discussion

Our study aimed to 1) examine the changes in people's visit patterns to eight types of destinations from Jan 2020 to Nov 2021 during the COVID-19 pandemic in NC, and 2) investigate how these changes vary with CBGs of different SES characteristics.

We found that people's visit patterns changed significantly during the lockdown. However, these changes vary for different destinations and different SES areas. Specifically, visits to all types of destinations except grocery stores experienced a reduction. Visits to grocery stores did not decrease during the study period because people need to go grocery shopping to maintain essential living. However, we also observed that disparities in grocery store visits among SES areas switched after the lockdown. This may be due to the growing popularity of and adoption of e-grocery shopping by people in high SES areas.

People in CBGs with low and medium SES status did not decrease their visits to retail destinations, which resonates with the hypothesis that low and moderate SES groups worked in retail occupations and needed to travel to jobs and income. The reduction in office visits for low SES groups was smaller compared to high SES groups, which may possibly be because of their inability to work remotely (Dasgupta et al., 2020; Pepe et al., 2020; McLaren, 2021; Brough et al., 2020; Huang et al., 2020.).

It is also interesting to note that visits to retail stores, restaurants, and bars recovered immediately after the lockdown for all SES areas. The findings suggest that mobility restrictions may be effective only for a short time for travel to retail stores, restaurants, and bars and restrictions become ineffective when re-opening starts. Furthermore, we did not see any statistically significant decline during the restriction stage while NC was attempting to implement modified stay-at-home

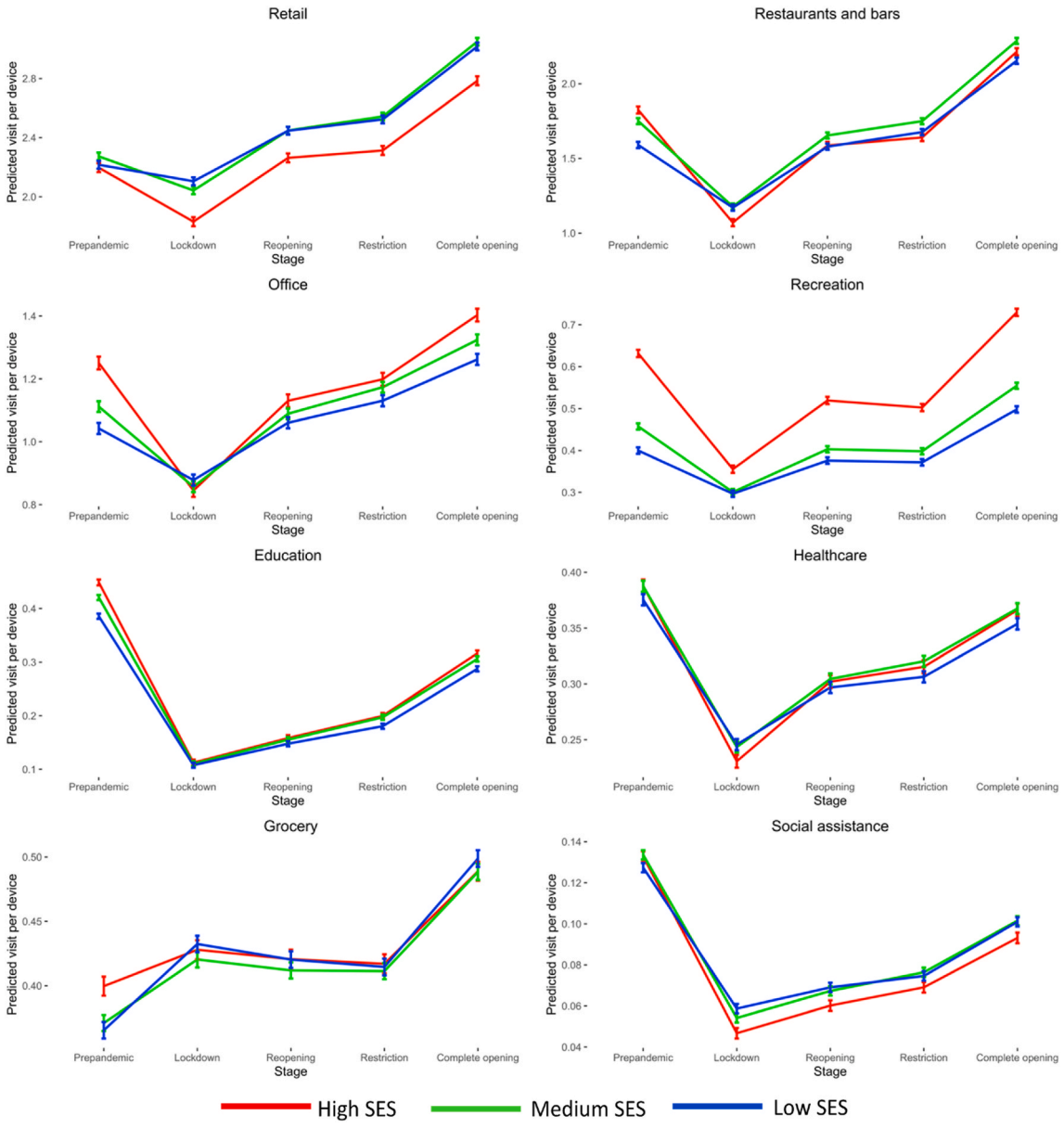

Fig. 3. Predicted visits per week per device

Note: Predicted visits per week per device are based on the modeling results in Table 2. When estimating the predicted visit per week per device, we assume that CBGs are in a metropolitan area with over 1 million population, and that the percent of white-collar workers, population, and employment density (natural log) are at the sample means.

orders to control the rising COVID-19 cases. It may suggest that people were no longer responsive to mobility restrictions.

Our study makes an important contribution to the literature on the impact of the COVID-19 pandemic on people's mobility patterns and travel behaviors. It is among the few to examine activity-travel behavior using longitudinal data. Distinct from other studies, our study examines the change in visits to different types of destinations across 23 months and different pandemic stages, allowing us to examine changes in mobility beyond the early stage of COVID-19.

This study has several limitations that should be addressed in future studies. First, we used mobile device data, which often under-represents low-income people with limited access to smartphones (Kishore et al., 2020). 24% of US adults with household income below $30,000 reported no access to a smartphone (Vogel, 2021). This may suggest that SafeGraph data does not accurately record visits by low-income people. Second, we could not differentiate trips between employees' trips and consumers' trips. Future studies to use other types of data, such as survey data would complement the results of this study. Third, we examined the activity-travel behavior at the CBG level without individual information. The findings could only apply to places, not people. We do not know the SES status of the person who conducts the trips. Future studies to use individual-level detailed mobility data could offer more insight on activity-travel behavior changes over time during the pandemic. Finally, we focused on disparities in the overall visit patterns by SES during the pandemic years but did not take into account the seasonality of visits, especially the visits to education, recreation, and social assistance facilities, which should be addressed by future studies.

6. Conclusion and policy implications

Analysis of the changes in activity-travel behavior during the pandemic and their associations with socio-economic status at the CBG level reveals four key findings. The findings may be useful for health policymakers seeking to control the spread of COVID-19 and for

transportation planning policymakers designing a sustainable and equitable transportation system.

CBGs with low and medium SES maintained high visits to retail establishments and offices during the lockdown. It may be because they are essential workers who are required to be present at their workplace. Low SES people are also more likely to use public transit (e.g., Giuliano, 2005;Federal Highway Administration, 2019), and public transit service was significantly disrupted during the pandemic (e.g., APTA, 2021). Therefore, transportation policymakers should facilitate safe and convenient public transit travel for those living in low SES areas. Specifically, transit agents may carefully identify the working destinations for CBGs with low SES status and maintain the operation of transit service for those residents to retail and office destinations during the pandemic.

Visits to restaurants and bars and retail stores bounced back immediately during the reopening stage despite the severe COVID-19 situation. The findings suggest that these types of destinations kept attracting high visit flow during the pandemic. To better prepare for future pandemics, public health policymakers should recognize the immediate recovery of the visits to these destinations and carefully design and implement public health policy and measures in these destinations to mitigate the spread of the virus.

Visits to all types of destinations did not drop during the restriction stage with modified stay-at-home orders compared to the re-opening stage. While initial lockdown orders greatly decreased travel, the modified stay-at-home order in effect on Dec 8, 2020, had no impact on mobility. This suggests that constraining travel for long periods of time is unlikely to work without strong governmental enforcement.

Visits to grocery stores varied less during the pandemic, yet low SES groups have a high number of visits to grocery stores. People visit grocery stores to obtain essentials for living. The study results indicate that a significant proportion of people need to conduct in-person grocery visits during the pandemic. Although e-shopping is becoming a new normal to replace in-person shopping, it is more popular for people in high SES areas to complement in-person shopping instead of substituting for it. Public health policymakers should recognize the importance of grocery stores when attempting to mitigate virus spread and they should design corresponding measures to protect grocery store consumers and workers.

CRediT authorship contribution statement

Jueyu Wang: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Nikhil Kaza:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Noreen C. McDonald:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Kshitiz Khanal:** Conceptualization, Writing – review & editing.

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