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Original Research

Neighbourhood influence on the fourth dose of diphtheria-tetanus-pertussis vaccination

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ABSTRACT

Objectives: Using 542,159 vaccination records from children born between April 1, 2007, and March 31, 2012, in the Michigan Care Improvement Registry and data from the American Community Survey, we determine if neighbourhood-level characteristics at the Census tract level and block level are associated with low uptake of the fourth dose of diphtheria–tetanus–acellular pertussis vaccine (DTaP4).

Study design: This study was a cross-sectional study.

Methods: We used exploratory factor analysis to determine important socio-economic factors at the Census block level and tract level. We then used generalised estimating equations to test the relationship between block- and tract-level socio-economic factors and DTaP4 uptake.

Results: DTaP4 coverage was 88.6% (95% confidence interval [CI]: 88.4%–88.7%) in Michigan. At the Census tract level, two factors surfaced as important for DTaP4 vaccination: ‘affluence’ (Cronbach's alpha = 0.88) and ‘socio-economic disadvantage’ (Cronbach's alpha = 0.89). At the Census block level, one factor was important: ‘affluence’ (Cronbach's alpha = 0.90). Affluence may relate to knowledge about medical exemptions and anti-vaccination sentiment, while socio-economic disadvantage may indicate limited access to healthcare resources. Children in high-affluence tracts had 1.08% lower vaccination coverage (95% CI: −1.62% to −0.55%) than children in low affluence tracts. Children in low socio-economic disadvantage tracts had 2.92% higher coverage than children in high socio-economic disadvantage tracts (95% CI: 2.58%–3.26%).

Conclusions: This study articulates the need to further understand the contribution of neighbourhood-level characteristics, from both affluent and socioeconomically

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disadvantaged areas to low vaccination rates. Developing a better understanding of these social environmental factors will help determine useful community-level interventions to improve vaccination rates and reduce disease burden.

Introduction

Although the U.S. vaccination program has successfully decreased incidence of a number of infectious diseases,[1] the number of reported pertussis cases has steadily risen since the 1980s.[2–4] By 2012, the U.S. reported its highest number of pertussis cases since 1955.[3] In 2014, 19 states, including Michigan, experienced an increase in the number of pertussis cases from the year prior,[4] likely attributable to an imperfect pertussis vaccine[5] and low vaccination coverage.[6] Low coverage could result from barriers to accessing vaccination services or from parents choosing not to vaccinate either due to personal preferences or contraindications (e.g., severe allergic reaction following prior dose).[7] Although pertussis vaccination is mandatory for grade school entry in Michigan, 4.2% of kindergarteners in 2017 had waived one or more of the mandated vaccines, and, of those with a waiver, only 5.0% had a medical waiver.[8] Compared to other states, Michigan has a relatively high proportion of children with non-medical vaccine exemptions,[9] and it allows for medical, religious or philosophical exemptions.[10]

Within Michigan, immunisation coverage varies regionally, and some of the lowest immunisation levels are found in Detroit. Data from the Michigan Care Improvement Registry (MCIR), the state's immunisation information system (IIS), show that in June 2018, only 60.6% of children aged 19–35 months in Detroit had completed the 4:3:1:3:3:1:4 series of diphtheria–tetanus–acellular pertussis (DTaP), polio, measles–mumps–rubella, *Haemophilus-influenzae* type b, hepatitis B, varicella and pneumococcal conjugate vaccines compared with 74.2% in the entire state.[11,12] Furthermore, the coverage of fourth dose DTaP (DTaP4) in Michigan is relatively low compared to other vaccinations in the state.[13] The paediatric DTaP schedule includes three vaccines in a primary series at 2, 4 and 6 months. The fourth dose can be given as early as 12 months but typically is administered between 15 and 18 months.[14]

A limited number of previous studies have found links between vaccination and various community characteristics, such as education level,[15] economic status,[16] political preferences,[17] and demographic composition.[18] Additionally, although research in social epidemiology has focused on psychosocial risk factors as upstream contributors to poor health outcomes,[19,20] including social support, chronic stress and neighbourhood decline,[21] it has seldom considered both socio-economic disadvantage and affluence simultaneously (Table 1),[22] particularly for infectious diseases.[23,24] Within Detroit, investigators have shown geographic and racial patterning of breast cancer[25] and infant mortality,[26] but not the impact of neighbourhood-level socio-economic characteristics on vaccination levels.[27] Michigan encompasses diverse racial and socio-economic environments, with highly segregated and densely populated urban centres, wealthy suburbs and vast expanses of rural areas, thus serving as a critical location to study the relationship between neighbourhood characteristics and vaccination uptake. In this study, we sought to determine the relationship between neighbourhood socio-economic environment and DTaP4 coverage.

Methods

Data sources

In Michigan, vaccine providers have a legal mandate to report all records of vaccine administration for persons aged <20 years. Started in 1998, MCIR is an electronic database that is automatically populated with birth records, unless the child has been opted-out. If a child receives a vaccine out of state, providers can input previous vaccination records into the system. Since 2000, a Web-based portal has existed to submit such records, allowing MCIR to interface with electronic health records at various healthcare facilities. We extracted records of children aged 2–7 years at the time of the creation of the dataset (i.e., born between April 1, 2007, and March 31, 2012) and created a binary indicator of whether they received a fourth dose of DTaP, regardless of when it was administered.

Residential addresses from responsible parties in MCIR were geocoded and matched to Census block and tract identification codes using SAS (version 9.4, Cary, NC). Without individual-level information on socio-economic status, we use Census block data, the smallest tabulation unit used by the United States Census Bureau, as a proxy for an individual's household characteristics. We use Census tract data, a ‘relatively permanent’ area roughly equivalent to a neighbourhood, as a proxy for an individual's neighbourhood characteristics.[28] Socio-economic attributes of Census blocks and tracts were obtained from 5-year estimates (2008–2012) of the American Community Survey (ACS). At the block level, we included the following attributes: education level, income category, professional or management occupation, age, unemployed and child living with parent. At the tract level, we included the following attributes: education level, income category, professional or management occupation, age, unemployed, child living with parent, on food stamps/Supplementary Nutrition Assistance Program (SNAP), with no vehicle, living below poverty, children aged <6 years who are on public insurance and race.

Table 1 – Key terms and definitions.

Terms	Definitions
Census block	The smallest tabulation unit used by the United States Census Bureau as a proxy for an individual's household characteristics
Census tract	A 'relatively permanent' area roughly equivalent to a neighbourhood as a proxy for an individual's neighbourhood characteristics
Socio-economic disadvantage	A multidimensional concept encompassing poverty, social class, social marginalization, negative social segregation and institutional discrimination
Affluence	A multidimensional concept referring to high levels of education, income and wealth, along with a greater concentration of white individuals

Derived variables

Summary block- and tract-level measures were created using exploratory factor analysis (EFA), a statistical method used to identify the underlying relationship between observed variables through the identification of latent factors. We extracted factors from the Census indicators with a PROMAX rotation through an iterated principal factor analysis and by setting the prior communality estimate for each variable to its squared multiple correlation with all other variables.[29] Separate EFAs were conducted at the block and tract levels. Observed variables with factor loadings above 0.70, a numeric value that represents the relationship of each observed variable to a latent factor, were retained as indicators of the underlying socio-economic environment. Factor scores, the continuous summary measure of the underlying socio-economic environment, were generated for each individual in the dataset. Each factor generated by an EFA indicates a different underlying or latent construct of the observed variables. We finally assessed the internal reliability of the factors with Cronbach's alpha.

Statistical analysis

To test the relationship between block- and tract-level factors and DTaP4 coverage, we constructed a model using generalised estimating equations (GEE) with an exchangeable correlation matrix at the block level and with a binomial distribution and identity link. The model provided absolute differences in vaccination uptake and 95% confidence intervals (CI) while controlling for the nested structure of the data. We first specified a model with the derived socio-economic environmental factors as main effects and then tested interactions between the block-level and tract-level factors in order to examine differences in effects across levels of spatial scale (i.e., could block-level factors modify access to health resources in tracts). To facilitate interpretation of the results, we categorised the socio-economic environmental factors (tract affluence and disadvantage) as either 'low' or 'high' based on −1 and +1 standard deviations from the mean factor value, respectively.

Results

A total of 542,159 children aged 2–7 years of age were included from the MCIR in the dataset. Some children did not have addresses on record and could not be geocoded. This was not differential by vaccine status. In total, 517,639 children residing in 7249 Census blocks and 2565 Census tracts were included in the analysis. The overall DTaP4 vaccination rate among children from 2007 to 2012 in Michigan was 88.8%, with the predominance of low vaccination occurring in Southeastern Michigan (Fig. 1).

The factor analysis yielded evidence of two factors at the tract level, representing an individual's tract socio-economic environment: 'affluence' (Cronbach's alpha = 0.88) and 'socio-economic disadvantage' (Cronbach's alpha = 0.89). 'Affluence' was composed of three attributes: proportion of adults with a college degree (loading of 0.90042), proportion with an income >$100,000 (loading of 0.83228) and proportion of adults with a professional or management occupation (loading of 0.80581). 'Socio-economic disadvantage' comprised five tract-level attributes: proportion of the population on food stamps/SNAP (loading of 0.90135), proportion with no vehicle (loading of 0.83672), proportion below poverty (loading of 0.80171), proportion of children aged <6 years on public insurance (loading of 0.72055) and proportion who are not white (loading of 0.67500).

Only one factor was apparent at the block level, representing the socio-economic environment: 'affluence' (Cronbach's alpha = 0.90). The 'affluence' block factor was composed of the same items as the equivalent tract-level factor: proportion of adults with a professional or management occupation (loading of 0.89348), proportion with a college degree (loading of 0.88068) and proportion with an income >$100,000 (loading of 0.81167). In tracts of high affluence (tract level), 31.3% of adults have incomes >$100,000, while 6.6% of adults have incomes >$100,000 in tracts of low affluence (Table 2). Thirteen percent of the population are below poverty in neighbourhoods of low socio-economic disadvantage (tract level), while 40.1% of the population are below poverty in tracts of high socio-economic disadvantage (Table 2). Additionally, tracts of high socio-economic disadvantage (tract level) had 69.3% of children aged <6 years on public insurance compared to 19.9% in tracts of low socio-economic disadvantage (Table 2). In the state of Michigan, the density of affluent tract environments is greater in the outskirts of Detroit, while socioeconomically disadvantaged tracts are more dense within Detroit (Fig. 2).

Results of the GEE models demonstrated that with all reference groups at 0 (i.e., having average values of block affluence, tract affluence and tract socio-economic disadvantage), coverage of DTaP4 in Michigan is 88.56% (95% CI: 88.43%–88.69%; Model 1, Table 3). Children living in more affluent blocks have higher uptake of vaccine (0.29% increase for each unit increase in the block affluence factor score).

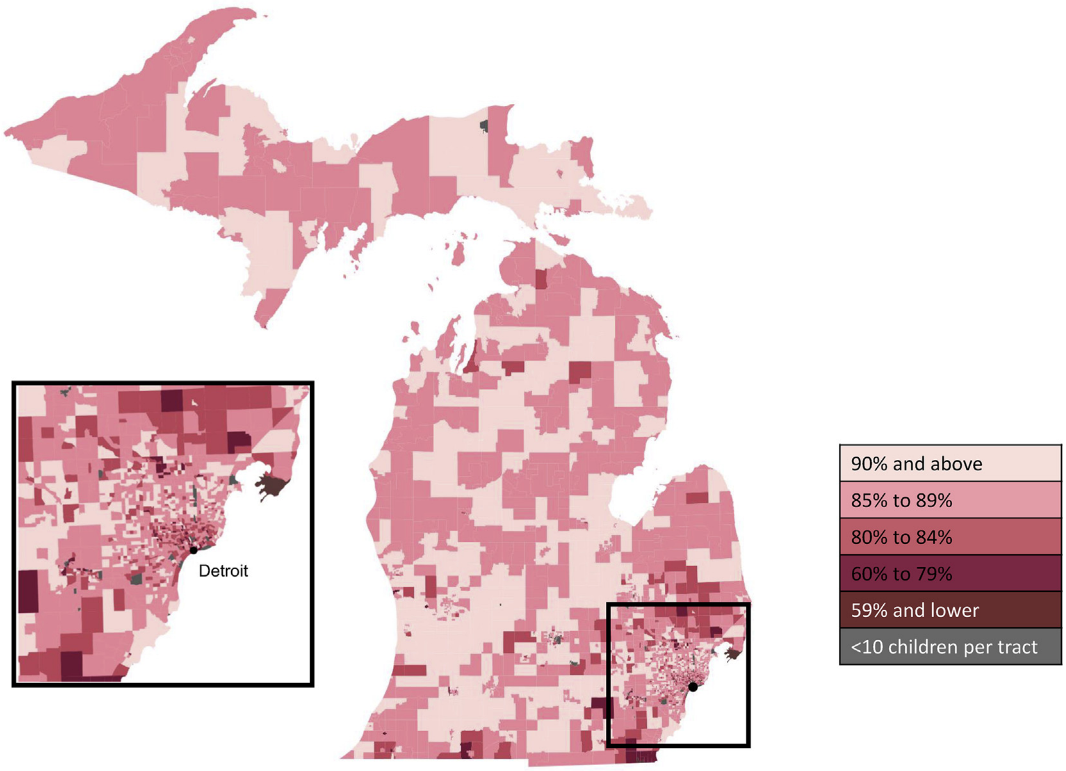

Fig. 1 – Fourth-dose diphtheria–tetanus–acellular pertussis vaccine coverage by Census tract in Michigan.

Conversely, children in tracts with higher affluence and tracts with higher socio-economic disadvantage have lower uptake of vaccine (0.54% and 1.46% lower, respectively; Model 1, Table 3).

Table 2 – Economic and demographic characteristics of Census block- and tract-level factors.

Neighbourhood characteristics (%)		
Block level	**Low block affluence**	**High block affluence**
College graduate	2.3	16.2
Greater than $100K income	6.1	32.7
Management position occupation	16.7	47.7
Tract level	**Low tract affluence**	**High tract affluence**
College graduate	3.0	16.5
Greater than $100K income	6.6	31.3
Management position occupation	20.9	44.2
Tract level	**Low tract SES disadvantage**	**High tract SES disadvantage**
Food stamps/SNAP	7.5	50.2
Without a car	2.6	13.9
Below poverty	13.0	40.1
Non-white	9.9	44.9
Children aged <6 years on public insurance	19.9	69.

SES, socio-economic status.
'Low' refers to neighbourhoods with factor values −1.5 to −0.5 from mean; and 'high' refers to a factor value 0.5 to 1.5 above the mean.

Model 2 (Table 3) tests the interaction between block affluence and tract socio-economic environment (both affluence and socio-economic disadvantage); both interaction terms were statistically significant. Without accounting for cross-level interactions, children in high-affluence tracts had 1.08% lower vaccination coverage (95% CI: −1.62% to −0.55%) than children in low-affluence tracts. In low-affluence tracts, children living in high-affluence blocks had 0.80% higher DTaP4 coverage (95% CI: 0.22%–1.37%). However, the protective effect of living in a high-affluence block is completely attenuated when the block is situated within a high-affluence tract (Fig. 3).

Without accounting for cross-level interactions, children living in less disadvantaged tracts had 2.92% higher coverage than children in tracts of high socio-economic disadvantage (95% CI: 2.58%–3.26%). This effect is even more pronounced for residents of high–affluent blocks living within low socio-economically disadvantaged tracts. Conversely, the protective effect of living in a high–affluence block is attenuated to non-significance when it is situated within a highly disadvantaged tract (Fig. 4).

Discussion

The recent spike in the number of pertussis cases in the United States has been unprecedented in nearly half a century. Using tract as a measure of neighbourhood and block as a proxy for the individual, our analysis suggests tract socio-economic disadvantage and tract affluence are separate social constructs that adversely affect vaccination uptake of

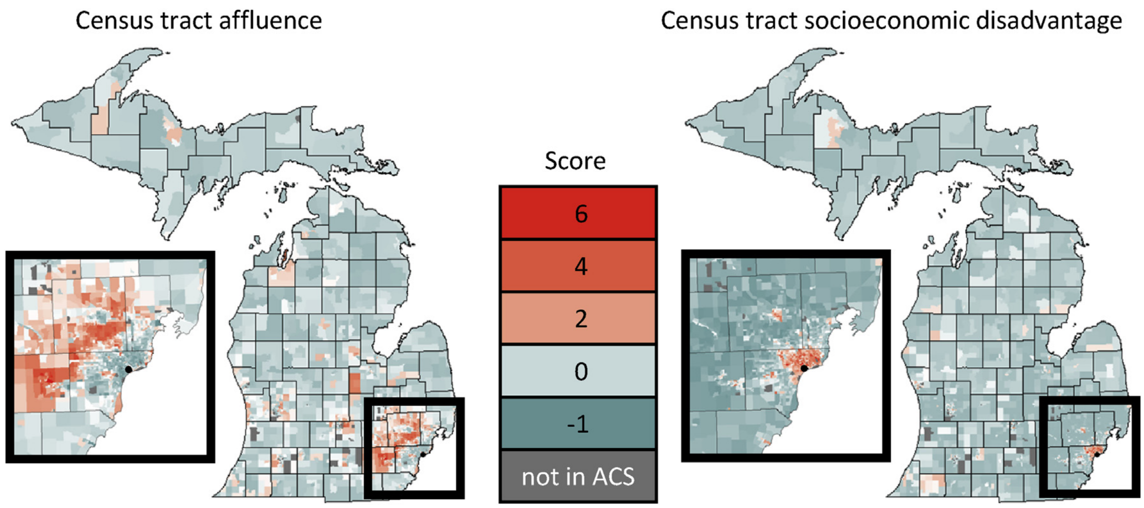

Fig. 2 – Census tract affluence score and socio-economic disadvantage score by Census tract in Michigan.

DTaP4. Our analysis also suggests that the tract social environment modifies individual vaccination behaviour in blocks of the same affluence. Targeted interventions for both types of tract populations could prevent childhood disease and increase coverage of DTaP4 and possibly other vaccines. Often studies only investigate neighbourhood poverty or disadvantage and not affluence as a determinant of health, which limits inference at the neighbourhood level.[22,30] Our analysis demonstrates these two social constructs are indeed independent within the neighbourhood socio-economic environment and should be considered separately by health professionals when determining targeted neighbourhood-level interventions for vaccinations.

Neighbourhood socio-economic disadvantage

Socio-economic disadvantage has been defined as a multidimensional concept encompassing poverty, social class, social marginalisation, negative social segregation and institutional discrimination.[31] The disadvantaged are likely faced with a zero-sum game in daily decision-making; factors such as lack of sick leave and inflexible work schedule (for those with employment) or a lack of reliable transport can impact decisions to take a child to clinic to get vaccinated. A caregiver's decision-making process and trust, in fact, are critical to understand for the improvement of healthcare-seeking behaviour.[32] Although the Vaccines for Children program covers the cost of vaccine for certain groups and Medicaid can reimburse administration fees, certain disadvantaged groups still face high barriers in accessing healthcare resources.[33,34] As such, working to help the disadvantaged requires the application of an equity lens to child health and acknowledging areas of low public health infrastructure.[35] There needs to be a greater investment in services in such areas. Moreover, the limited time and access to health care in this population underscores the need for healthcare providers to assess immunisation status at every visit and to limit missed opportunities for vaccination. Although reasons for non-vaccination for the affluent and socio-economically disadvantaged are quite dissimilar, communicating positive health behaviour effectively is critical for both populations. This study outlines that the health disadvantages of inequality are not confined to the poor.[36,37]

Table 3 – Differences in vaccination uptake by neighbourhood factors in Michigan, according to a generalised estimating equations model with a binomial distribution and identity link.

Parameter	Risk difference models (%) Estimate	95% LL	95% UL	P
Model 1 (no interaction term)				
Intercept	88.56	88.43	88.69	<0.0001
Block affluence	0.29	0.04	0.54	0.0241
Tract affluence	−0.54	−0.81	−0.27	<0.0001
Tract disadvantage	−1.46	−1.63	−1.29	<0.0001
Model 2 (interaction term)				
Intercept	88.43	88.26	88.60	<0.0001
Block affluence	0.22	−0.03	0.48	0.0836
Tract affluence	−0.54	−0.86	−0.23	0.0006
Tract disadvantage	−1.74	−1.97	−1.50	<0.0001
Block affluence × tract affluence	−0.17	−0.29	−0.06	0.0028
Block affluence × tract disadvantage	−0.55	−0.77	−0.32	<0.0001

LL, lower limit; UL, upper limit.

Neighbourhood affluence

Although concentrated poverty has been noted to contribute to health-compromising attitudes and behaviours,[38] few studies have articulated the influence of middle-class or more affluent residents on compromised community health. One such study by Browning et al. supports the importance of the presence of a stabilising affluent class within impoverished neighbourhoods (such as the Census tracts measured in this study) and asserts the positive influence affluent persons can have by improving access to health and economic resources.[22]

Unlike socio-economic disadvantage, affluence has been associated with high levels of education, income and wealth, along with a greater concentration of white individuals. Few

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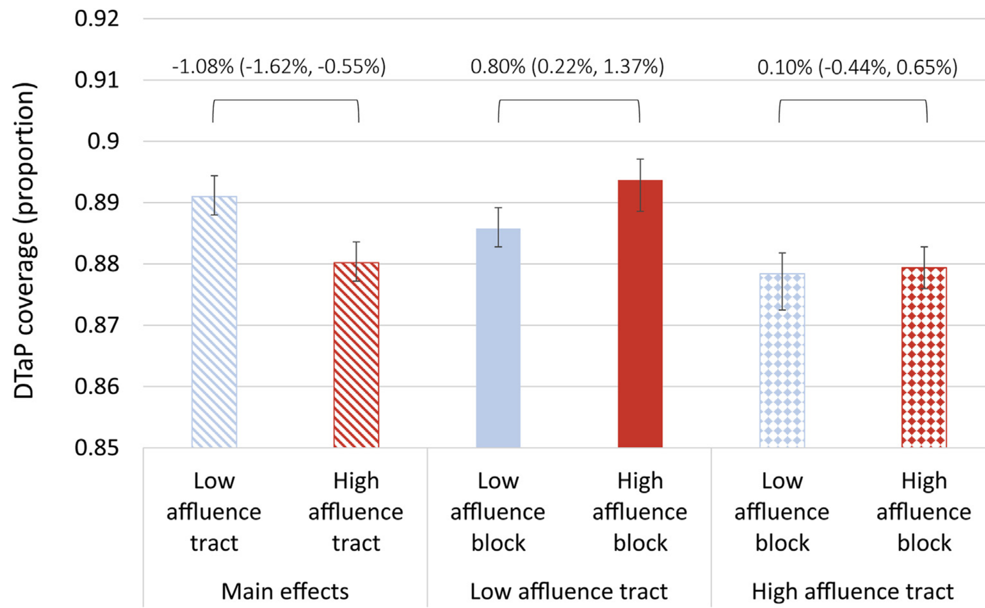

Fig. 3 – Fourth-dose diphtheria–tetanus–acellular pertussis vaccine coverage by Census tract affluence. 'Low' and 'high' are one standard deviation below and above the mean, respectively.

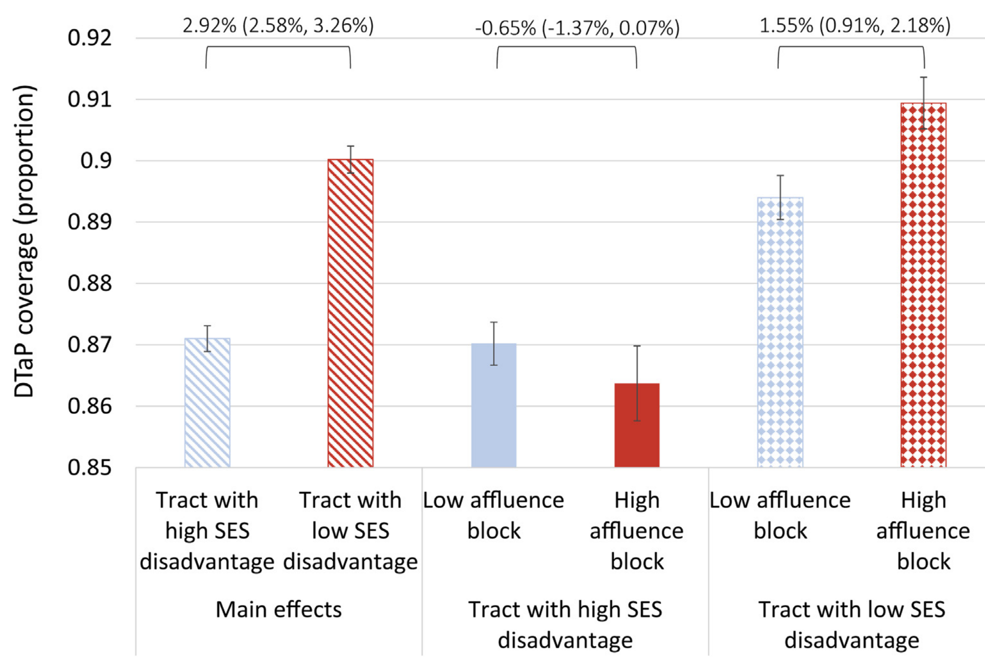

Fig. 4 – Fourth-dose diphtheria–tetanus–acellular pertussis vaccine coverage by Census tract socio-economic disadvantage. 'Low' and 'high' are one standard deviation below and above the mean, respectively.

studies have examined the influence of concentrated affluence on health, and ones that do again suggest the presence of affluent residents is essential to sustain neighbourhood (tract-level) social organisation which, in turn, positively affect health.[30,39] Our results, however, show that in the context of vaccines, having persons of high affluence (with block level as a proxy) living within highly socioeconomically disadvantaged neighbourhoods (tract-level) has no effect on increasing vaccination rates; there are no positive effects of neighbourhood heterogeneity. However, when persons of high affluence (block level as proxy) live within low socio-economically disadvantaged neighbourhoods (tract level), there is a significant increase in vaccination rates compared to low-affluent persons living within low socioeconomically disadvantaged neighbourhoods. Similarly, for high-affluent persons living within low-affluent neighbourhoods, there is a significant increase in vaccination rates compared to a more homogenous neighbourhood of low-affluent persons living within low-affluent neighbourhoods. This suggests that in order for a positive health effect to occur, the disparity between the disadvantaged and affluent should be minimal.

While affluent individuals may have greater access to health resources (which could lead to greater acceptance of vaccine but also more knowledge of medical exemptions), they also are subject to media, peer-to-peer influence and social stigma,[40] which may potentiate anti-vaccine biases. Parents can opt for personal belief exemptions to mandatory vaccination policies at schools and perceive they are choosing a no-harm option for their child.[41,42] In affluent neighbourhoods specifically, parents are less likely to see the manifestations of disease and therefore less likely to recognise the consequences of not vaccinating.[42] Somewhat paradoxically, this also can mean that affluent neighbourhoods can be at higher risk for outbreaks of vaccine-preventable disease; in a pertussis outbreak in 2010 in Oregon, higher income areas had higher pertussis rates.[43]

Limitations

Although this study identifies new findings, there are limitations. By acquiring information from the statewide immunisation registry, we could obtain detailed vaccination information from almost every Michigan resident, except for parents who opted their children out of the system. We did not have access to individual-level information such as race or parent education level, which has been linked to child vaccination status.[44] Instead, we used block-level information as a proxy for household-level characteristics. Furthermore, we only considered objective neighbourhood definitions based on Census data and not subjective definitions. Although one study has identified the importance of subjective definitions,[45] most studies that examine the effects of neighbourhoods on health only consider objective definitions. Finally, we did not test how the observed effects of vaccination behaviour may be geographically clustered in Michigan or change temporally.

Future studies

For future advances of this study, we suspect there will be more careful theorisation of the causal mechanisms of affluence and socio-economic disadvantage on health and the effect of neighbourhood heterogeneity. For intervention work, it is important for health professionals to consider neighbourhoods and associational involvement or social capital as points of intervention.[46] Although much research on social capital has focused on disadvantaged neighbourhoods, it will be important to identify how social capital affects vaccine decision-making amongst affluent versus disadvantaged neighbourhoods.[47] Avenues for investigating vaccine decision-making should include social constructs broken down into relevant domains for policy action at the neighbourhood level[47] and community development for improving access to health resources and providing health education.[48]

Additionally, healthcare providers, a main source of influence and vaccine recommendation,[49,50] should utilise existing functions within the IIS – such as generating profile reports, recalls and reminders – to improve vaccine uptake.[51] Healthcare providers should spend more time to better understand patient issues in accessing vaccinations. Of significance, engaging in interventions earlier in the vaccination regimen could reduce delayed vaccination of each subsequent vaccination; improving timeliness of third-dose DTaP reduces undervaccination of DTaP4.[52]

Conclusions

This analysis illustrates geographic areas of affluence and socio-economic disadvantage in the state of Michigan, pertinent information for establishing areas to intervene and for health professionals to access. Further analyses should consider spatial scan statistics to identify clustered areas with low immunisation rates that require focused intervention.[53] With targeted interventions at the neighbourhood level, we can reduce the observed disparities between neighbourhoods in different affluent and socio-economic gradients. Furthermore, although the neighbourhood context as described in this article may be unique to the United States, the implications that socio-economic disparity influences vaccination coverage differentially extends beyond borders. Our data suggest that countries developing IISs to monitor vaccines or conducting vaccine studies should be aware that different socioenvironmental contexts shape behaviour, which in turn contributes to vaccine coverage as much as healthcare access.

Author statements

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Ethical approval

This study was approved by the University of Michigan Health Sciences and Behavioral Sciences Institutional Review Board (#HUM00093541) and by the Michigan Department of Health and Human Services Institutional Review Board (#201408-06-XA).

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Competing interests

The authors have no conflicts of interest relevant to this article to disclose and have no financial relationships relevant to this article to disclose.

REFERENCES

1. Roush SW, Murphy TV. Historical comparisons of morbidity and mortality for vaccine-preventable diseases in the United States. *JAMA* 2007;**298**(18):2155–63.

2. Davis SF, Strebel PM, Cochi SL, Zell ER, Hadler SC. *Pertussis surveillance–United States, 1989-1991*. MMWR CDC Surveill Summ; 1992.
3. Centers for Disease Control and Prevention. *Pertussis cases by year (1922-2014) [Internet]*. 2015 [cited 2016 Oct 17]. Available from: http://www.cdc.gov/pertussis/surv-reporting/cases-by-year.html.
4. Centers for Disease Control and Prevention. *2013 Final pertussis surveillance report. Atlanta, GA*. 2014.
5. Lavine J, Broutin H, Harvill ET, Bjørnstad ON. Imperfect vaccine-induced immunity and whooping cough transmission to infants. *Vaccine* 2010 Dec 10;**29**(1):11–6.
6. Cherry JD. Epidemic pertussis and acellular pertussis vaccine failure in the 21st century. *Pediatrics* 2015;**135**(6):1130–2.
7. CDC. Pertussis. In: *Epidemiology and prevention of vaccine-preventable diseases*. 13th ed. Washington, DC: Public Health Foundation; 2012. p. 261–78.
8. Michigan Department of Health and Human Services. *Immunization status of school children in Michigan, 2015 [Internet]*. 2016 [cited 2016 Nov 10]. Available from: http://www.michigan.gov/documents/mdch/School_Summary_2014_483316_7.pdf.
9. Seither R, Calhoun K, Street EJ, Mellerson J, Knighton CL, Tippins A, et al. Vaccination coverage for selected vaccines, exemption rates, and provisional enrollment among children in kindergarten — United States, 2016–17 school year. *MMWR Morb Mortal Wkly Rep* 2017;**66**(40):1073–80.
10. Centers for Disease Control and Prevention. *State school and childcare vaccination laws [Internet]*. Public Health Law Program; 2017 [cited 2018 Oct 5]. Available from: https://www.cdc.gov/phlp/publications/topic/vaccinations.html.
11. Michigan Department of Health and Human Services. *County quarterly immunization report card: Detroit [Internet]*. 2018 [cited 2018 Oct 5]. Available from: https://www.michigan.gov/documents/mdch/Detroit_447430_7.pdf.
12. Centers for Disease Control and Prevention. *Estimated vaccination coverage [Internet]*. 2014 NIS; 2015 [cited 2015 Oct 20]. Available from: http://www.cdc.gov/vaccines/imz-managers/coverage/nis/child/tables/14/tab02_antigen_iap_2014.pdf.
13. Wagner AL, Eccleston AM, Potter RC, Swanson RG, Boulton ML. Vaccination timeliness at age 24 months in Michigan children born 2006-2010. *Am J Prev Med* 2018;**54**(1):96–102.
14. Liang JL, Tiwari T, Moro P, Messonnier NE, Reingold A, Sawyer M, et al. Prevention of pertussis, tetanus, and diphtheria with vaccines in the United States: recommendations of the advisory committee on immunization practices (ACIP). *MMWR Morb Mortal Wkly Rep* 2018;**67**(No. RR-2):1–44.
15. Whitehead SJ, Cui KX, De AK, Ayers T, Effler PV. Identifying risk factors for underimmunization by using geocoding matched to census tracts: a statewide assessment of children in Hawaii. *Pediatrics* 2007 Sep;**120**(3):e535–42.
16. Henry KA, Stroup AM, Warner EL, Kepka D. Geographic factors and human papillomavirus (HPV) vaccination initiation among adolescent girls in the United States. *Cancer Epidemiol Biomark Prev* 2016;(13):1–10.
17. Rondy M, van Lier A, van de Kassteele J, Rust L, de Melker H. Determinants for HPV vaccine uptake in The Netherlands: a multilevel study. *Vaccine* 2010 Feb 25;**28**(9):2070–5.
18. Wagner AL, Sun X, Huang Z, Ren J, Mukherjee B, Wells EV, et al. On-time measles and pneumococcal vaccination of Shanghai children: the impact of individual- and neighborhood-level factors. *Pediatr Infect Dis J* 2016;**35**(10):e311–7.
19. House JS, Landis KR, Umberson D. *Social relationships and health*, vol. 241. Science; 1988. p. 540–5.
20. House JS. Understanding social factors and inequalities in Health: 20th century progress and 21st century prospects. *J Health Soc Behav* 2002;**43**(2):125–42.
21. Wilson WJ. *The truly disadvantaged: the inner city, the underclass, and public policy*. Chicago, IL: The University of Chicago; 1987.
22. Browning CR, Cagney KA, Wen M. Explaining variation in health status across space and time: implications for racial and ethnic disparities in self-rated health. *Soc Sci Med* 2003;**57**(7):1221–35.
23. Cohen JM, Wilson ML, Aiello AE. Analysis of social epidemiology research on infectious diseases: historical patterns and future opportunities. *J Epidemiol Community Health* 2007 Dec;**61**(12):1021–7.
24. Noppert GA, Kubale JT, Wilson ML. Analyses of infectious disease patterns and drivers largely lack insights from social epidemiology: contemporary patterns and future opportunities. *J Epidemiol Community Health* 2017;**71**(4):350–5.
25. Dai D. Black residential segregation, disparities in spatial access to health care facilities, and late-stage breast cancer diagnosis in metropolitan Detroit. *Health Place* 2010;**16**(5):1038–52.
26. Schulz AJ, Williams DR, Israel B a, Lempert LB. Racial and spatial relations as fundamental determinants of health in Detroit. *Milbank Q* 2002;**80**(4):677–707.
27. Morenoff JD, House JS, Hansen BB, Williams DR, Kaplan GA, Hunte HE. Understanding social disparities in hypertension prevalence, awareness, treatment, and control: the role of neighborhood context. *Soc Sci Med* 2007;**65**:1853–66.
28. United States Census Bureau. *United States census geographic areas reference manual [Internet]*. 2015 [cited 2018 Apr 26]. Available from: https://www.census.gov/geo/reference/garm.html.
29. Thompson B. *Exploratory and confirmatory factor analysis: understanding concepts and applications*. Washington, DC: American Psychological Association; 2004.
30. Hou F, Myles J. Neighbourhood inequality, neighbourhood affluence and population health. *Soc Sci Med* 2005;**60**(7):1557–69.
31. Cederberg M, Hartsmar N, Lingärde S. *Educational policies that address social inequality thematic report*. Socioeconomic Disadvantage; 2009.
32. Benin AL, Wisler-Scher DJ, Colson E, Shapiro ED, Holmboe ES. Qualitative analysis of mothers' decision-making about vaccines for infants: the importance of trust. *Pediatrics* 2006 May;**117**(5):1532–41.
33. Kirby JB, Kaneda T. Neighborhood socioeconomic disadvantage and access to health care. *J Health Soc Behav* 2005;**46**(1):15–31.
34. Bor W, Najman JM, Andersen M, Morrison J, Williams G. Socioeconomic disadvantage and child morbidity: an Australian longitudinal study. *Soc Sci Med* 1993;**36**(8):1053–61.
35. Victora CG, Wagstaff A, Schellenberg JA, Gwatkin D, Claeson M, Habicht J-P. Applying an equity lens to child health and mortality: more of the same is not enough. *Lancet* 2003;**362**(9379):233–41.
36. Wilkinson RG, Pickett KE. Income inequality and population health: a review and explanation of the evidence. *Soc Sci Med* 2006;**62**(7):1768–84.
37. Wilkinson RG. Low relative income affects mortality. *Br Med J* 1998;**316**:1611.
38. Fitzpatrick K, LaGory M. *Unhealthy places: the ecology of risk in the urban landscape*. New York, NY: Routledge; 2000.
39. Wen M, Browning CR, Cagney KA. Poverty, affluence, and income inequality: neighborhood economic structure and its implications for health. *Soc Sci Med* 2003;**57**(5):843–60.

40. Shapiro Nina. *Why are the rich most likely to not vaccinate their children in the US? [Internet]*. 2016 [cited 2016 Oct 17]. Available from: http://www.drninashapiro.com/portfolio/why-are-rich-to-not-vaccinate-their-children-in-the-us.
41. Kata A. Anti-vaccine activists, Web 2.0, and the postmodern paradigm – an overview of tactics and tropes used online by the anti-vaccination movement. *Vaccine* 2012;**30**(25):3778–89.
42. Offit PA. *Deadly choices: how the anti-vaccine movement threatens us all*. Philadelphia, PA: Basic Books, Perseus Books Group; 2011.
43. Robison SG, Liko J, Cieslak PR. Differences in pertussis incidence by income among Oregon teens during an outbreak. *J Vaccine* 2015;**2015**:1–4.
44. Elam-Evans LD, Yankey D, Singleton JA, Kolasa M. National, state, and selected local area vaccination coverage among children aged 19 - 35 Months — United States, 2013. *MMWR Morb Mortal Wkly Rep* 2014;**63**(34):741–8.
45. Weden MM, Carpiano RM, Robert SA. Subjective and objective neighborhood characteristics and adult health. *Soc Sci Med* 2008;**66**(6):1256–70.
46. Veenstra G, Luginaah I, Wakefield S, Birch S, Eyles J, Elliott S. Who you know, where you live: social capital, neighbourhood and health. *Soc Sci Med* 2005;**60**(12):2799–818.
47. Forrest R, Kearns A. Social cohesion, social capital and the neighbourhood. *Urban Stud* 2001;**38**(12):2125–43.
48. Jutte DP, Miller JL, Erickson DJ. Neighborhood adversity, child health, and the role for community development. *Pediatrics* 2015;**135**(Suppl):S48–57.
49. Heiss SN, Carmack HJ, Chadwick AE. Effects of interpersonal communication, knowledge, and attitudes on pertussis vaccination in Vermont. *J Commun Healthc* 2015;**8**(3):207–19.
50. Groom H, Hopkins DP, Pabst LJ, Murphy Morgan J, Patel M, Calonge N, et al. Immunization information systems to increase vaccination rates. *J Public Health Manag Pract* 2015;**21**(3):227–48.
51. Shultz CG, Malouin JM. A systems approach to improving Tdap immunization within 5 community-based family practice settings: working differently (and better) by transforming the structure and process of care. *Am J Public Health Am J Public Health* 2015;**105**(10).
52. Zhao Z, Smith PJ, Hill HA. Missed opportunities for simultaneous administration of the fourth dose of DTaP among children in the United States. *Vaccine* 2017;**35**(24):3191–5.
53. Lieu TA, Thomas Ray G, Klein NP, Chung C, Kulldorff M. Geographic clusters in underimmunization and vaccine refusal. *Pediatrics* 2014;**135**(2):280–9.