Spatial variations of COVID-19 risk by age in Toronto, Canada

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Abstract

The risk of coronavirus disease 2019 (COVID-19) may vary by age, biological, socioeconomic, behavioural and logistical reasons may be attributed to these variations. In Toronto, Canada, the aging population has been severely impacted, accounting for 92% of all COVID-19 deaths. Four age groups: 60-69 years, 70-79 years, 80-89 years and ≥90 years in Toronto neighbourhoods were investigated for clustering tendencies using space-time statistics. Cohen's Kappa coefficient was computed to assess variations in risk by neighbourhood between different age groups. The findings suggest that knowledge of health risks and health behaviour varied by age across neighbourhoods in Toronto. Therefore, understanding the socioecological context of the communities and targeting age-appropriate intervention strategies is important for planning an effective mechanism for controlling the disease.

Introduction

Coronavirus disease 2019 (COVID-19) has brought unprecedented challenges to the world, posing a great threat to society, with over 179 million cases and 3.9 million deaths in 219 countries around the world, according to the World Health Organization (WHO, 2021). First reported in December 2019 in Wuhan, China (Masrur *et al*., 2020), COVID-19 emerged as a disease of particular risk for the aging population (Santesmasses *et al*., 2020). The infection, caused by an enveloped single-stranded positive RNA virus named the severe acute respiratory syndrome coronavirus (SARS-CoV-2), generally starts as a respiratory illness (Chen *et al*., 2020), but it was soon clear that it is a systemic disease (Mahajan *et al*., 2020; Temgoua *et al*., 2020). In Canada, the first case of COVID-19 was identified in Toronto on January 25, 2000, in a 51-year-old male who had recently travelled back from Wuhan (Schwartz *et al*., 2020). More than 2.8 million cases and 31,679 deaths due to COVID-19 were reported in Canada as of January 18, 2022 (Public Health Agency of Canada, 2020). Most of these cases and deaths struck Canada's two most populous provinces, Ontario (956,607 cases and 10,628 deaths) and Quebec (801,153 cases and 12,364 deaths) (Public Health Agency of Canada, 2020; Shim, 2021).

Aging turned out to be a prominent risk factor for severe disease outcomes such as death, and this was also evident in Canada (Hoffmann and Wolf, 2021; O'Brien *et al*., 2020; Wingert *et al*., 2021). The estimated death rate from COVID-19 ranges from 5.9% to 34.4% for adults ≥60 years in Canada (Government of Canada, 2020). Toronto, Canada's most populous city, has been strongly impacted by the COVID-19, particularly striking the aging population with high rates of infection, hospitalization and mortality (Verma *et al*., 2021). As of January 23, 2022, the city of Toronto Health unit reported the highest (9% of all cases) COVID-19 case count in the country, with 264,443 cumulative cases and 1.4% case fatalities (Canada, 2020). Even though the total cases for the population over 60 years of age consisted of only 16% of all cases in Toronto, this population accounted for 92% of all deaths and 65% of hospitalizations due to COVID-19 in the region as of January 23, 2022 (Public Health Ontario, 2022).

COVID-19 disproportionally affects older adults with respect to severity and adverse health outcomes (Mueller *et al*., 2020), leading to increased rates of hospitalization, admission to Intensive Care Units (ICU) and often death (Chen *et al*., 2021). Hospitalization and death from COVID-19 are the highest among adults ≥60 years of age (Verity *et al*., 2020) and those with pre-existing health conditions and/or impaired immune responses (Richardson *et al*., 2020; Santesmasses *et al*., 2020; Wu and McGoogan, 2020). Why older adults are at increased risk could be due to biological [*e.g*., age-associated decline in lung capacity and immunosenescence (Santesmasses *et al*., 2020)], socioeconomic [the aging population living in Toronto neighbourhoods with lower income appeared to be overrepresented with regard to COVID infection rates (Verma *et al*., 2021)] and behavioural reasons [increased infection risk (Politi *et al*., 2021; Sasaki *et al*., 2021; Strang *et al*., 2020)] as well as logistical challenges in immunizing seniors.

Positive health behaviour, such as getting vaccinated and following personal hygiene and social distancing rules, would be

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See online Appendix for additional material.

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beneficial in reducing the disease risk (Golden *et al*., 2011). However, responses may also differ based on personal knowledge, health behaviour and beliefs among different age groups (Alsan *et al*., 2020). An American study on COVID-19 observed that older adults are less likely to wear face masks or change their health behaviour than younger adults (Barber and Kim, 2021). Another study analysed how social distancing varies with age and found that the expected number of close contacts with non-household members decreases rapidly with age (Canning *et al*., 2020).

Furthermore, the impact of logistical challenges such as delays in timely intervention and effective vaccination strategies may cause variances in disease risk among the elderly population. According to data from the Institute for Clinical Evaluative Sciences (ICES) presented by Ontario's Science advisory table on May 20, 2021, seniors in Toronto had a lower vaccination rate even though vaccines were available for months for this age group (Sarrouh and Bowden, 2021; Science Table Ontario, 2022). Based on the report by Ontario's Science advisory, in Toronto and its neighbouring Peel Region, where the COVID-19 infection rate had been consistently high, the percentage of seniors vaccinated was lower than the rest of the population. Vaccination gaps were also observed on May 17, 2021, where up to 73-74% of people over 60 living in the most high-risk neighbourhoods in Ontario received at least one dose of the vaccine (Science Table Ontario, 2022). Even though former studies have found variations in COVID-19 incidence rates by age (Davies *et al*., 2020; Ho *et al*., 2020; Sinclair and Abdelhafiz, 2020; Hoffmann and Wolf, 2021) and have highlighted the importance of early age-specific intervention strategies, studies on spatial heterogeneity of the risk generated by age are difficult to find.

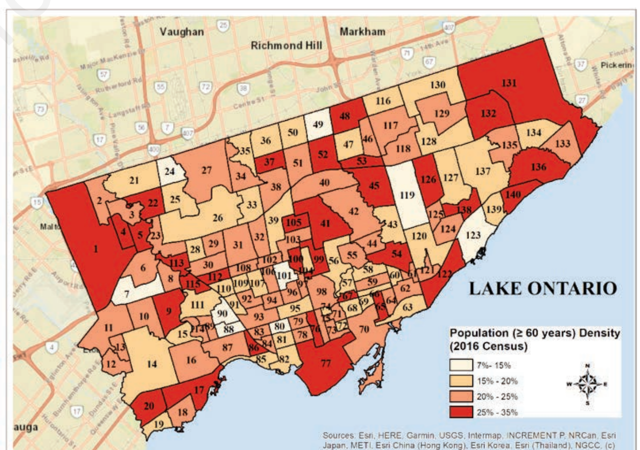
Over the past few decades, major advances in data availability, computational capacity and data-driven spatial techniques have contributed to significant advances in complex modelling of spatial data (Chowell and Rothenberg, 2018). Spatial statistical methods are useful in infectious disease surveillance as they allow researchers to track emerging infectious diseases, evaluate disease risks and identify the communities at risk by producing maps (Kim and Castro, 2020). Once a disease outbreak is spread in a community, a prompt community-level intervention program may help control the further spread of the disease to the nearby communities. Knowledge of disease risk and health behaviour could vary by age among the aging population (≥60 years) and poor knowledge and health behaviour could increase the risk of the disease in the community. Therefore, it is important to understand spatial patterns of risk in the communities driven by specific age groups to plan an effective intervention. This study aims to identify and evaluate the spatial heterogeneities in COVID-19 risk by age group in the population aged ≥60 years) in Toronto, Canada.

Materials and methods

Study area

With a land area of 630 km^2, the city of Toronto is located in the southwestern corner of Ontario, Canada (Figure 1) and near the north-western shore of Lake Ontario. The city of Toronto is widely diverse, with 51.5% of the population being a visible minority (defined by the Government of Canada as '*persons, other than aboriginal peoples, who are non-Caucasian in race or non-white in colour*') and 51.2% of the population being born outside of Canada (City of Toronto, 2021a). The study area consisted of 140 geographically distinct neighbourhoods in Toronto, where approximately half of the older adults have ethnically diverse backgrounds (Channer *et al*., 2020). In particular, Toronto's western, eastern and central neighbourhoods have a very high concentration of visible minorities (City of Toronto, 2017a).

Toronto is a land of many opportunities, particularly for the youth, with a high population density of 630 persons per km^2 (City of Toronto, 2021a). However, in the last several decades, there has been a sharp increase in Toronto's aging population. As of the 2016 Census, the demography of Toronto comprised 21.2% population >60 years, a figure expected to double by the year 2041 (City of Toronto, 2017b). In all of Toronto, many neighbourhoods such as Bay Street Corridor and Waterford communities in the South, West Humber-Clairville, Rexdale-Kipling in the Northwest, Alderwood and Mimico in the Southeast, Malvern and West Hill in the East and Lawrence Park North and Yonge-Eglinton in downtown Toronto have a high concentration (25-35%: 2016 Census) of an aging population (Figure 1). The unique 140 neighbourhoods in Toronto vary in terms of socioeconomic vulnerabilities as well as cultural, ethnic and immigration status differences. However, these differences also lead to inequalities. The neighbourhoods in Toronto range from wealthy areas such as Forest Hill, Casa Loma and Rosedale to low-income neighbourhoods, such as West Humber-Clairville, Rouge and Waterford-Communities (Wang and Ramroop, 2018). The majority of the neighbourhoods in Toronto have a high concentration of older adults (65+) with low incomes



1	West Humber-Clairville	36	Newtonbrook West	71	Cabbagetown-South St. James Town	106	Humewood-Cedarvale
2	Mount Olive-Silverstone-Jamestown	37	Willowdale West	72	Regent Park	107	Oakwood Village
3	Thistletown-Beaumond Heights	38	Lansing-Westgate	73	Moss Park	108	Briar Hill-Belgravia
4	Rexdale-Kipling	39	Bedford Park-Nortown	74	North St. James Town	109	Caledonia-Fairbank
5	Elms-Old Rexdale	40	St.Andrew-Windfields	75	Church-Yonge Corridor	110	Keelesdale-Eglinton West
6	Kingsview Village-The Westway	41	Bridle Path-Sunnybrook-York Mills	76	Bay Street Corridor	111	Rockcliffe-Smythe
7	Willowridge-Martingrove-Richview	42	Banbury-Don Mills	77	Waterfront Communities-The Island	112	Beechborough-Greenbrook
8	Humber Heights-Westmount	43	Victoria Village	78	Kensington-Chinatown	113	Weston
9	Edenbridge-Humber Valley	44	Flemingdon Park	79	University	114	Lambton Baby Point
10	Princess-Rosethorn	45	Parkwoods-Donalda	80	Palmerston-Little Italy	115	Mount Dennis
11	Eringate-Centennial-West Deane	46	Pleasant View	81	Trinity-Bellwoods	116	Steeles
12	Markland Wood	47	Don Valley Village	82	Niagara	117	L'Amoreaux
13	Etobicoke West Mall	48	Hillcrest Village	83	Dufferin Grove	118	Tam O'Shanter-Sullivan
14	Islington-City Centre West	49	Bayview Woods-Steeles	84	Little Portugal	119	Wexford/Maryvale
15	Kingsway South	50	Newtonbrook East	85	South Parkdale	120	Clairlea-Birchmount
16	Stonegate-Queensway	51	Willowdale East	86	Roncesvalles	121	Oakridge
17	Mimico (includes Humber Bay Shores)	52	Bayview Village	87	High Park-Swansea	122	Birchcliffe-Cliffside
18	New Toronto	53	Henry Farm	88	High Park North	123	Cliffcrest
19	Long Branch	54	O'Connor-Parkview	89	Runnymede-Bloor West Village	124	Kennedy Park
20	Alderwood	55	Thorncliffe Park	90	Junction Area	125	Ionview
21	Humber Summit	56	Leaside-Bennington	91	Weston-Pelham Park	126	Dorset Park
22	Humbermede	57	Broadview North	92	Corso Italia-Davenport	127	Bendale
23	Pelmo Park-Humberlea	58	Old East York	93	Dovercourt-Wallace Emerson-Junction	128	Agincourt South-Malvern West
24	Black Creek	59	Danforth East York	94	Wychwood	129	Agincourt North
25	Glenfield-Jane Heights	60	Woodbine-Lumsden	95	Annex	130	Milliken
26	Downsview-Roding-CFB	61	Taylor-Massey	96	Casa Loma	131	Rouge
27	York University Heights	62	East End-Danforth	97	Yonge-St.Clair	132	Malvern
28	Rustic	63	The Beaches	98	Rosedale-Moore Park	133	Centennial Scarborough
29	Maple Leaf	64	Woodbine Corridor	99	Mount Pleasant East	134	Highland Creek
30	Brookhaven-Amesbury	65	Greenwood-Coxwell	100	Yonge-Eglinton	135	Morningside
31	Yorkdale-Glen Park	66	Danforth	101	Forest Hill South	136	West Hill
32	Englemount-Lawrence	67	Playter Estates-Danforth	102	Forest Hill North	137	Woburn
33	Clanton Park	68	North Riverdale	103	Lawrence Park South	138	Eglinton East
34	Bathurst Manor	69	Blake-Jones	104	Mount Pleasant West	139	Scarborough Village
35	Westminster-Branson	70	South Riverdale	105	Lawrence Park North	140	Guildwood

Figure 1. The study area in Toronto, Canada. All 140 neighbourhoods in Toronto, Canada and their numbers are displayed.

(City of Toronto, 2017a). It is interesting to note that many of these live in the inner core of the city, such as the Cabbagetown, Kensington, Waterford communities and Bay Street corridor neighbourhoods (Channer *et al*., 2020).

Data

The COVID-19 dataset was collected from the City of Toronto's open data portal (City of Toronto, 2022). The dataset contains demographic, geographic and degree of severity of all confirmed and probable cases reported to and managed by, Toronto Public Health which extracts these data from the provincial Case & Contact Management System (CCM) (City of Toronto, 2020a). These data, updated on a weekly basis (City of Toronto, 2020a), contain the date of onset, date of diagnosis, the neighbourhood of residence, sex and age group of each case. The COVID-19 data for the population ≥60 years from January 21, 2020 (first reported case) to May 31, 2021 were collected, including both sporadic and outbreak-associated cases to account for the total disease burden in the neighbourhoods. Each case was linked to the centroid of the neighbourhood, with the data aggregated into four age groups: I (60-69 years); II (70-79 years); III (80-89 years) and IV (≥90 years). The neighbourhood profiles and 2016 census dataset from Toronto's Social Policy Analysis & Research Unit, Statistics Canada (City of Toronto, 2020b) were used. The neighbourhood profiles are created to assist local research and planning and the geographic data of the boundaries of the neighbourhoods were also obtained from the City of Toronto's open data portal (City of Toronto, 2020b).

Space-time cluster assessment

The cluster analysis, applied to retrospectively identify the geographic areas and periods of potential COVID-19 clusters, was based on Kulldorff's SaTScan™, version 9.7 (Kulldorff, 2009; (Kulldorff and Nagarwalla, 1995; Ngui *et al*., 2013). The software allowed to identify spatial and space-time clusters while adjusting for the heterogeneous population. The study population was divided into the four population strata based on age and the differences in risk clusters between these groups were assessed. I used the discrete Poisson model to account for the population in each neighbourhood when searching for significantly high-risk clusters. The scan parameters ranged from January 2020 to May 2021, with a one-month time intervals. The maximum spatial cluster size was set at 10% of the population at risk after evaluating the effects of switching this value to 10%, 20%, 30%, 40% and 50%. Based on this evaluation, 10% of the study population provided an optimal cluster size displaying local-level variations of risk and thus this size was selected for analysis. The temporal window was set at 20%. I performed a sensitivity test by setting 10% of the study time period as the maximum time window. With this setting, the size of the clusters was larger than those obtained by setting 20% of the study period (Figure S1 in Appendix). This indicates that setting a smaller time window makes the clusters homogenous over the study area, and the local level variation of the phenomenon is obscured in a smaller time window.

The scan statistic calculated the relative risk of COVID-19 incidence for a cluster using the ratio of observed to expected cases. This method tests the null hypothesis that there is an increased risk of COVID-19 incidence, represented by relative risk, within the window compared to the area outside the window. The relative risk of disease for the clusters with a corresponding P-value is generated based on Monte-Carlo simulations. The number of Monte Carlo simulations was restricted to 999. The level of significance was set at P=<0.05. The relative risk (RR) (Kulldorff, 2009; Rao *et al*., 2017) is defined as follows:

$$RR = \frac{c/e}{(O-o)/(O-e)} \qquad (1)$$

where o is the total number of observed COVID-19 cases within the cluster, e is the expected number of cases in the cluster and O is the total number of observed cases in the study area. A relative risk (RR) greater than 1 indicates a high COVID-19 incidence rate compared to the rest of the study area for a detected cluster. The cluster data were then imported into ArcGIS software to create COVID-19 high-risk maps for the different population groups.

Tests for agreement

I used McNemar's chi-square test (Adedokun and Burgess, 2012) to examine whether the proportion of the discordant pairs (High-Low and Low-High) of neighbourhoods was statistically significantly high or not. The Cohen's Kappa coefficients (Cohen, 1960) were calculated to evaluate the degrees of concordance between the geographic patterns of risk neighbourhoods across the four age groups. According to the Kappa coefficient, which varies between 0 and 1, the degree of concordance was determined as follows: poor (k<0.2), fair (0.2≤k<0.4), moderate (0.4≤k<0.6), good (0.6≤k<0.8); excellent (k>0.8) and perfect (k=1) as done by Landis and Koch (1977).

Results

Descriptive statistics

Among the total of 31,194 cases, 14,965 (47.9%) were found in the age group I; 7462 (23.9%) in age group II; 5667 (18.1%) in age group III and 3100 (9.9%) in age group IV. Since there were 580,645 individuals ≥60 years and among those, 284,330 individuals were in the age group I; 169,740 in age group II; 101,400 in age group III; and 25,175 in age group IV, according to the 2016 census, the incidence rate (per 1000) was 53.7 for all ≥60 years; 52.6 for the age group I; 43.9 for age group II; 55.8 for age group III and 122.9 for age group IV.

The monthly number of cases showed a similar trend for all age groups (Figure 2). While age groups I-III experienced a sharp increase from February 2021, age group IV remained almost constant during the study period. As seen in Figure 2, there was a higher incidence rate for age group IV compared to the three other age groups.

Space-time analysis results

The characteristics of the COVID-19 case clusters detected in this analysis are provided in Tables 1 and 2. Figure 3 shows the map of the significant (P<0.05) clusters. Neighbourhoods not at significantly higher risk for COVID-19 were defined as low risk. There were 12 significantly high-risk clusters containing 74 neighbourhoods for all age groups. The highest relative risk (RR≥6.0) was recorded in the southwestern and southern parts of Toronto (clusters 6, 8 and 11) between March and May 2020 (Figure 3 and Table 1). The age group I was identified in 12 significantly high-

Table 1. Significant COVID-19 high-risk clusters for the population aged ≥60 years in Toronto, Canada.

Cluster number	Time period	Neighbours (No.)	Observed cases (No.)	Expected cases (No.)	Relative risk
1	Nov 2020-Jan 2021	13	2488	513.52	5.18
2	Nov 2020-Jan 2021	7	1338	236.32	5.87
3	Dec 2020-Jan 2021	9	800	201.49	4.05
4	Nov 2020-Jan 2021	6	669	183.70	3.70
5	Dec 2020-Jan 2021	16	946	361.91	2.66
6	Mar 2020-Apr 2020	8	209	24.91	8.44
7	Apr 2020	3	438	143.65	3.08
8	Apr 2020	1	106	7.08	15.03
9	Nov 2020-Jan 2021	3	422	146.27	2.91
10	Oct 2020-Nov 2020	1	119	22.60	5.28
11	Apr 2020-May 2020	1	82	13.22	6.22
12	Apr 2020	6	27	8.45	3.20

Cluster level of significance: P<0.05.

Table 2. Significant high-risk clusters of COVID-19 by age group in Toronto, Canada.

Cluster (no.)	Time period	Neighbour (no.)	Observed cases (no.)	Expected cases (no.)	Relative risk (no.)	Time period	Neighbours (no.)	Observed cases (no.)	Expected cases (no.)	Relative risk (no.)
	Age group I (60-69 years)					Age group II (70-79 years)				
1	Nov 2020-Jan 2021	13	1186	265.85	4.76	Nov 2020-Jan 2021	13	539	120.90	4.73
2	Nov 2020-Jan 2021	12	1134	262.86	4.59	Nov 2020-Jan 2021	7	344	53.78	6.66
3	Apr 2021	14	331	73.68	4.57	Dec 2020	1	55	2.16	25.63
4	Mar 2021-Apr 2021	10	362	106.41	3.46	Apr 2021	16	165	42.89	3.91
5	Dec 2020-Jan 2021	9	307	100.07	3.11	Dec 2020-Feb 2021	3	114	22.15	5.21
6	Dec 2020-Jan 2021	4	167	47.43	3.55	Nov 2020-Jan 2021	6	157	44.24	3.60
7	Dec 2020-Jan 2021	9	262	101.75	2.60	Apr 2021	12	126	38.65	3.30
8	Apr 2021	15	232	84.37	2.78	Nov 2020-Jan 2021	5	106	35.91	2.98
9	Dec 2020	1	41	3.65	11.28	Mar 2020-Apr 2020	1	29	3.40	8.57
10	Feb 2021-Apr 2021	3	105	29.40	3.59	Apr 2020-May 2020	1	27	2.93	9.24
11	Apr 2021	1	18	4.47	4.03	Oct 2020-Nov 2020	1	33	5.32	6.23
12	Apr 2021	1	13	4.28	3.04	Apr 2020	1	18	1.70	10.63
	Age group III (80-89 years)					Age group IV (≥90 years)				
1	Nov 2020-Jan 2021	13	481	93.19	5.55	Dec 2020-Jan 2021	6	211	11.37	19.84
2	Dec 2020-Feb 2021	9	245	49.76	5.10	Apr 2020	8	127	10.25	12.87
3	Apr-May 2020	8	199	32.84	6.24	Nov 2020-Jan 2021	18	215	53.47	4.25
4	Mar-Apr 2020	1	83	4.19	20.10	Apr-May 2020	10	146	25.21	6.03
5	Nov 2020-Jan 2021	6	167	37.34	4.58	Nov 2020-Jan 2021	12	204	50.40	4.26
6	Dec 2020-Jan 2021	16	212	63.07	3.45	Mar-Apr 2020	1	41	0.58	71.48
7	Nov 2020-Jan 2021	3	109	17.35	6.38	Dec 2020-Jan 2021	2	62	4.36	14.50
8	Apr 2020	1	53	3.02	17.73	Dec 2020	1	43	1.62	26.83
9	Apr 2020	3	87	13.62	6.47	Nov-Dec 2020	1	39	1.82	21.74
10	Apr 2020	1	33	0.96	34.69	Apr 2020	1	26	0.43	61.15
11	Apr-May 2020	3	80	12.10	6.69	Nov 2020-Jan 2021	3	63	9.97	6.43
12	Dec-Jan 2021	3	60	10.69	5.66	Apr 2020	6	49	5.82	8.53
13	Apr 2020	6	65	13.67	4.80	Oct-Nov 2020	1	35	2.40	14.76
14	Oct-Nov 2020	1	36	3.66	9.89	Oct-Nov 2020	1	23	1.45	15.94
15	Oct-Nov 2020	1	25	3.89	6.45	Jun 2020	1	21	3.22	6.57
16	Jun 2020	1	24	7.59	3.17	Jan 2021	4	25	5.83	4.31

Cluster level of significance: P<0.05.

risk clusters that contained 92 neighbourhoods, with the highest relative risk (RR≥6.0) observed in the Annex neighbourhood in December 2020. Age group II was identified in 12 significant high-risk clusters that included 67 neighbourhoods, with the highest relative risk (RR≥6.0) observed in the Northwest and downtown Toronto (clusters 2, 3 and 10-12). Age group III was identified in 16 significantly high-risk clusters that included 76 neighbourhoods, with the highest relative risk (RR≥6.0) in western, eastern and southern Toronto. Lastly, age group IV was identified in 16 significantly high-risk clusters that included 76 neighbourhoods, with the highest relative risk (RR≥6.0) in the 42 neighbourhoods and different parts of Toronto (Figure 3 and Table 2).

Figure 4 shows the significantly high-risk neighbourhoods by age group. The map shows that 31 (22%) neighbourhoods in dark red were at significantly high risk and 14 (10%) neighbourhoods in white were at low risk among all age groups. 10 neighbourhoods were only at high risk for group I, one neighbourhood was only at high risk for group II, 6 neighbourhoods were only at high risk for group III and 15 neighbourhoods were only at high risk for group IV.

Test for agreement

Only half of the various age group comparisons with respect to the agreement reached a high level of statistical significance (Table 3).

Discussion

The maps generated in this study provide a visual impression of the magnitude of risk of COVID-19 in the neighbourhoods of Toronto by age group. The findings are consistent with our assumptions that the spatial risk of COVID-19 varies by age group. As discussed earlier, these variations in risk could be attributed to the spatial variations of socioeconomic differences, knowledge, belief, role in the family, work environment and health behaviour of the people living in the neighbourhood. The disparities observed in COVID-19 risk among aging populations emphasize the need to understand the impact of age of the people on the incidences of COVID-19.

The socioeconomic inequalities could be a factor attributed to the high risks seen in many neighbourhoods. Importantly, the high population density in the north-eastern part of Toronto may have contributed to the large cluster of high-risk neighbourhoods for all age groups (except group IV) noted in this area. Age group IV had the lowest number of high-risk neighbourhoods compared to other age groups and this age group had only 4.3% of the total population and 9.9% of all COVID-19 cases, which could explain the fewer high-risk neighbourhoods for that age group. The results also suggest that poor knowledge and health behaviour of a particular age group in a neighbourhood could have increased the risk in the neighbourhood for that age group.

Several efforts were made by the local, provincial and federal governments to support the senior citizens of Toronto during this pandemic. For example, vaccination was prioritized, in-home immunization was provided, outbreaks in long-term care centres were targeted for prevention and special social support was given (City of Toronto, 2021b, 2021c, 2020c; C. of City of Toronto, 2021). In addition, a mobile vaccination strategy to bring vaccines

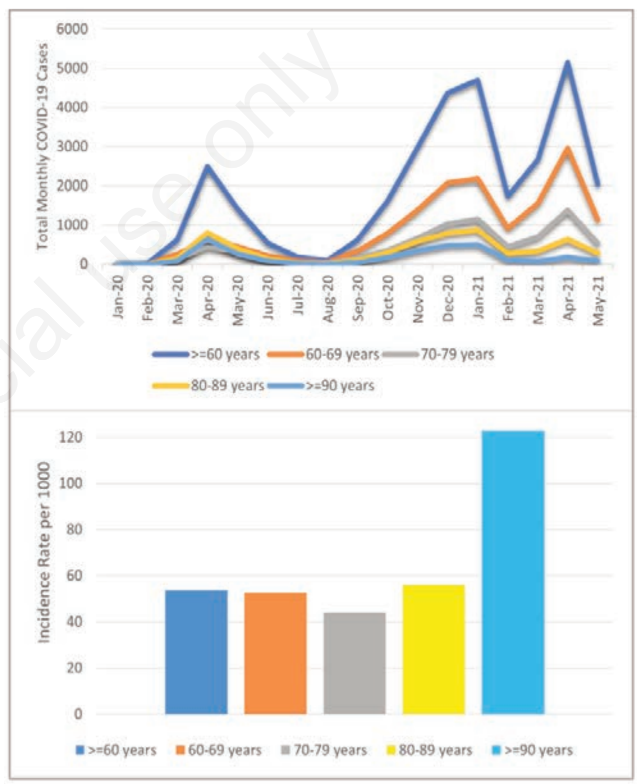


Figure 2. Monthly numbers of COVID-19 cases and incidence rates by age January 2020 to May 2021 in Toronto, Canada.

Table 3. Risk relationships between neighbourhoods with respect to age group.

Age Group	Pair-wise concordance and discordance				Agreement	Kappa	McNemar
	High/High	Low/Low	High/Low	Low/High	(%)	(95% CI)	(P-value)
Age group I *vs* Age group II	61	42	31	6	73.57%	0.47 (0.34-0.61)	<0.001*
Age group I *vs* Age group III	61	33	31	15	67.14%	0.32 (0.17-0.47)	0.01*
Age group I *vs* Age group IV	51	23	41	25	52.85%	0.03 (-0.13-0.19)	0.04*
Age group II *vss* Age group III	48	45	19	28	66.42%	0.33 (0.17-0.48)	0.18
Age group II *vs* Age group IV	40	37	27	36	55.00%	0.10 (-0.06-0.26)	0.25
Age group III *vs* Age group IV	46	34	30	30	57.14%	0.13 (-0.02-0.30)	1.00

I, 60-69 years; II, 70-79 years; III, 80-89 years; IV, ≥90 years. *Significance at P<0.05.

to areas with low vaccination coverage and high-risk areas was initiated (City of Toronto, 2021d). Despite these efforts, the aging population in Toronto continues to face challenges with a high incidence of COVID-19, hospitalization and death rates.

The identification of age-based hotspots provided information on which populations were the most vulnerable and where to find public health activities. Thus, the results can create better awareness planning logistics indicating places targeted for lockdowns, rapid testing and vaccination sites. The findings also suggest that age-appropriate intervention efforts focusing on hotspots would be effective for controlling outbreaks. Hotspots could be prioritized at the local level for age-appropriate public health action plans. The public health policies and response efforts also need to address age differences in health behaviour, raise disease awareness, strengthen policies to take more effective self-protective measures and encourage positive health behaviours among the vulnerable population groups to improve overall population health.

A major strength of this study is that our analysis has provided

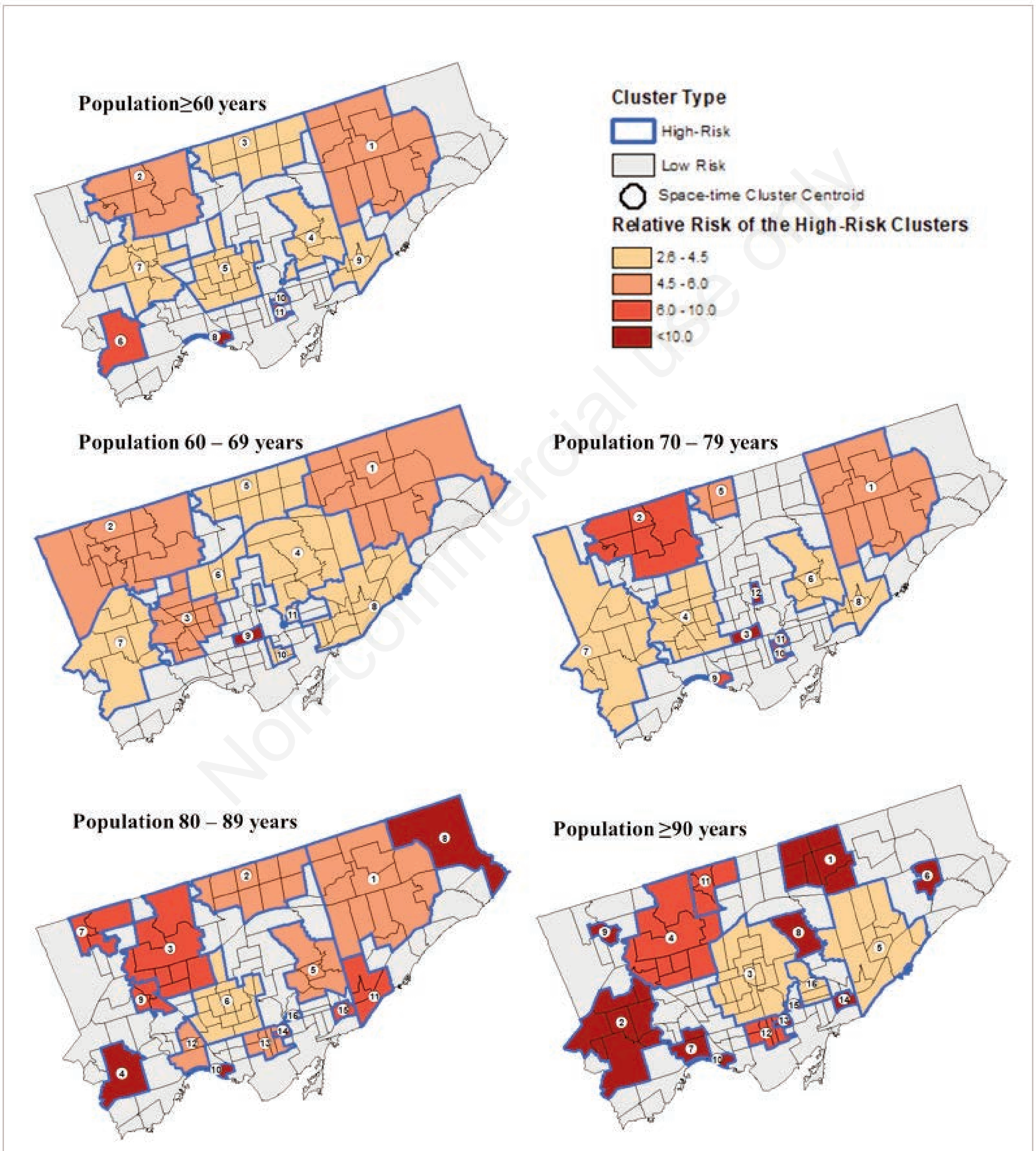


Figure 3. Significant high-risk clusters of COVID-19 by age group in Toronto, Canada. Time period: January 2020-May 2021; P-values obtained through 999 times Monte Carlo simulations; neighbourhoods inside the high-risk clusters were statistically insignificant at P<0.05.

a greater insight into the variations of risk clusters among different population groups suggesting an efficient, targeted intervention. A second point to be made is that the spatial analyses were conducted at a small-area scale, which allowed a closer look into the risk of COVID-19 in the city (Piel *et al*., 2020). A third advantage is the use of the most recent data on COVID-19, which allowed the identification of new and emerging clusters of the disease. However, there are also some limitations. First, since COVID-19 can be asymptomatic, many cases might have been overlooked. On the other hand, it would have been impractical to do a complete serosurvey for capturing asymptomatic cases. Second, since we did not have any knowledge of the spatial processes of the disease, we used a circular window to detect the cluster. However, SaTScan software has difficulty detecting actual non-circular irregularly shaped clusters in a study area (Rao *et al*., 2017). Third, knowledge of disease risk and health behaviour data for the study were not available from any sources, limiting us to evaluating the association of the clusters with the knowledge of disease risk and health behaviour data of the people in the clusters. In future research, it would be useful to collect data on the knowledge of health risks and health behaviour, such as handwashing, wearing face masks in public, knowledge and beliefs among the study population to help evaluate the association of the clusters with the knowledge and health behaviour among different age groups within the community.

Conclusions

Geographically appropriate risk-reduction programs using spatial tools are integral components of epidemiology and disease risk assessment. As the elderly are the most vulnerable part of society, the study was stratified by age, which assisted in raising awareness about the differences in risk clusters, implying that understanding the socioecological context of the communities is important for making an effective intervention plan that would promote ‘flattening’ of the COVID-19 epidemiological curve. The findings of this study may help focus on who and where interventions, such as planning for testing sites, lockdown measures and vaccination initiatives, should be targeted.

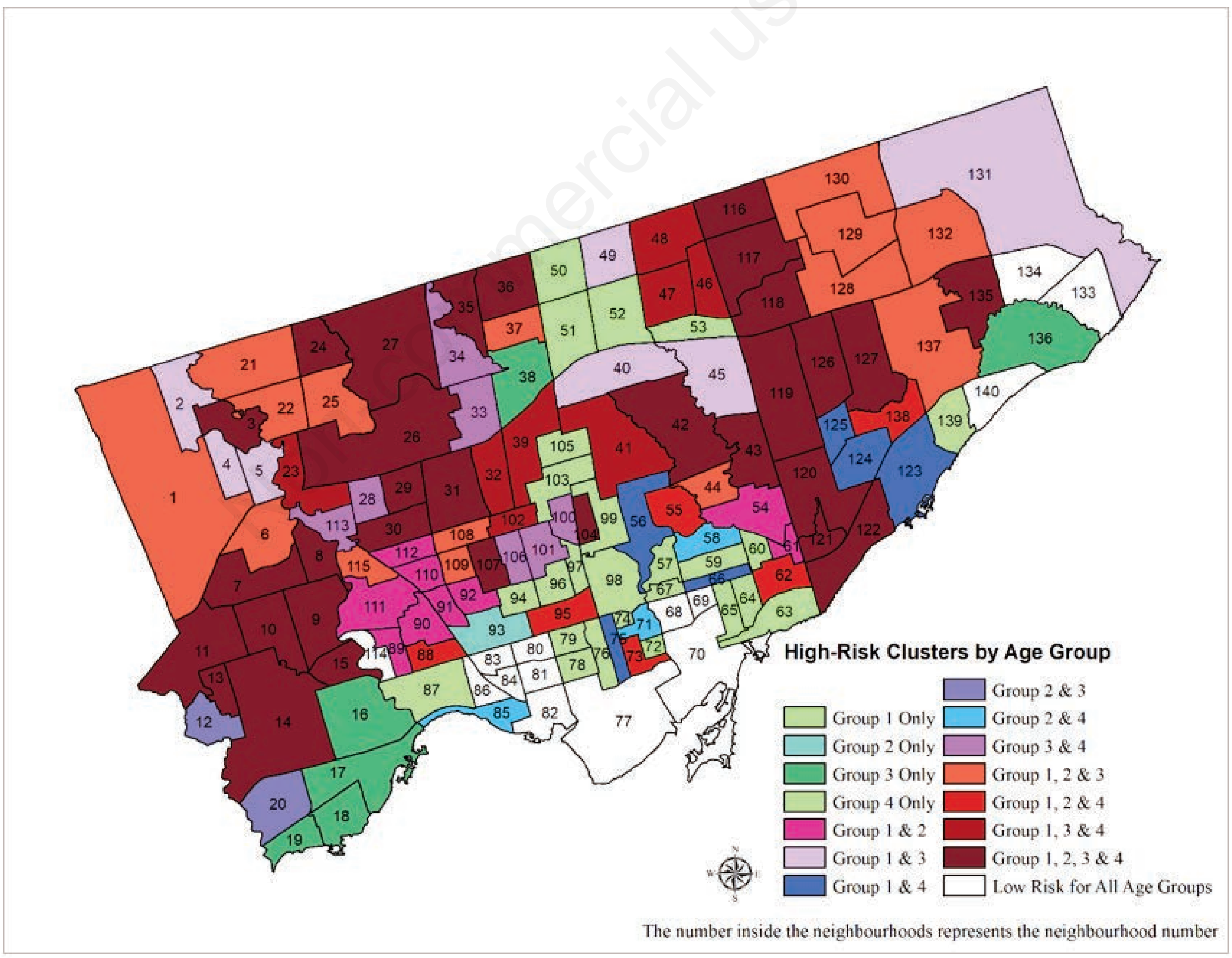


Figure 4. Significantly high-risk neighbourhoods of COVID-19 by age groups, January 2020-May 2021, Toronto, Canada. Time period: January 2020-May 2021; ‘Group 1 only’ refers to clusters that are high-risk for age group 1 only; ‘Group 1 and 2’ refers to clusters that are high-risk for both age group 1 and 2; *etc.*

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