Social contact mixing: An introduction and the assessment of shifts in contact mixing patterns in response to non-pharmaceutical interventions

Fields-CQAM Thematic Program on Integrative Modeling of Emerging Infectious Disease Outbreaks

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Outline

- Introduction to contact mixing
- Adapting contact matrices to different demographics
- Infer alterations in contact mixing in response to non-pharmaceutical interventions (NPIs)
- Remarks, broader picture

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Transmission model (Homogeneous mixing)

Stratification:

- Susceptible to infection
- Infectious individuals
- Removed

$$S' = -\frac{\beta}{N} SI$$
$$I' = \frac{\beta}{N} SI - \gamma I$$
$$R' = \gamma I$$

Assumptions:

1. Closed environment;
2. Rate of new infected is proportional to the number of susceptible;
3. Removal rate proportional to number of infectious individuals.

$$S(t) + I(t) + R(t) \equiv N$$

The basic reproduction number, denoted by R_0, represents the average number of secondary infectious infected by an individual during their period of infectiousness. [2]

1. Ma, Z., Zhou, Y., & Wu, J. (2009a). *Modeling and dynamics of infectious diseases* (Vol. 11). World Scientific.

Transmission model (Heterogeneous mixing)

Additional stratification:
Population is stratified into *n*-age groups (index *i =1,…, n)*

$$S_i' = -\Sigma_{j=1}^{n} \beta C_{ij} S_i \frac{I_j}{N_j}$$

$$I_i' = \Sigma_{j=1}^{n} \beta C_{ij} S_i \frac{I_j}{N_j} - \gamma I_i$$

$$R_i' = \gamma I_i$$

Constant across age classes

- Susceptibility to infection
- Recovery rate

Contact matrix: C_{ij} (n x n)
Units (entrywise): contacts per unit time.

The basic reproduction number, denoted by R_0, represents the average number of secondary infectious infected by a typical individual during their period of infectiousness. [3]

2. Diekmann, O., Heesterbeek, J. A. P., & Metz, J. A. J. (1990a). On the definition and the computation of the basic reproduction ratio R0 in models for infectious diseases in heterogeneous populations. *Journal of Mathematical Biology*, *28*(4), 365–382.

Setting the stage

Motivation:

"If the research question is an age-structured question then use an age-structured model."

Definition and context:

In general, a contact refers to either direct physical contact (e.g., person-to-person, droplet spread from cough or sneeze, etc.) or indirect contact (interaction with contaminated food, water, insects).

Focus in this lecture: Contacts relevant for person-to-person transmission of respiratory illnesses.

Establishing a contact mixing matrix

- **C = ?**

- **Population of interest**

Region	Children	Adults	Total	Age structure
A	1,000	9,000	10,000	N = [1000, 9000]

- **Hypothetical: We perform a study; we ask survey participants to record their daily contacts in terms of the ages contacted and number of contacts.**

Survey results → $C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} = \begin{bmatrix} 14 & 3 \\ 2 & 12 \end{bmatrix}$

Reciprocal contacts

$C = \begin{bmatrix} 14 & 3 \\ 2 & 12 \end{bmatrix}$; (Contact survey)

We must have $C_{ij}N_i = C_{ji}N_j$ (Reciprocity condition).

However, $C_{12}N_1 = 3 \times 1000 \neq C_{21}N_2 = 2 \times 9000.$ **[Violation of conservation law]**

Pair-wise correction (Reciprocity correction)

$$C'_{ij} = \frac{1}{2N_i}\left(C_{ij}N_i + C_{ji}N_j\right).$$

$$C' = \begin{bmatrix} 14 & 10.5 \\ 1.17 & 12 \end{bmatrix}.$$ **(Reciprocity correction)**

3. Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.

Projections to different demographics

Challenge: Our survey was conducted in region A and we are asked to conduct modelling for region B;

- **We adapt established contact matrix C to represent mixing in region B.**

Region	Children	Adults	Total
A	1,000	9,000	10,000
B	2,000	8,000	10,000

$C' = ?$

Established transformations and terminology

Transformations

Method 1 (M1): Pair-wise correction

$$C'_{ij} = \frac{1}{2N'_i}\left(C_{ij}N_i + C_{ji}N_j\right),$$

Method 2 (M2): Density correction

$$C'_{ij} = C_{ij}\frac{NN'_j}{N_jN'},$$

Method 3 (M3): Density correction + normalization

$$C'_{ij} = C_{ij}\frac{N'N'_j}{N_j\sum_{i,j}C_{ij}\frac{N'_iN'_j}{N_j}}.$$

Definitions

Reciprocity condition:

$$C_{ij}N_i = C_{ji}N_j.$$

Mean connectivity $< \boldsymbol{k} >$**, or the average number of contacts per individual, is**

$$< k > = \frac{1}{N}\sum_{i,j} C_{ij}N_i.$$

Notation:

N: population by age, original demography (n −dimensional vector);

N': population by age, target demography (n −dimensional vector).

3. Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.

An illustration with machinery

Hypothetical contact survey:

Data → $C = \begin{bmatrix} 14 & 3 \\ 2 & 12 \end{bmatrix}$

Region	Children	Adults	Total	Age structure
A	1,000	9,000	10,000	N = [1000, 9000]
B	2,000	8,000	10,000	N' = [2000, 8000]

[Data] $C = \begin{bmatrix} 14 & 3 \\ 2 & 12 \end{bmatrix}; \quad < k > = 14.3$

Reciprocity correction $C = \begin{bmatrix} 14 & 10.5 \\ 1.17 & 12 \end{bmatrix}; < k > = 14.3$

M2 (Density correction) $C = \begin{bmatrix} 28 & 9.3 \\ 2.33 & 10.67 \end{bmatrix}; < k > = 17.9$

M3 (Density correction + normalization) $C = \begin{bmatrix} 22.4 & 7.5 \\ 1.87 & 8.5 \end{bmatrix}; < k > = 14.3$

$N = 10{,}000 \times [0.1 \quad 0.9]$

$N' = 10{,}000 \times [0.2 \quad 0.8]$

Contact mixing: Seminal and relevant works

- Social contact surveys in eight European countries were conducted between May 2005 and September 2006 to quantify age-specific contact heterogeneity

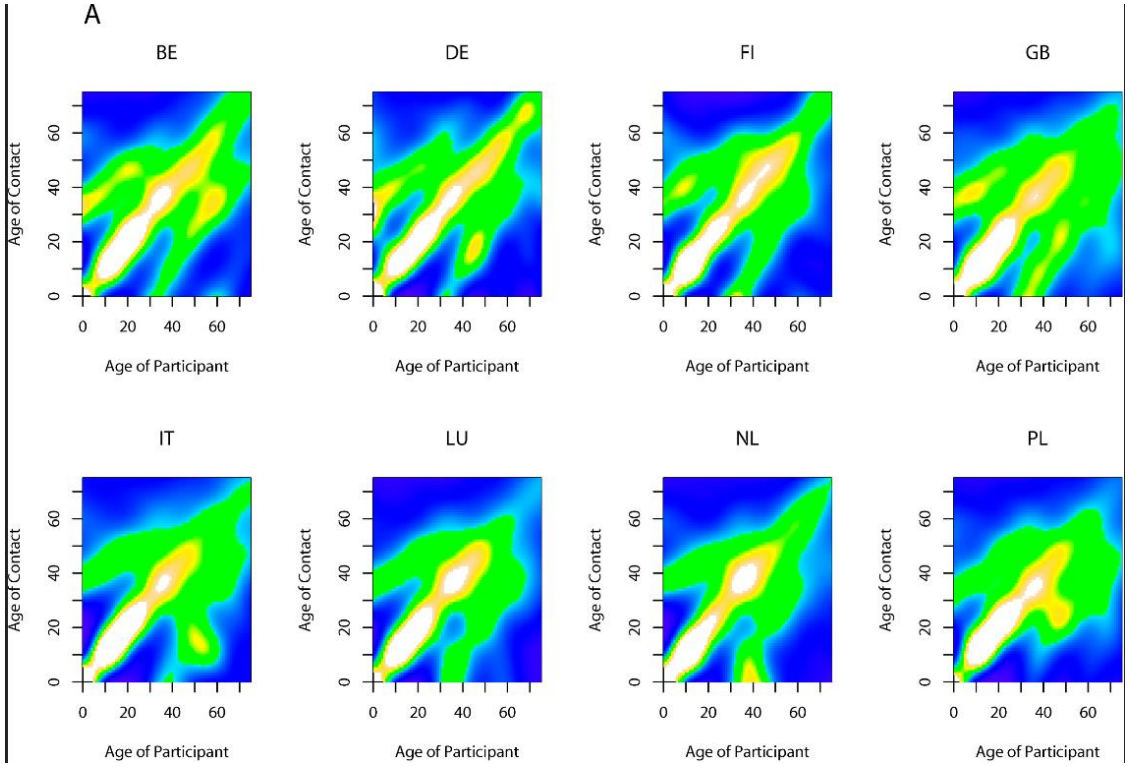
- Contact survey → Contact matrix

- Assortative mixing

- Role of children and adolescents

“Contact”:

- skin-to-skin contact such as a kiss or handshake (a physical contact);
- or a two-way conversation with three or more words in the physical presence of another person but no skin-to-skin contact.



4. Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., ... & Heijne, J. (2008). Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Medicine*, *5*(3), e74.

INSTRUCTIONS

Please read these instructions before you start to make filling in the diary an easier task.

- We would like you to record in the diary **every** person that you have **contact with** on your assigned day
- A contact is defined as:
  - EITHER a **two-way conversation** with three or more words in the physical presence of another person,
  - OR physical **skin-to-skin contact** (for example a handshake, hug, kiss or contact sports).
- Write down **every person that you contact** during the day, regardless of whether the contact was long or short, and whether you know the person or not.
- Contacts made exclusively by **telephone** or **mobile phone** should **NOT** be recorded.
- If you contact the same person several times in the course of the day, only record him/her once, and record the total time you spent with that person over the entire day. So each person you meet during the day and have contact with should only have one line in the diary: **one person, one line.**
- Please provide some information on your contact, namely:
  - Age.
  - Gender.
  - How long the contact with the person was over the entire day.
  - Places where contact(s) occurred (you may indicate several locations).
  - How often you contact this person in general.
  - Whether there was skin-to-skin contact.
- If you don't know the exact age, give an **estimate of the age range** (e.g. 40-45) and try to make it as narrow as possible.
- **Estimate** the total **duration** of time spent in presence of the contact person that day. Example: 5-15 minutes for a contact in a shop or 1-4 hours for longer contact caring for a child at home.
- After you have finished recording the diary, we suggest that you double check the diary entries by trying to **remember** all of your **activities** to make sure you haven't missed any contact persons.
- The **order** in which you write down your contact persons is **not important**. The easiest is to use a **chronological order** according to when you met the person for the first time during your assigned day and then add anyone else that you might remember as you go through your daily activities.
- For the purposes of this study, the day starts at 5 a.m. on the morning of the day assigned, and ends at 5 a.m. the next morning.

4. Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., ... & Heijne, J. (2008). Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Medicine*, *5*(3), e74.

EXAMPLE

This is an example of how somebody might fill in one page of the diary

Age (or range)	Gender F	Gender M	Did you touch his/her skin? Y	N	How often do you have contact with this person in general? Daily or almost daily	About once or twice a week	About once or twice a month	Less than once a month	Never met before	Where did you have contact? (tick all which apply on your assigned day) Home	School / College	Work	Transport	Leisure	Other	Total time spent with person during whole day Under 5 mins	5-15 mins	15 mins – 1 hr	1 – 4 hrs	More than 4 hrs
☐9(- ☐☐)	☐	☑	☑	☐	☑	☐	☐	☐	☐	☑	☐	☐	☑	☐	☐	☐	☐	☐	☑	☐
25(- 30)	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☐	☐	☑	☐	☐
25(- 29)	☑	☐	☐	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☐
30(- 35)	☐	☑	☐	☑	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☑	☐	☐	☑	☐	☐
67(- ☐☐)	☐	☑	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☐	☑	☐	☐	☑	☐	☐
30(- 39)	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☑	☐	☑	☐	☐	☐	☐
17(- 22)	☐	☑	☐	☑	☐	☐	☐	☐	☑	☐	☐	☐	☐	☑	☐	☑	☐	☐	☐	☐
35(- 42)	☑	☐	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☑	☐	☑	☐	☐	☐	☐
42(- ☐☐)	☐	☑	☑	☐	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐
40(- 45)	☐	☑	☐	☑	☐	☐	☐	☑	☐	☐	☐	☐	☐	☐	☑	☑	☐	☐	☐	☐
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First line: You spoke for ten minutes with your 9-year old son on the way to taking him to school in the morning. In the evening, you played with him from 6 p.m. to 8 p.m. and gave him a kiss before going to the bed.

Second line: You spoke with a young saleswoman in your favourite shoe store, which you go to several times a year. Today you tried out several pairs of shoes.

Please take this diary with you during the day and fill it in now and then when you have time. Thank you for your cooperation.

4. Mossong, J., Hens, N., Jit, M., Beutels, P., Auranen, K., Mikolajczyk, R., ... & Heijne, J. (2008). Social contacts and mixing patterns relevant to the spread of infectious diseases. *PLoS Medicine*, *5*(3), e74.

Contact mixing: Seminal and relevant works

Projections of POLYMOD results based on:

- Labor force participation rates,
- School enrolment, and
- Household structures

in 152 countries.[5] ; **[Updated in 2020, preprint [6]]**

- **For a review, see Hoang et al.[7]**

- **Canada**

5. Prem, K., Cook, A. R., & Jit, M. (2017). Projecting social contact matrices in 152 countries using contact surveys and demographic data. *PLoS Computational Biology*, *13*(9), e1005697.

6. Prem, K. *et al.* Projecting contact matrices in 177 geographical regions: an update and comparison with empirical data for the COVID-19 era. *medRxiv* (2020).

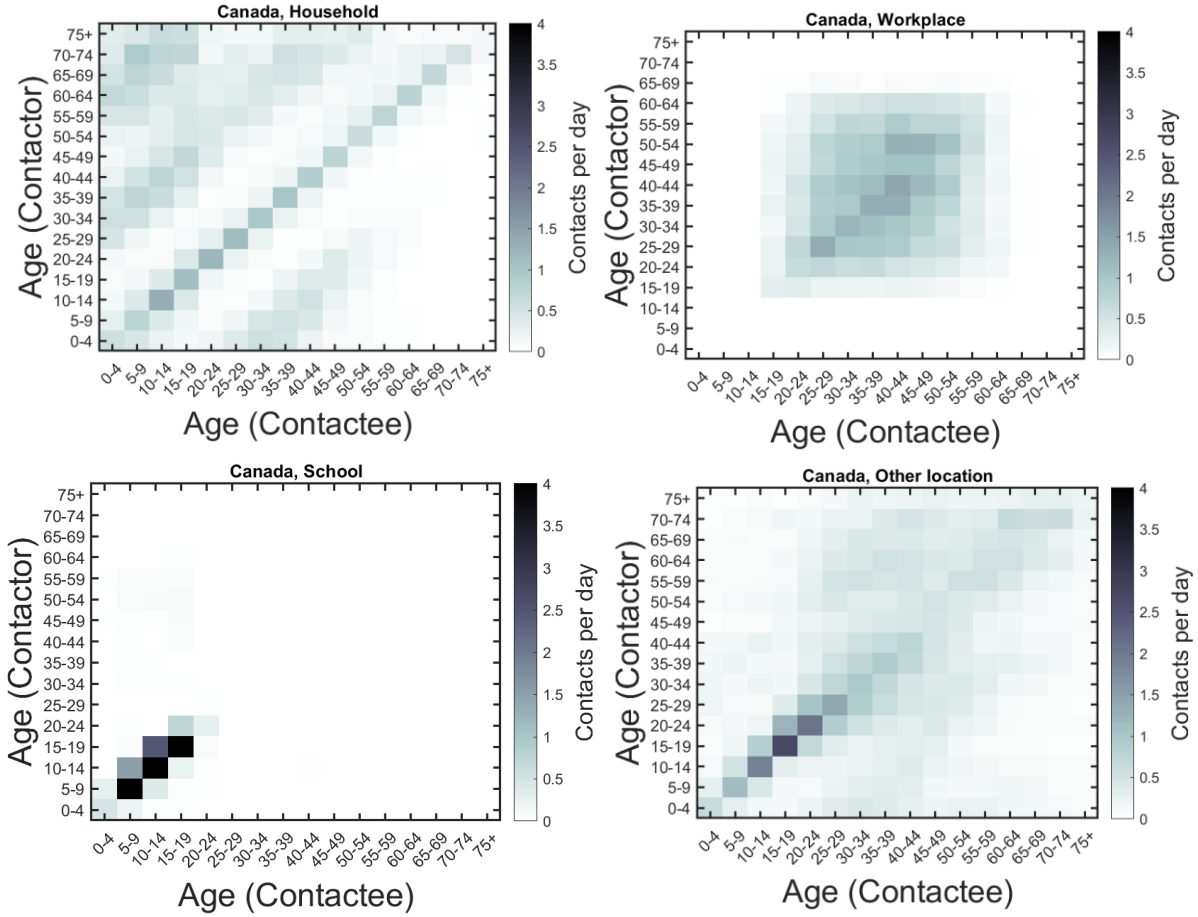
7. Hoang, T., Coletti, P., Melegaro, A., Wallinga, J., Grijalva, C. G., Edmunds, J. W., ... & Hens, N. (2019). A systematic review of social contact surveys to inform transmission models of close-contact infections. *Epidemiology (Cambridge, Mass.)*, *30*(5), 723.

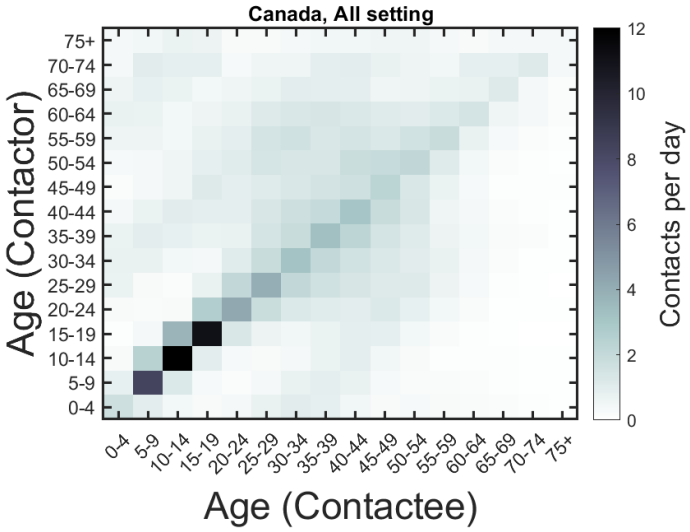
Established setting-specific contact matrices

Canadian reference household, workplace, community and school contact matrices C^H, C^W, C^C, C^S.

$$< k > = \frac{1}{N} \sum_{i,j} C_{ij} N_i.$$

$$= 14.5.$$





6. Prem, K. *et al.* Projecting contact matrices in 177 geographical regions: an update and comparison with empirical data for the COVID-19 era. *medRxiv* (2020).

Establishing contact matrices for Toronto: A practical example

Method: Series of matrix transformations

Data: Canadian reference household, workplace, community and school contact matrices C^H, C^W, C^C, C^S. [6]

1. Reciprocity correction:

$$C_{ij} \rightarrow \frac{1}{2N_i}(C_{ij}N_i + C_{ji}N_j),$$

2. Adjust each reference matrix C^{Ref} , for Canada, to the matrix C, for Toronto, according to the demography of Toronto using:

$$C'_{ij} = C_{ij}^{Ref} \frac{N'N'_j}{N_j \sum_{i,j} C_{ij} \frac{N'_i N'_j}{N_j}} \qquad < k > = \frac{1}{N} \sum_{i,j} C_{ij}^{Ref} N_i.$$

3. Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.

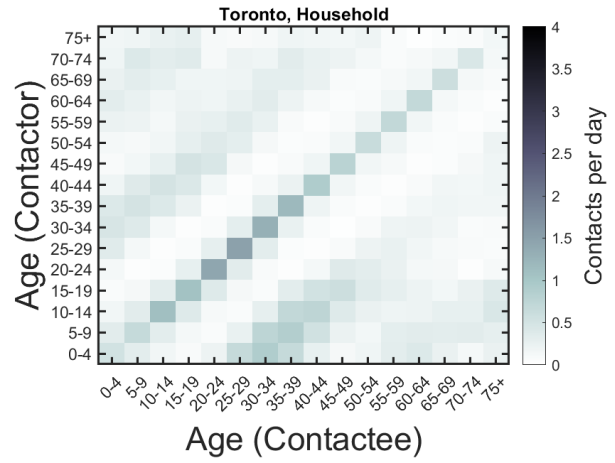
6. Prem, K. *et al.* Projecting contact matrices in 177 geographical regions: an update and comparison with empirical data for the COVID-19 era. *medRxiv* (2020).

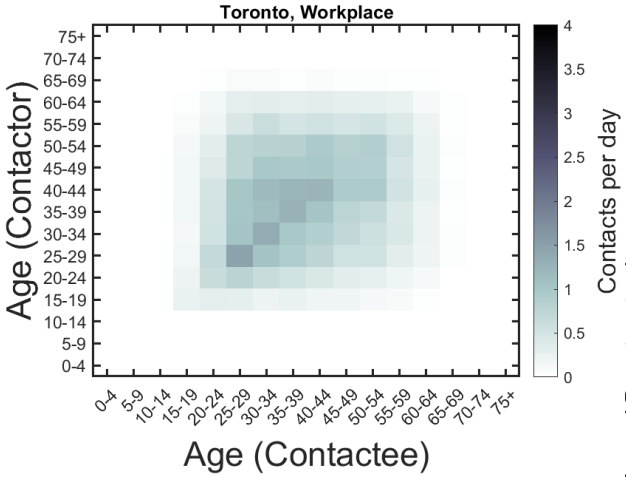
Resultant contact matrices: Toronto

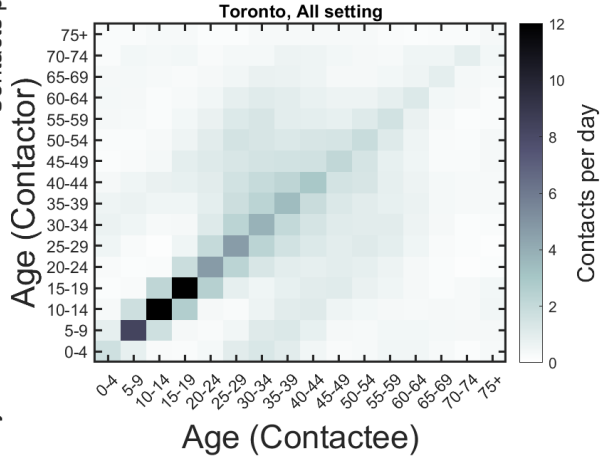
Method: Series of matrix transformations

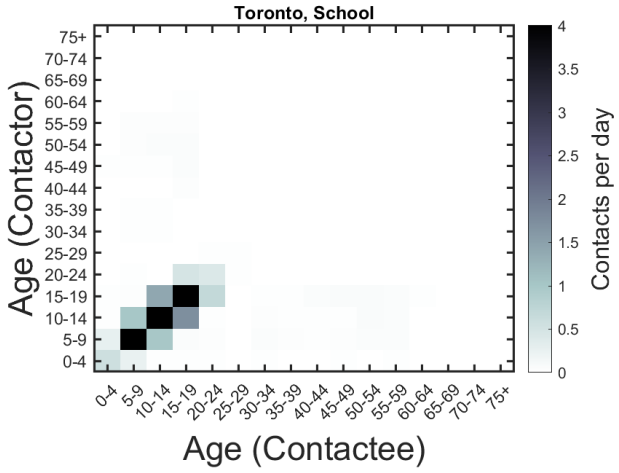
$$< k > = \frac{1}{N} \sum_{i,j} C_{ij} N_i.$$

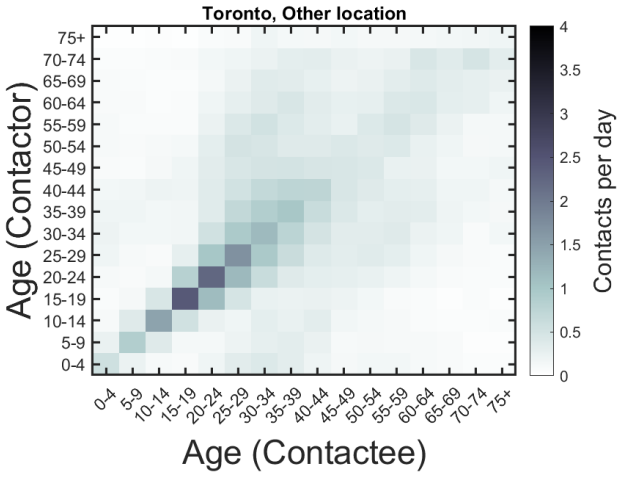
$$= 14.5.$$











Establishing contact matrices for Toronto

- **Adapt to the desired age subdivision format**

$$C_{kl}^{6} = \frac{1}{N_k^6} \sum_{i=1}^{16} \sum_{j=1}^{16} C_{ij}^{16} N_i \frac{\bar{N}_{jl}}{N_j} \frac{\bar{N}_{ik}}{N_i},$$

where $\bar{N}_{jl}$ ($\bar{N}_{ik}$) represents the overlapped population in the old age group j (i) and new age group l (k). And C_{ij}^{16} and C_{kl}^{6} are the entries of the contact matrix for the old and new age structure, respectively. N_k^6 is the population in age group k for the new age structure.

Table 1. Connection table N_{jl} for intervention evaluation and reopening scenario analysis mixing matrix.

		Target age classes					
		0-5	**6-13**	**14-17**	**18-24**	**25-64**	**65+**
Original age classes	**0-4**	0-4					
	5-9	5	6-9				
	10-14		10-13	14			
	15-19			15-17	18-19		
	20-24					20-24	
	25-29					25-29	
	30-34					30-34	
	35-39					35-39	
	40-44					40-44	
	45-49					45-49	
	50-54					50-54	
	55-59					55-59	
	60-64					60-64	
	65-69						65-69
	70-74						70-74

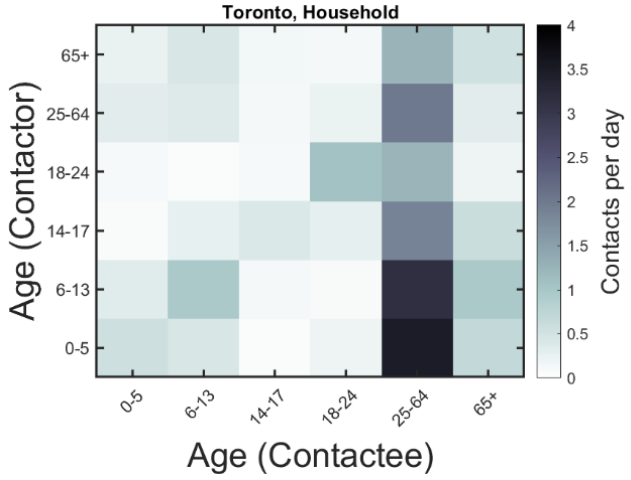
8. McCarthy, Z., Xiao, Y., Scarabel, F., Tang, B., Bragazzi, N. L., Nah, K., ... & Wu, J. (2020). Quantifying the shift in social contact patterns in response to non-pharmaceutical interventions. *Journal of Mathematics in Industry*, *10*(1), 1-25.

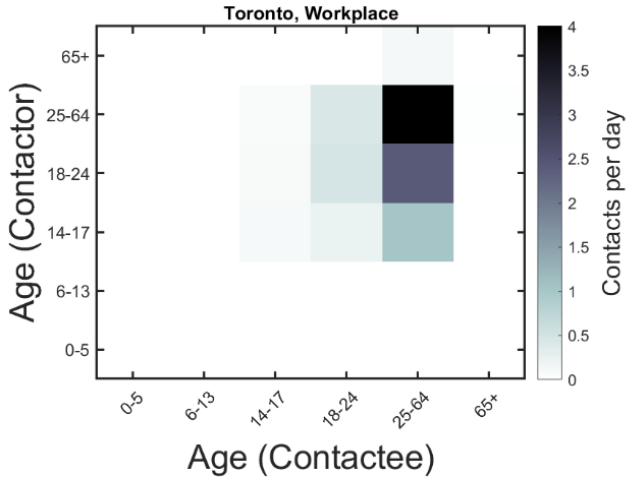
Establishing contact matrices for Toronto

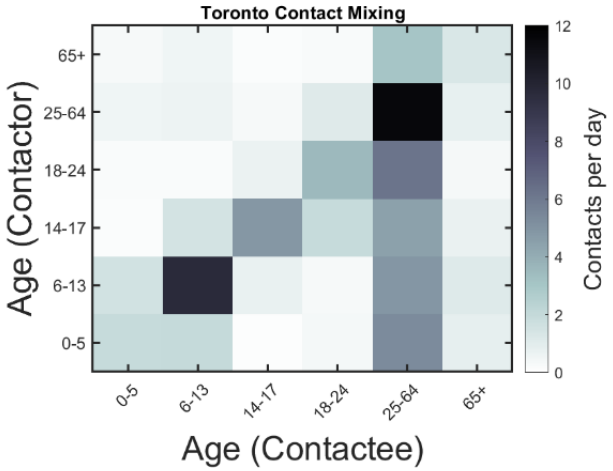
The resultant mixing matrices capturing features of the Toronto demographic are shown as heatmaps.

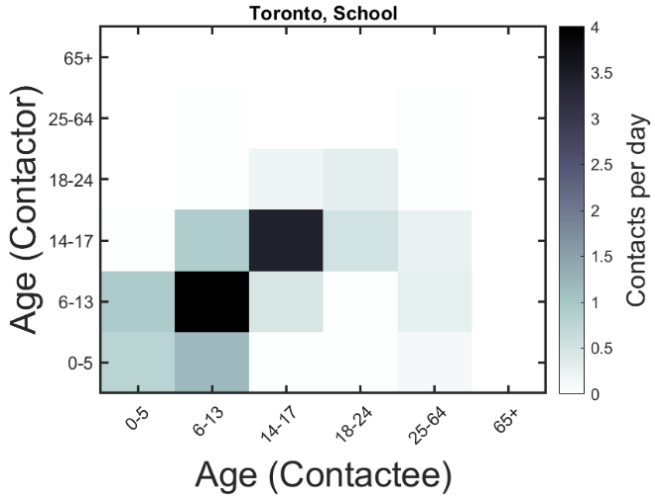
$$< k > = \frac{1}{N} \sum_{i,j} C_{ij} N_i.$$

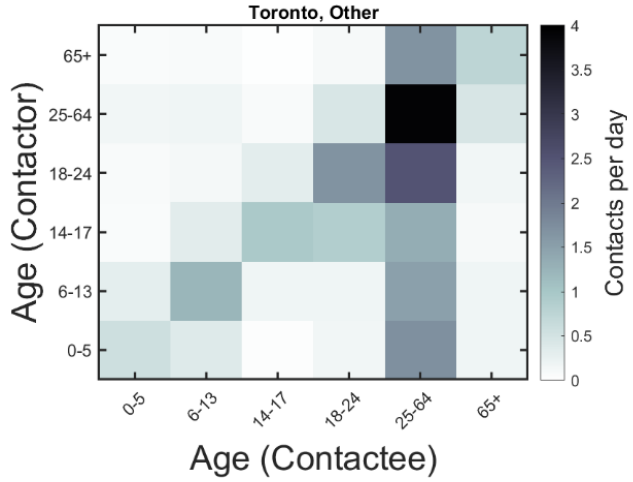
$$= 13.03.$$



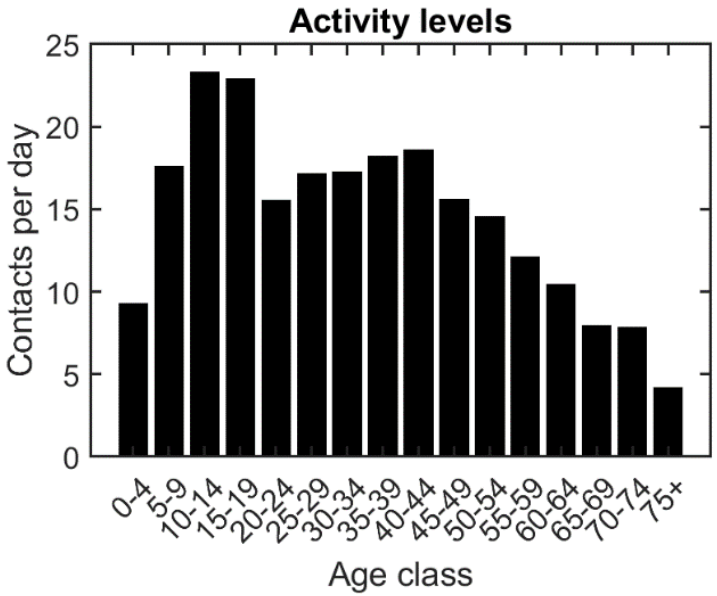


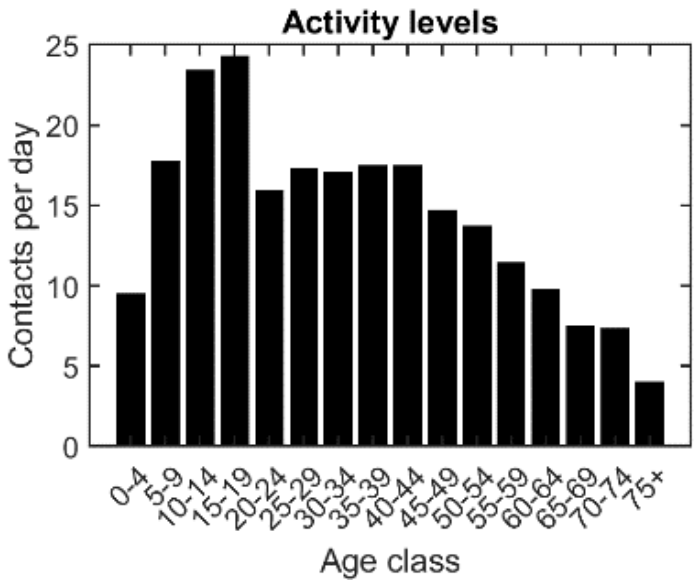


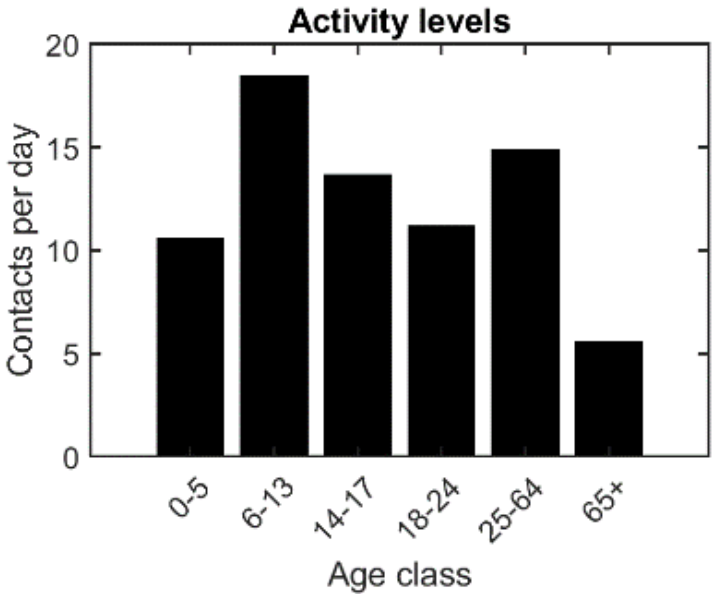




Establishing contact matrices for Toronto







Activity levels according to age class. Activity levels calculated from **A)** Canada Synthetic 2019, [6] **B)** Toronto Synthetic 2019 with 16 age classes, **C)** Toronto Synthetic 2019, 6 age class.

6. Prem, K. *et al.* Projecting contact matrices in 177 geographical regions: an update and comparison with empirical data for the COVID-19 era. *medRxiv* (2020).

Application and COVID-19 Era

- **Integration into transmission dynamics model;**

- **NPIs (and relaxations) and impacts on mixing.**

Shifting mixing patterns in response to public health interventions

Ontario's response: A series of public health interventions taken such as school closure, physical distancing advisories, non-essential workplace closure.

Four distinct phases:

- February 26 – March 14 (phase 0) **[Monitoring and travel advisories]**
- March 14 – 17 (phase 1) **[Public school closure]**
- March 18 – 23 (phase 2) **[State of emergency and physical distancing]**
- March 24 – May 16 (phase 3) **[Non-essential workplace closure]**

Data requirements

Data sources:

- **Established contact matrices;[5, 6]**
- **Age-structured population data;[9]**

Modelling techniques:

- **Alter contact mixing based on changing demographics;[3]**
- **Alter age class subdivisions (Appendix A).[8]**

3.Arregui, S., Aleta, A., Sanz, J., & Moreno, Y. (2018). Projecting social contact matrices to different demographic structures. *PLoS Computational Biology*, *14*(12), e1006638.

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