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Geographical variation of COVID-19 vaccination coverage, ethnic diversity and population composition in Flanders

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ABSTRACT

The vaccination coverage in Flanders is high, but some regions show lower vaccination willingness as compared to the overall vaccination coverage. Beginning November of 2021, the vaccination rate in Flanders was above 93% in age groups above 45 years, and around 85% in the age groups 12 to 44 years. Apart from Flanders as a whole, focus here is on the health sector Maasland, which has a slightly lower vaccination rate, especially in the age groups 12 to 44 years. In the Maasland region, located on the eastern border of Flanders, there are between 1% and 10% less vaccinated individuals than expected according to the vaccination rate in the whole of Flanders, with lowest vaccination rates in the south of the Maasland region. We study the impact of ethnic diversity in the population, population composition with respect to the ethnicity of individuals (in the sense of how the local population composition differs from the Flemish average), and socio-economic status on the vaccination rate at the level of the statistical sector, apart from the effect of age. We explain the statistical methods to investigate geographical differences and illustrate how one can deal with incomplete information in vaccination registries. Ethnic diversity in a region is associated with lower vaccination rates, as is a lower regional socio-economic status. The composition of the population in Maasland is associated with a 35% reduction in the odds to get vaccinated as compared to the overall Flemish population.

Introduction

Countries worldwide are using COVID-19 vaccines in the fight against the global pandemic, hoping that high vaccination rates will allow to get a better grip on the ongoing pandemic. Countries around the globe have rolled out a national vaccination plan in 2021. At the end of 2021, with the COVID-19 omicron variant becoming more prevalent in many countries, many countries are considering to speed up the booster vaccinations to stay ahead of this very contagious variant. While in many countries vaccines are by now available for all inhabitants above a certain age, there is vaccine hesitancy to some degree in various population subgroups. Attaining a good vaccination coverage amongst different regions and populations is however important to avoid continuous circulation of the virus in local communities within a given country.

The US Center for Disease Control and Prevention (CDC) reports that there are differences in the vaccination coverage between urban and rural counties in the United States [10], with lower vaccination coverage in rural counties. In addition, they report lower vaccination coverage in counties with higher levels of social vulnerability [6]. In the United Kingdom, it was observed that health care workers from some ethnic minority groups are more likely to be vaccine hesitant than their White British colleagues [14]. Also Kamal et al. [7] and Bhanu et al. [3] report increased vaccination hesitancy in minority ethnic groups in the UK as well as in other countries. A survey in low- and middle-income countries pointed at a positive association between vaccine acceptance with higher income, lower age, and no earlier infection with COVID-19 [4]. Cascini et al. [5] indicated that, next to socio-demographic factors, also

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a negative perception of vaccine efficacy, safety, convenience, and price play an important role in vaccine hesitancy. Also in Flanders, the Dutchspeaking northern part of Belgium, Valckx et al. [13] reports differences in vaccine willingness amongst locations. This study, based on the Great Corona Survey, shows least vaccination willingness in individuals with low educational background, large household size, difficult financial situation and low mental well-being.

In this paper, we will examine reasons for higher and lower vaccination coverage by investigating the regional disparities between vaccination coverage in Flanders. Since information at the individual level is lacking, the analysis is based on basic information at aggregate level (statistical sector). As subsequent vaccination rounds are deployed and more are planned in which a high vaccination coverage is paramount, it is of utmost importance to study and primarily address reasons for vaccine hesitance. The Belgian vaccination program started in December 2020. The strategy was to first vaccinate nursing home residents, health care workers, the general elderly and vulnerable population, and finally progressively younger individuals. By mid October 2021, all Belgian citizens from the age of 12 years onwards have had the opportunity to get fully vaccinated. The goal of this study was to investigate whether there are areas which need to be identified as risk regions with lower vaccination coverage and whether or not this can be linked to the ethnic diversity and composition of the population with respect to age and origin. For the identification of risk regions we zoom in on one of the primary care zones in Flanders, namely the Maasland region, a region in Flanders with high ethnic diversity. We present the statistical methods that can be used to investigate the local vaccination coverage, accounting for known differences in population distribution. As this is also challenging in terms of data availability, focus is on aggregated data and attention is given on how to deal with incomplete registration data.

The remainder of the paper is organized as follows. In Section 2, the data used for analysis are described, with methodology presented in Section 3. Results are given in Section 4 and discussed in Section 5.

Data

Study region

We focus this study on Flanders (Flemish Region of Belgium) and in particular the regional primary care zone Maasland. Flanders is the largest region in Belgium and includes around 5.8 million inhabitants above the age of 12 years. It is subdivided into 300 municipalities which are further subdivided into 9,194 statistical sectors. The statistical sector is the most refined administrative aggregation used in Belgium. The statistical sectors in Flanders have a mean area size of 1.55 km^2 (IQR: 0.26–1.52) and median population size above 12 years of 640 (IQR: 185–871).

Flanders has been sub-divided into 60 primary care zones, to better coordinate the work of local authorities, health care providers and aid and rescue workers. The zones are geographically defined, formed by one or more municipalities and managed by a care board. During the COVID19 pandemic, the primary care zones were responsible for the organisation of the vaccination centres. The primary care zone Maasland consists of 5 municipalities (Dilsen-Stokkem, Kinrooi, Lanaken, Maaseik, and Maasmechelen) and 195 statistical sectors and includes around 108 k inhabitants above the age of 12 years.

Vaccination

The number of vaccinated individuals and inhabitants in Flanders on November 10, 2021 are obtained from the Flemish Control Tower (in Dutch "Vlaamse controletoren"), which was set up in August 2020 by the Agency for Care & Health [1], a department of the Flemish government. The Flemish Control Tower is an (online) platform to inform local authorities, mayors, governors and health care districts on the pandemic situation at a small geographical scale. By this time, all Belgian inhabitants (≥age 12 years) did have had the opportunity to get fully vaccinated (one dose for the Janssen Vaccine, and two doses for Comirnaty, Spikevax, and Vaxzevria). The number of vaccinated individuals, and the population size, are available in age groups 12–17, 18–44, 45–64, 65–84 and 84+, per statistical sector.

Some data issues occur at the level of the statistical sector. First, the age-specific population numbers per statistical sector were collected on 1/1/2021, but as small deviations in the population counts occur over time due to changes of address, mortality, and population dynamics, this is only an approximation of the actual population numbers. When the vaccination coverage is high, this can, especially in small statistical sectors, result in a situation where the reported number of vaccinated individuals is slightly above the population numbers. As these errors make less than 1% of the population totals, we ignore these errors by truncating the vaccination counts at the population count. A second challenge in the data is that there is approximately 5% of the vaccinated individuals for whom the residential address is only known up to the level of the municipality, and not at the fine level of the statistical sector. If we would ignore the individuals for which we do not have complete information, this would result in an underestimation of the real vaccination rate. In the methods section, we describe how this issue is addressed.

Population demography

Information about the population background (ethnic origin) is available at the level of the statistical sector.

The Flemish population consists for 72.5% of individuals from Belgian origin. Fig. 1 shows the overall composition of the Flemish population for individuals from non-Belgian origin. The largest proportion of individuals in Flanders from non-Belgian origin are from Maghreb countries (Northwest Africa, especially Morocco) and from the Netherlands. The composition is geographically

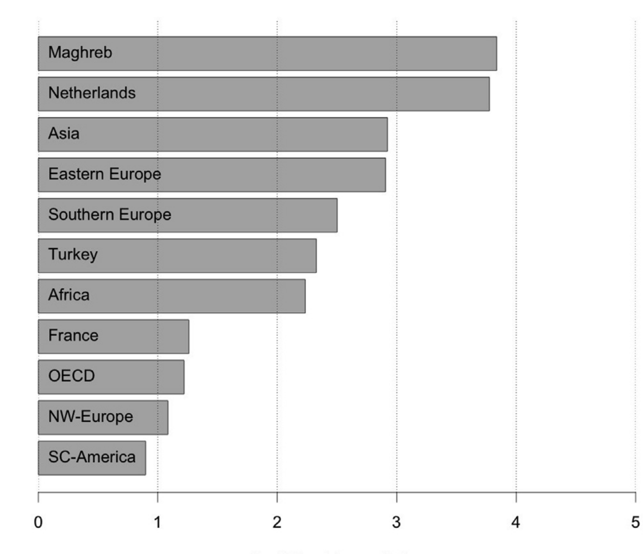

Fig. 1. Percentage of Flemish population by (non-Belgian) origin: Maghreb (Northwest Africa), the Netherlands, Asia, Eastern- and Southern-Europe, Turkey, other countries from Africa (non-Maghreb), France, other rich countries (OECD), North- and WestEurope and South- and Central-America.

varying, with in the Maasland region a smaller proportion of individuals of Belgian origin (53.7%), and a high proportion of individuals from the Netherlands (16.96%), due to its location near the Flemish-Dutch border, followed by individuals from Southern Europe (8.0%) and Turkey (5.4%).

In addition, the percentage of inhabitants that get an increased health insurance contribution (individuals with an income below a certain threshold) is used as a proxy for the socio-economic status of the population in the statistical sector. In Flanders, the mean percentage of inhabitants with increased health insurance contribution is 12.65%. This percentage is varying a lot in Flanders, with the percentage ranging from 0 to 88% (IQR: 7.00–16.00) amongst the statistical sectors.

Methods

Spatial model

We first investigated the geographical differences in the vaccination rate within the Maasland region when compared to the vaccination rate in Flanders. Let Y_{ij} be the number of vaccinated individuals in statistical sector i in age group j, and N_{ij} the corresponding population sizes. We compare the total number of vaccinated individuals in a statistical sector i, i.e. $Y_i = \sum_j Y_{ij}$, with the expected number of vaccinated individuals based on the age-specific vaccination rate in Flanders.

$$r_j = \frac{\sum_i Y_{ij}}{\sum_i N_{ij}}$$

and the age-distribution of the population living in area i [9]. The age-standardized expected number of vaccinated individuals according to the vaccination rate in Flanders is.

$$E_i = \sum_j r_j N_{ij}.$$

In order to investigate whether or not the vaccination in Maasland differs from the vaccination rate in Flanders, we use the following model.

$$Y_i \sim Poisson(\theta_i E_i),$$

$$\log(\theta_i) = \alpha + b_i,$$

$$b_i = \frac{1}{\sqrt{\tau}}\left(\sqrt{1-\phi}\,v_i + \sqrt{\phi}\,u_i\right),$$

$$v_i \sim N(0, \sigma_v^2) and u_i \sim N(0, \frac{1}{\tau_u} Q_{ii}^{-})$$

where θ_i denotes the area-specific relative risk [8], an estimate of the age-standardized vaccination ratio. The random effect b_i is used to take into account extra-Poisson variation and spatial correlation due to unmeasured effects, and.

is defined as a weighted average of a spatially structured random effect u_i that accounts for spatial correlation and an unstructured random effect v_i that accounts for pure overdispersion. The parameter ϕ measures the proportion of variance explained by the spatially structured effect [11] Note that the Q^- denotes the generalised inverse of the precision matrix Q with entries $Q_{ij} = -1$ when areas i and j are neighboring, $Q_{ij} = 0$ when areas i and j are not neighboring, and diagonal elements $Q_{ii} = n_{\delta i}$, representing the number of neighbors of area i [2]. Note that when the age-standardized vaccination ratio θ_i is below 1, the number of vaccinated individuals in that area is lower than expected according to the vaccination rate in Flanders.

Diversity model

Let $(p_{1i},\ldots,p_{Ki})$ be the population composition in terms of origin in statistical sector i, where p_{ki} is the population fraction of origin k in sector i. The ethnic diversity of the population can be summarized by the Shannon Equitability index.

$$S_i = -\frac{\sum_{k=1}^{K} p_{ki}\log(p_{ki})}{\log(K)},$$

where higher values correspond to more ethnic diversity in the population. If $S_i = 0$ the community consists of only one population group (low ethnic diversity) while $S_i = 1$ applies when all population groups represent exactly $1/K$-th of the population (high ethnic diversity).

In order to investigate the impact of population composition and/or ethnic diversity on the vaccination rate in different age groups, two types of models are fitted to the age-specific vaccination rates. The first model quantifies the impact of the ethnic diversity on the vaccination rate in a statistical sector:

$$Y_{ij} \sim Binom(\pi_{ij}, N_{ij}),$$

$$logit(\pi_{ij}) = \alpha_j + f_j(S_i)$$

where π_{ij} is the vaccination rate in age-group j in statistical sector i, $\frac{\exp(\alpha_j)}{1+\exp(\alpha_j)}$ is the age-specific vaccination rate in a completely homogeneous population (in the sense that it consists of only one ethnic population group) and $f_j(S_i)$ measures the impact of the population diversity of the statistical sector on the vaccination rate. Alternative model formulations are investigated, such a linear effect or quadratic effect of the Shannon index or a non-linear spline model, and inclusion of the socio-economic status (SES), i.e.

$$logit(\pi_{ij}) = \alpha_j + f_j(S_i) + \beta SES_i$$

A dispersion factor is included in the model to allow for overdispersion in the data via a quasibinomial approach.

The second model investigates the impact of the ethnic composition of the population on the vaccination rate, as compared to the overall ethnic composition in Flanders:

$$Y_{ij} \sim Binom(\pi_{ij}, N_{ij}),$$

$$logit(\pi_{ij}) = \alpha_j + \sum_{k=2}^{K} \delta_k (p_{ki} - p_k)$$

where p_{ki} represents the proportion of population group k in statistical sector i and p_k the corresponding proportion in the whole of Flanders. Note that p_{1i} corresponds to the proportion of individuals from Belgian origin, and is not taken into account as a covariate, because of the collinearity of the variables, i.e., the sum of the proportions is 1. As a result, the age-specific parameter $\frac{\exp(\alpha_j)}{1+\exp(\alpha_j)}$ is to be interpreted as the vaccination rate in age group j when the population has the same ethnic composition as the entire Flemish population, and δ_k quantifies the association between the proportion of population group k and the vaccination rate. Also in this model, we account for over-dispersion.

Multiple imputation model

As a result of the absence of full information about the statistical sector level for a number of people, a multiple imputation method is used. Indeed, a complete case analysis of vaccination rate for individuals for which the residential address is known at the statistical sector level would lead to considerable underestimation of the vaccination rate. Let Z_{mj} be the number of vaccinated individuals in municipality m and in age group j, for which the statistical sector is unknown.

Further, $Y_{i(m)j}$ denotes the reported number of vaccinated individuals in statistical sector i and in municipality m with corresponding population size $N_{i(m)j}$. We randomly redistributed the Z_{mj} vaccinated individuals over all statistical sectors $i \in m$, by randomly sampling Z_{mj} individuals (without replacement) from the set of $\{N_{i(m)j} - Y_{i(m)j} | i \in m\}$ (reported) non-vaccinated individuals, with sampling probability for each individual in this set given by the reported vaccination rate in the statistical sector $Y_{i(m)j}/N_{i(m)j}$. We simulate 20 imputed datasets. Each imputed dataset is analysed separately using the models mentioned in the previous sections, and results are combined according to Rubin's approach [12].

Results

The vaccination coverage in Flanders is high, with overall vaccination rates of 86.5%, 88.5%, 93.7%, 97.1%, and 93.0%, respectively, in age groups 12–17, 18–44, 45–64, 65–84, and 85 + on November 10, 2021.

Fig. 2 shows the vaccination rates per statistical sector in Flanders (black dots) and in the health care zone Maasland (blue dots) per age group. The size of the dots is proportional to the size of the corresponding population. The black and blue lines show the average vaccination coverage in Flanders and Maasland, respectively. While vaccination is high, it can be observed that there is also quite some variation in the vaccination rate amongst statistical sectors. Especially in the younger age group (12–17 and 18–44), there seems to be higher vaccine hesitancy, in the whole of Flanders (black dots). It is also exactly in these age groups that the vaccination rate in the health care zone Maasland (blue dots) seems to be slightly lower as compared to the whole of Flanders. Note that the vaccination coverage is less than 80% in 12.1% of the Flemish statistical sectors and in 17.9% of the Maasland' health care region.

The estimated age-standardized vaccination ratio, based on the spatial model as described in Section 3.1, is given in Fig. 3. The boundaries of the Maasland region, with municipalities Kinrooi, Maaseik, Dilsen-Stokkem, Maasmechelen and Lanaken from north to south, are indicated in the map. A map of the vaccination ratio in

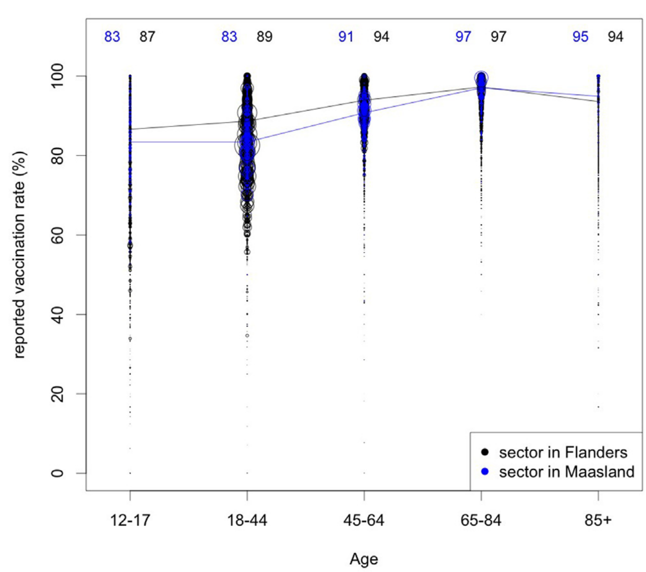

Fig. 2. Vaccination rates per statistical sector and age group in Flanders (black dots) and in the health care zone Maasland (blue dots). The black and blue lines (and the blue and black values on top of the figure) show the average vaccination readiness in Flanders and Maasland, respectively.

the Maasland health care region as compared to Flanders, is given in the Appendix (Fig. 6). It can be seen that there are several regions in Flanders with age-standardized ratio below one, indicating that the observed number of vaccinated individuals in those areas is lower than expected according to the age-specific vaccination rate in the whole of Flanders. The most important areas are: the region around.

Brussels, the region around the city of Antwerp, the northern region at the boundary with the Netherlands, and the Maasland region. Within the Maasland region, there is a north–south trend with in the north between 1% and 3% less vaccinated individuals as expected, and in the south between 3% and 10% less vaccinated individuals as expected according to the vaccination rate in Flanders. Note that a lower vaccination rate is also seen at the border between Lanaken and the Netherlands.

The Shannon index as described in Section 3.2 is a measure of the ethnic diversity in the region, with higher values corresponding to a more ethnic diverse region. In Flanders, it varies between 0 and 0.91, with median 0.35 and inter-quantile range (0.26–0.46). An east–west gradient can be seen in the ethnic diversity, with regions in the east of Flanders being more ethnic diverse as compared to regions in the west (Fig. 7 in the Appendix). In addition, in and around large cities, the ethnic diversity is larger as compared to more rural areas. The most ethnic diverse regions are the regions around Brussels, Antwerp and the Maasland region. In the Maasland health sector, the Shannon index has median 0.51 and inter-quantile range (0.42–0.60), and has therefore a larger ethnic diversity among its population as compared to the overall Flemish population.

This is visualized in Fig. 8 (Appendix), showing a histogram of the Shannon index in Flanders (grey) and the Maasland health sector (blue). The percentage of inhabitants that get increased health insurance contribution is more scattered in Flanders (Fig. 9 in the appendix).

The impact of age and socio-economic status on the vaccination rate is summarized in Table 1. There are important differences in the vaccination rate amongst different age groups, with the highest vaccination rate in the age group 65–84, followed by the age groups 45–64 and 85+. Regions with a lower socio-economic status have a lower vaccination rate. The effect of ethnic diversity in the different age groups is visualized in Fig. 4, with the colours correspond to the different age groups. The histogram at the bottom of the figure is a presentation of the frequency of the Shannon index amongst the statistical sectors in Flanders, and the vertical line corresponds to the median Shannon index in Flanders. The odds of being vaccinated is highest in areas where the Shannon diversity lies between 0.2 and 0.4. Smaller vaccination rates are seen for all age groups in regions with a more ethnic diverse population. Higher diversity in the region has the strongest decline in odds for the youngest age groups (12–17 and 18–44), followed by the age group 65–84. Smaller vaccination rates are also observed in regions with a limited ethnic diverse population. The odds of being vaccinated decreases by 54% in the youngest age group, followed by 48% in the age group 65–84, 40% in the age group 18–64 and 20% in the oldest age group, when the diversity index equals 0.51 (the median value in Maasland) as compared to an area where the diversity index equals 0.35 (the median value in Flanders).

The geographical variation in the vaccination rate in Flanders is also related to the population composition. Fig. 5 shows the impact of ethnicity on the vaccination coverage in Flanders. All effects are below 1, indicating that any deviation from a population with a completely Belgian origin reduces the vaccination rate in the statistical sector. The effect in areas with higher population proportions from Eastern-Europe and France stand out (reduction in the odds around 5% per unit increase in the population percentage), followed by the effect of population proportions from OECD countries

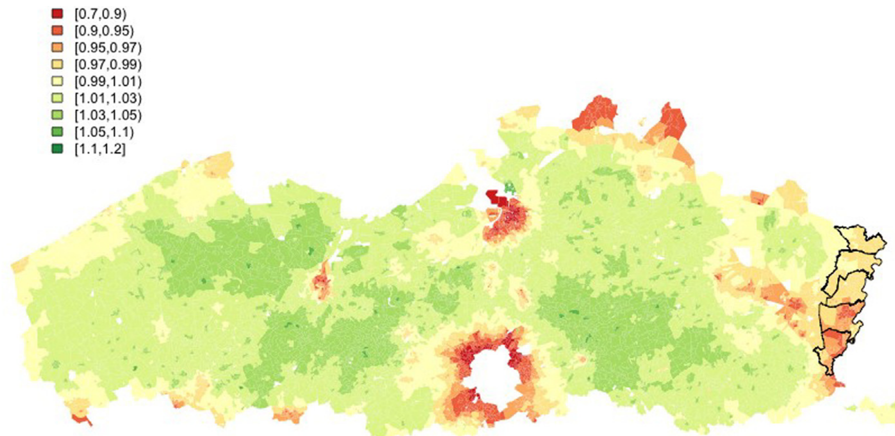

Fig. 3. Estimated age-standardized vaccination ratios as compared to the vaccination rate in Flanders, based on the spatial model. Areas with vaccination ratio below 1 are indicated in orange/red, while areas with vaccination ratio above 1 in light/dark green. The boundaries of the municipalities of the Maasland region are shown.

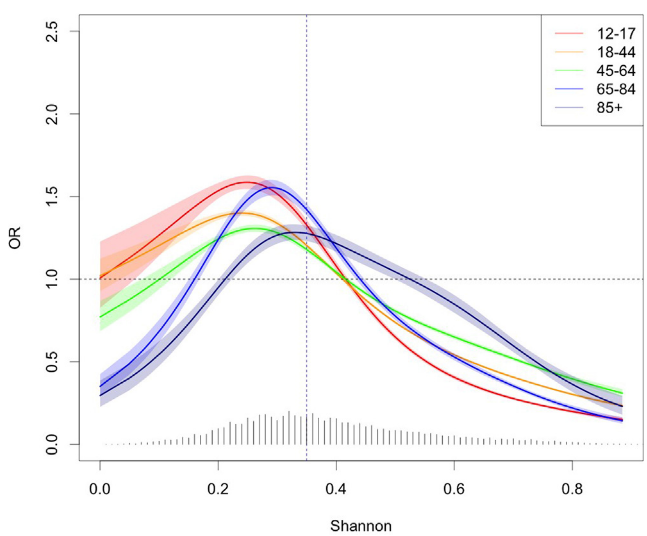

Fig. 4. Multiplicative effects of diversity (Shannon index) on the odds to be vaccinated in an area, with 95% confidence interval, based on the diversity model. The colours correspond to the different age groups. The histogram at the bottom of the figure is a presentation of the frequency of the Shannon index amongst the statistical sectors in Flanders, and the vertical line corresponds to the median Shannon index in Flanders.

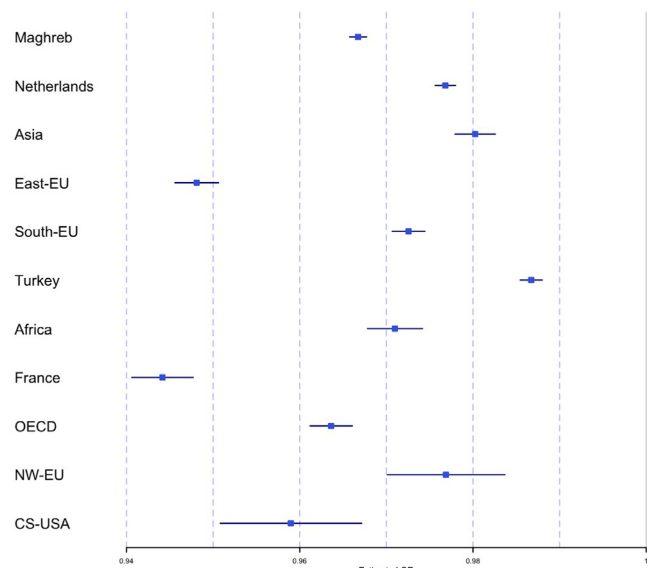

Fig. 5. Multiplicative effects of composition on the odds to be vaccinated in an area, corresponding to a 1% increase in population proportion of origin from Maghreb (Northwest Africa), the Netherlands, Asia, East- and Southern-Europe, Turkey, other countries from Africa (non-Maghreb), France, other rich countries (OECD), North- and West-Europe and South- and Central-America. The dots are the point estimates, the horizontal lines the 95% confidence intervals.

and Central- and South-America (reduction in the odds around 4% per unit increase in the population percentage) and Maghreb, Africa and South-EU (reduction in the odds around 3% per unit increase in the population percentage). In line with previous results, it is observed that regions with a higher proportion of individuals from non-Belgian origin, and thus with higher ethnicity, have a lower vaccination coverage. For the Maasland region, with a high proportion of individuals with origin in the Netherlands, Southern-Europe and Turkey, the composition of the population accounts for a reduction of 35.2% (38.9% − 31.1%) of the odds to get vaccinated as compared to the Flemish population composition.

Discussion

The vaccination campaign in Flanders has been a success, with overall high vaccination rates in all age groups. This study shows that there is quite some heterogeneity amongst regions, with some regions having a lower vaccination coverage. There are differences in the vaccination rate of individuals in different age groups, with the children (age 12–17) having the lowest vaccination rate and the elderly (age 65–84) the highest vaccination rate. This possibly results from older people to be first vaccinated in the national vaccination program, although at the time of study all individuals have had the chance to get fully vaccinated, and this could thus indicate higher vaccine hesitance in younger individuals. While age can partly explain differences in vaccination rates amongst regions, another important factor that hampers vaccination in some regions is the population composition with respect to ethnicity and socio-economic status. Areas with a more diverse population and with lower socio-economic status have lower vaccination coverage. The impact of different ethnicity groups on the vaccination rate varies, and depends on the local composition of the population. For the Maasland health care region, the ethnic composition of the population explains a reduction of 35.2% (38.9% − 31.1%) of the odds to get vaccinated.

Similar results about impact of age and socio-economic status were observed in the individual survey by Valckx et al. [13]. In the present study, we found an additional factor influencing the

Table 1
Odds ratio (OR) estimates of binomial regression model corresponding to the age effect as compared to the age group 12–17, and the effect of lower socio-economic status (proportion inhabitants with increased health insurance contribution, LowSES). Lower (LL) and upper (UL) limits are given as well.

Parameter	*OR*	LL	UL
Age 18–44	1.106	1.082	1.131
Age 45–64	1.901	1.858	1.945
Age 65–84	4.577	4.443	4.714
Age 85+	1.651	1.592	1.713
LowSES	0.688	0.650	0.728

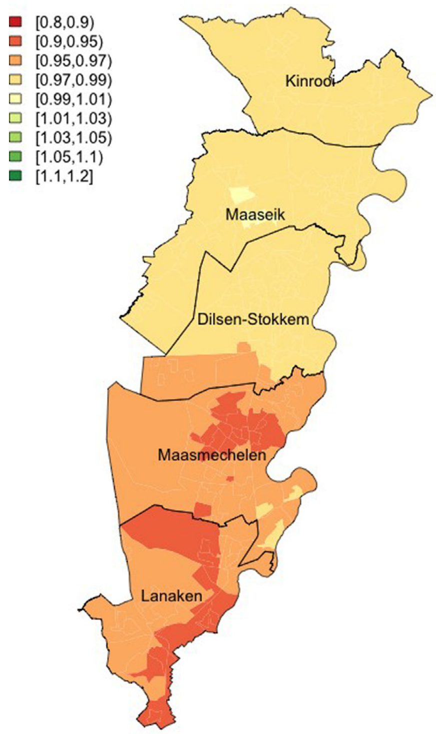

Fig. 6. Geographical variation of age-standardised vaccination ratio in the Maasland region by November 10, 2021.

vaccine willingness, namely the diversity and composition in ethnic origin of the population. Possible reasons for this can be the influence from homeland via television and social media and

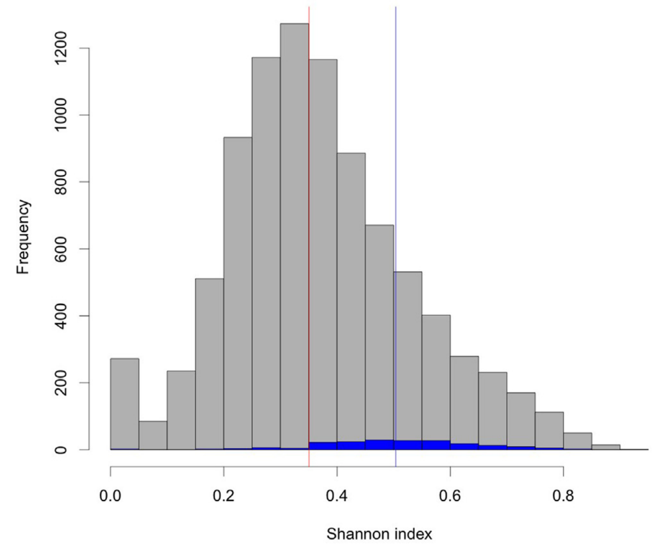

Fig. 8. Histogram of Shannon index in Flanders (grey) and in Maasland (blue). The vertical lines correspond to the median in Flanders (red) and Maasland (blue).

influence by peer community. While language could be a barrier, it should be mentioned that information brochures on the vaccination campaign were made available in different languages, both on paper and online. On the other hand, it could be that this information did not properly reach the people that it was intended for, or that the trust in the Belgian vaccination campaign in more diverse regions was lower. Note that the Flemish vaccination centers work with volunteers, whether or not reimbursed as professionals, and the lack of volunteers of non-Belgian origin in Maasland may cause a lack of confidence in the Flemish approach to the vaccination campaign. In future campaigns, it might therefore be useful to try and involve volunteers and professionals of non-Belgian origin.

The vaccination coverage in Flanders is relatively high from an international perspective (Our World in Data, https://github.com/owid/covid-19-data/tree/master/public/data).

Some Southern European countries have a slightly higher vaccination rate (Portugal reached 88% at the end of November, and Spain 80%). Eastern European countries, in reverse, have relatively low vaccination rates (Bulgaria 25%, Romania 39%, Slovakia, Slovenia, and Serbia about 45%, Poland 54%, Czechia 59%, and Lithuania 66%). France reached 70% at the end of November, after a major overhaul of its campaign starting mid-July 2021. Morocco was at

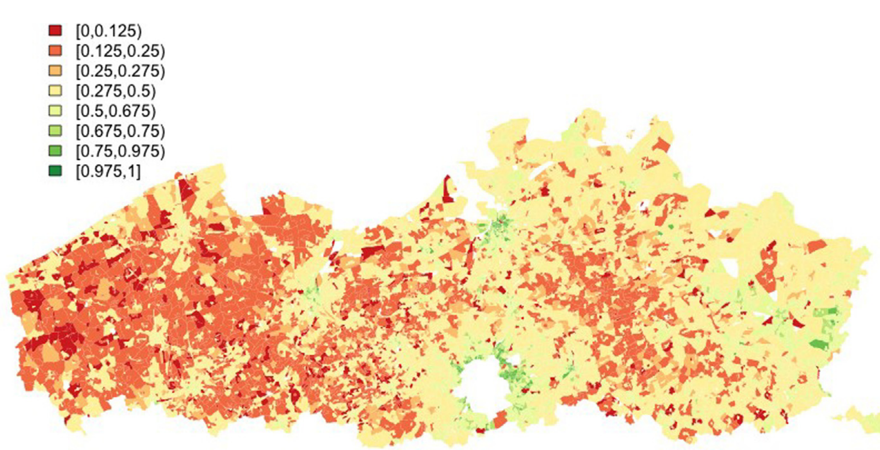

Fig. 7. Geographical distribution of diversity index in Flanders.

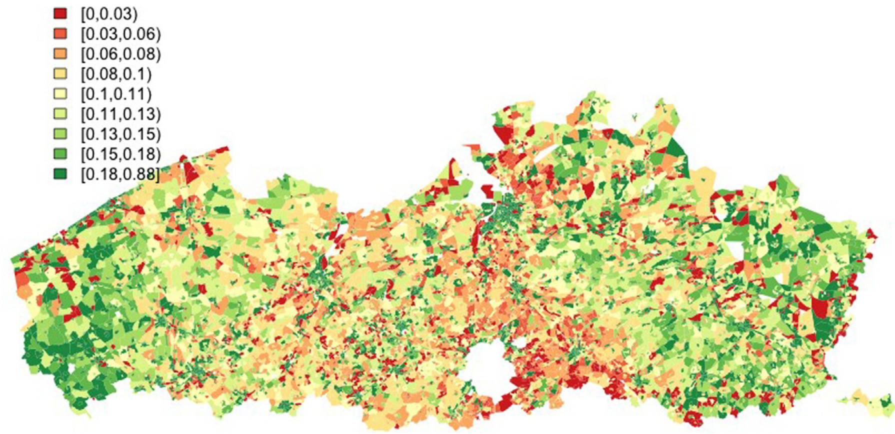

Fig. 9. Geographical distribution of proportion of individuals with increased health insurance contribution in Flanders.

61% and Turkey at 66%. Latin America has reached relatively high vaccination coverage, with Brazil at 76% and Chile even 88%, like Portugal. The low vaccination rates in Eastern Europe and France are in line with the effects observed in this study. Statistical sectors in Flanders and in the Maasland health sector with a larger proportion of inhabitants originally from these countries have a lower vaccination coverage.

The concepts of ethnic diversity and ethnic population composition are linked, although different. While diversity is a summary measure on how diverse the population is, the population composition are the proportions corresponding to the different ethnic population groups. The advantage of studying the impact of ethnic diversity has the advantage of simplicity, as it typically consists of a single summary measure of the population. Using the population composition on the other hand allows us to measure individual impacts of population groups, if the impact of different groups on the vaccination rate is different. Interpretation of the latter analysis has to be done with care, as the measured associations can only be interpreted at the population level, while it is tempting to translate it also to the individual level. A disadvantage of the use of the population composition is that many parameters need to be estimated, and multicollinearity can occur if there is an association amongst population groups. The number of parameters could however be reduced by combining multiple population groups with similar characteristics. As diversity and composition are different concepts, it would be interesting to also investigate the two effects together. In this setting however, in which only aggregate information on the vaccination rate is available, this led to multicollinearity issues. It is recommended to further study this in future using individual level information, in which way the impact of diversity of the community and individual origin can be separated.

As far as we know this is the first study examining the impact of determinants related to ethnic composition on regional vaccination coverage in Flanders. This knowledge can help in improving the design of the vaccination campaigns. An important remark of this study is that aggregated data are used to investigate the impact of diversity and population composition on the vaccination rate. Care is needed not to interpret the observed effects at an individual level. It would therefore be interesting to further collect and examine individually-based data to also understand which individual considerations are important to decide whether or not to get vaccinated in Flanders, for example using the Great Corona Study [13]. Another important note of this study is that it is based on official numbers of vaccinated individuals. No information on the number of individuals that were vaccinated in their country of origin is available. This is especially important for individuals from Turkey, Eastern Europe and the Netherlands. Several inhabitants from Turkish and Eastern European origin indicate that they have been vaccinated in their homeland during the holiday period July-August 2021, although with a vaccine not recognized in the European Union and therefore not registered in Belgium. In addition, while it was noted that the boundary region between Lanaken and the Netherlands has a low vaccination ratio as compared to Flanders, this is a region with a lot of inhabitants from the Netherlands who might have been vaccinated in the Netherlands via an employer, but which also has not been registered in Belgium.

In future analyses, we will follow-up the vaccination rate in the younger age groups. In Belgium, vaccination was recently approved in children younger than 12 years of age. The vaccination rate in this age group will be studied. The vaccination campaign started December 2021, and the acceptance of the booster vaccine will be carefully followed.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

References

[1] Agency for Care & Health (2021) Handleiding controletoren COVID-19. URL https://www.zorg-en-gezondheid.be/handleiding-controletoren-covid-19. Accessed on 01 February 2021.

[2] Besag J, York J, Mollié A. Bayesian image restoration with two applications in spatial statistics. Ann Inst Stat Math 1991;43:1–59. https://doi.org/10.1007/BF00116466.

[3] Bhanu C, Gopal DP, Walters K, Chaudhry UAR, Kesselheim AS. Vaccination uptake amongst older adults from minority ethnic backgrounds: A systematic review. PLoS Med 2021;18(11):e1003826. https://doi.org/10.1371/journal.pmed.1003826.

[4] Bono SA, Faria de Moura Villela E, Siau CS, Chen WS, Pengpid S, Hasan MT, et al. Factors affecting covid-19 vaccine acceptance: An international survey among

low- and middle-income countries. Vaccines 2021;9(5):515. https://doi.org/10.3390/vaccines9050515.
[5] Cascini F, Pantovic A, Al-Ajlouni Y, Failla G, Ricciardi W. Attitudes, acceptance and hesitancy among the general population worldwide to receive the COVID-19 vaccines and their contributing factors: A systematic review. EClinicalMedicine 2021;40:101113. https://doi.org/10.1016/j.eclinm.2021.101113.
[6] Hughes MM, Wang A, Grossman MK, Pun E, Whiteman A, Deng Li, et al. County-level covid-19 vaccination coverage and social vulnerability — united states, december 14, 2020–march 1, 2021. MMWR Morb Mortal Wkly Rep 2021;70(12):431–6.
[7] Kamal A, Hodson A, Pearce JM. A rapid systematic review of factors influencing covid-19 vaccination uptake in minority ethnic groups in the UK. Vaccines 2021;9(10):1121. https://doi.org/10.3390/vaccines9101121.
[8] Lawson AB. Bayesian disease mapping: hierarchical modeling in spatial epidemiology. Chapman and Hall/CRC Press; 2013.
[9] Lee D. A comparison of conditional autoregressive models used in Bayesian disease mapping. Spatial and Spatio-temporal Epidemiology 2011;2(2):79–89. https://doi.org/10.1016/j.sste.2011.03.001.
[10] Murthy BP, Sterrett N, Weller D, Zell E, Reynolds L, Toblin RL, et al. Disparities in covid-19 vaccination coverage between urban and rural counties — united states, december 14, 2020–april 10, 2021. MMWR Morb Mortal Wkly Rep 2021:759–64. https://doi.org/10.15585/mmwr.mm7109a2.
[11] Riebler A, Sorbye SH, S.D.R.H.. Bayesian spatial model for disease mapping that accounts for scaling. Stat Methods Med Res 2016;1145–1165. https://doi.org/10.1177/0962280216660421.
[12] Rubin DB. Multiple imputation after 18+ years. J Am Stat Assoc 1996;91(434):473–89.
[13] Valckx S, Cr'evecoeur J, Verelst F, Vranckx M, Hendrickx G, Hens N, et al. Individuals factors influencing covid-19 vaccine acceptance in between and during pandemic waves (july-december 2020). Vaccine, 40: 2022; 151–61, https://doi.org/10.1016/j.vaccine.2021.10.073.
[14] Woolf K, McManus C, Martin CA, Nellums LB, et al. Ethnic differences in sars-cov-2 vaccine hesitancy in united kingdom healthcare workers: Results from the uk-reach prospective nationwide cohort study 10018. The Lancet Regional Health 2021. https://doi.org/10.1016/j.lanepe.2021.100180.