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Research Article

# Spatial patterns of excess mortality in the first year of the COVID-19 pandemic in Germany

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## Keywords
*COVID-19,*
*Excess mortality,*
*Standardized Mortality Ratios,*
*Spatial analysis,*
*Regional analysis*

## Abstract
In order to quantify the societal impact of the Corona pandemic, several studies have estimated excess mortality rather than infections or COVID-19-related deaths. The question of whether there was excess mortality associated with COVID-19 in Germany in the first year of the pandemic is controversial, as there are different ways of calculating this. From the perspective of health geography, however, this question must be answered with a spatial approach since epidemics are spatial diffusion processes and mortality varies regionally. This study aims to test whether there is excess mortality at a regional level in Germany in 2020, whether it is spatially dependent and whether all-cause mortality is associated with COVID-19-related deaths. Excess mortality is investigated at a small-scale spatial level (NUTS 3; 400 counties) and under consideration of demographic changes by calculating Standardized Mortality Ratios (SMRs). SMRs and COVID-19-related deaths per 100,000 people are tested for spatial dependence by the Moran's I index. It is, furthermore, tested whether all-cause mortality is associated with COVID-19-related deaths by correlation coefficients. Excess mortality can be detected in only a minority of counties, regardless of age group, confirming previous results of no excess mortality overall. However, there are large regional disparities of all-cause mortality and COVID-19-related deaths. In older age groups, both indicators show spatial dependence. These results make it possible to identify COVID-19 hotspots. (Excess) mortality in older age groups is impacted by COVID-19, but this association is not found for young and middle age groups.

***Highlights:***

*-Excess mortality is used to measure the societal impact of the corona pandemic*

*-Regional all-cause mortality and COVID deaths in Germany for 2020 are analysed*

*-Excess mortality has occurred in a minority of counties*

*-Regional mortality and COVID-19-related deaths show spatial dependence*

*-Excess mortality among older people is impacted by COVID but not among younger people*

## 1. INTRODUCTION

Since the emergence of the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2) and the Coronavirus disease 2019 (COVID-19), which is the respiratory illness caused by SARS-CoV-2, there has been a discussion about the overall societal effects of the pandemic. These impacts can be, for example, an overwhelming of the healthcare system (due to many serious illnesses at the same time) or deaths attributed to COVID-19. Estimates of the infection fatality rate (IFR) of SARS-CoV-2 from epidemiological studies range between 0.00% and 1.54% with a median value of 0.23%. The risk increases drastically with age (Ioannidis, 2021). Based on a literature review, a German study defines all people of 65 years and older as the COVID-19 “risk group”, with several previous illnesses (e.g., heart disease, obesity) playing an important role in the probability of a severe course (Rommel et al., 2021).

To account for the “burden of disease” of the COVID-19 pandemic, many studies look at excess mortality instead of using data on confirmed infections and deaths because this data is often subject to uncertainties, including variations in testing or different definitions of a COVID-19 death (e.g., Kowall et al., 2021; Kontopantelis et al., 2021; Michelozzi et al., 2020; Stang et al., 2020). Excess mortality describes an increased mortality compared to an expected value. Analysis of excess mortality allows mortality from COVID-19 to be quantified by comparing actual deaths with expected deaths that would have occurred without the pandemic (Kowall et al., 2021).

For 2020, the Federal Office of Statistics of Germany estimates 71,000 excess deaths (Statistisches Bundesamt, 2021a). Kowall et al. (2021) and Stang et al. (2020) argue that the analysis of mortality over time must incorporate demographic changes within the society, as a disproportionate increase of older age groups must lead to higher mortality. In Germany, the population increased from 82.2 million in 2016 to 83.2 million in 2020 (+1.21%). In the same time, inhabitants of 80 years and older increased from 4.7 million to 5.7 million (+20.13%) (Statistische Ämter des Bundes und der Länder, 2022a). Whilst accounting for demographic changes, Kowall et al. (2021) analysed excess mortality in Germany, Sweden, and Spain, and cannot find excess mortality in Germany in 2020.

From the perspective of health geography, the spread of an infectious disease must be regarded as a spatial phenomenon (Elliott & Wartenberg, 2004). The spread of a virus (or, more general, pathogen) is a spatial diffusion process, with regional differences in the transmission within and between regions (Cliff & Haggett, 2006; Charu et al., 2017; Viboud et al., 2006). Infection waves can be asynchronous between regions of the regarded country and can also vary greatly in severity. This is due to population heterogeneity, which includes interpersonal differences in contact networks and “super-spreading events” at the local level, with both resulting in strong regional variations in timing and extent of outbreaks (Chowell et al., 2015; Thomas et al., 2020). Transmission between regions is driven by spatial interactions. There are spillovers of transmission due to human mobility across administrative borders such as commuting (Charaudeau et al., 2014; Charu et al., 2017; Dalziel et al., 2013; Viboud et al., 2006). Studies with a spatial approach have found both regional disparities and spatial dependence of COVID-19 cases and deaths for the first pandemic wave in spring 2020 (Bourdin et al., 2021; Saffary et al., 2020; Wang et al., 2021; Wieland, 2020). It is, thus, to be expected a) that there are also regional disparities in (excess) mortality, and b) that mortality levels in nearby regions are more similar than with respect to more distant regions.

The current study investigates spatial patterns of excess mortality in Germany in 2020. Since the question of whether excess mortality existed at all is controversial, this study attempts to answer this question from a spatial perspective, which leads to the first research question: *Are there regions with excess mortality and, if so, how many?* For the reasons given above regarding the spatial aspects of the spread of infectious diseases, the second research question is: *Is there a spatial dependence of (excess) mortality in the sense of identifiable “hotspots”?* However, (excess) mortality can have many different reasons and does not necessarily have to be attributed to the spread of COVID-19. An association between all-over mortality and COVID-19-related deaths has not yet been directly investigated, at least not for the German case. Therefore, the third research question is: *Is regional all-cause (excess) mortality associated with COVID-19-related deaths?*

(Excess) mortality is analysed a) at a small-scale spatial level, and b) under consideration of demographic changes in Germany. The analysis is conducted at the NUTS 3 level (counties; in German: "Landkreise", *N* = 400) which is the second smallest spatial unit for which official statistical data is available in Germany, and the smallest unit for which COVID-19 cases and deaths are available. This type of analysis is almost unique so far, since previous studies refer to larger spatial units (e.g., Doukissas et al., 2018; Kowall et al., 2021), which may not adequately reflect the small-scale nature of the spatial spread of an infectious disease. The data used for the analysis and the related statistical methods are presented in the next section (section 2). The results are shown in section 3 and discussed in section 4. In section 5, conclusions and limitations of the study are presented.

## 2. MATERIAL AND METHODS

### 2.1 Data

Data on regional all-cause deaths was retrieved from the *Regionaldatenbank Deutschland*, which provides official statistics at the subnational level (16 states, 400 counties, approx. 11,000 municipalities). Table 12613-93-01-4 was used, which contains total all-cause deaths by age group at the county level (Statistische Ämter des Bundes und der Länder, 2022b). The county dataset does not include mortality data disaggregated by age group and sex and time (monthly or weekly). Thus, the current analysis is conducted at the cumulative level (whole year) and for age groups. In some cases, total deaths for a specific age group in a specific county are not available because the numerical value is unknown or not to be disclosed (due to data protection laws). This only applies for younger age groups (<35) in some counties with a small population size. These counties were excluded in the subsequent analysis of the respective age groups.

Regional population sizes by age group were extracted from the same service using table 12411-09-01-4 (Statistische Ämter des Bundes und der Länder, 2022a). As the subsequent analysis relates to mortality during a given year, the population in year *t* is regarded as the population on December 31st of year *t*-1.

The total number of COVID-19-related deaths at the county level was extracted from the COVID-19 case dataset, which is provided by the German *Robert Koch-Institut* (*RKI*), Germany's governmental public health institute. This dataset includes all case reports including information on age group, sex, place of residence (county), date of confirmation, and, in some cases, date of onset of symptoms, as well as the information whether it is a case of death or not (Robert Koch Institut, 2022a). Note that this dataset includes people who died directly from COVID-19 ("died from"), as well as deceased people who were infected with SARS-CoV-2 and for whom it cannot be conclusively proven what the cause of death was ("died with"), especially in the case of serious pre-existing conditions. The decision as to what is classified as a COVID-19 death is up to the respective regional health department (Robert Koch Institut, 2022b). The dataset does not provide information about the date of death, and available statistics about weekly COVID-19-related deaths are not published at the county level (Robert Koch Institut, 2022c). Thus, COVID-19-related deaths had to be extracted based on the date of confirmation by comparing the weekly confirmed deaths with the sum of COVID-19-related deaths on condition of a specific confirmation date. The best match was achieved when using a confirmation date up to 2020/12/21 with 42,063 deaths, which is very close to the official numerical value of 41,648 COVID-19-related deaths in the dataset containing deaths by month.

Boundaries of German counties were retrieved from the county dataset (shapefile) provided by the RKI (Robert Koch Institut, 2022d). The data sources had to be harmonized due to different age categories. Mortality and population data were adjusted to the age groups in the RKI dataset (<5, 5-14, 15-34, 35-59, 60-79, 80+). As there have been few COVID-19-related deaths in the age groups below 35, the first three age groups (<5, 5-14, 15-34) were aggregated, which leads to four age groups in the subsequent analysis (0-34, 35-59, 60-79, and 80+). County boundaries and COVID-19 death numbers had to be harmonized as well because, in the RKI dataset, the capital Berlin is divided into 11 districts, resulting in 411 regions. By contrast, the regional mortality dataset contains Berlin as a whole county. Thus, COVID-19 deaths had to be summed up over whole Berlin.

## 2.2 Statistical analysis

Following previous studies on excess mortality (Doukissas et al., 2018; Kowall et al., 2021; Morfeld et al., 2021; Stang et al., 2020), *Standardized Mortality Ratios* (*SMR*s) were calculated for each age group (0-34, 35-59, 60-79, and 80+) and county (*N* = 400). SMRs compare observed mortality in a given time with expected mortality, with the latter being derived from previous mortality in a reference period. Following Kowall et al. (2021), to account for demographic changes over time, the observed and expected mortality was calculated from age-specific *mortality rates* instead of the age-specific number of total deaths. The mortality rate (sometimes referred to as *crude death rate*) of age group *a* in year *t* and region *i* is:

$$MR_{a,i,t} = \frac{D_{a,i,t}}{POP_{a,i,t}} 100 \qquad (1)$$

where $D_{a,i,t}$ is the number of all-cause deaths in age group *a* in year *t* and region *i*, and $POP_{a,i,t}$ is the population size in age group *a* in year *t* and region *i*.
Here, the expected mortality rate for 2020 is defined as the median of the mortality rates in the reference period. Following previous studies on COVID-related excess mortality in Germany (Kowall et al., 2021; Morfeld et al., 2021; Stang et al., 2020; Statistisches Bundesamt, 2021a), the reference period is 2016-2019. The SMR for age group *a* in region *i* in 2020 is:

$$SMR_{a,i,2020} = \frac{MR_{a,i,2020}}{E(MR_{a,i,2020})} = \frac{MR_{a,i,2020}}{q_{0.5}(MR_{a,i,2016-2019})} \qquad (2)$$

COVID-19-related deaths for 2020 were calculated as the cumulative number of confirmed COVID-19 fatalities (as defined in the RKI dataset) in age group *a* in region *i* at time *t* relative to the population:

$$MC_{a,i,2020} = \frac{DC_{a,i,2020}}{POP_{a,i,2020}} 100000 \qquad (3)$$

where $DC_{a,i,2020}$ is the number of COVID-19-related deaths in age group *a* in 2020 and region *i*, and $POP_{a,i,2020}$ is the population size in age group *a* in 2020 in region *i*.
As in Doukissas et al. (2018), to account for spatial dependence, the age group specific indicators for excess mortality and COVID-19-related deaths were tested for spatial autocorrelation using Moran's I coefficient (Moran, 1950). This index measures overall spatial autocorrelation in terms of a regression of regional values and values of nearby spatial units (Bivand & Wong, 2018; Doukissas et al. 2018; Griffith, 2009; Wieland, 2020):

$$I = \frac{N}{\sum_i^N \sum_j^N w_{ij}} \frac{\sum_i^N \sum_j^N w_{ij}(x_i - X)(x_j - X)}{\sum_i^N (x_i - X)^2} \qquad (4)$$

where *N* is the number of regions (counties), *i* and *j* are regions, $x_i$ and $x_j$ are the values of the regarded variable *x* (here: *SMR* and *MC*, respectively) in region *i* and *j*, *X* is the arithmetic mean of the regarded variable *x*, and $w_{ij}$ is the spatial weighting matrix.
The expected value of *I* depends on the number of regions:

$$E(I) = \frac{-1}{N-1} \quad (5)$$

The test for statistical significance investigates whether the observed value of *I* is significantly greater than the expected value *E(I)*. This analysis requires a weighting matrix, $w_{ij}$, for the definition of spatial proximity of the regarded spatial units. Here, the weighting is binary and includes all neighboring counties, which means that the weighting for county *i* with respect to another county *j* is equal to one if they are adjacent (sharing one or more points) and equal to zero if not (Queen contiguous spatial weighting). Thus, it is tested whether the values of a given region is spatially autocorrelated with respect to its neighbors (Bivand & Wong, 2018; Wieland, 2020). As one cannot expect that all indicators of mortality and COVID-19-related deaths are normally distributed, the variables (*SMR* and *MC*) are transformed by natural logarithms.

The relationship between regional mortality and COVID-19-related deaths for each age group is investigated is a bivariate way. Due to possible non-normality, the indicators were tested for statistical dependence with a nonparametric measure, the Spearman rank correlation coefficient ($r_{Sp}$).

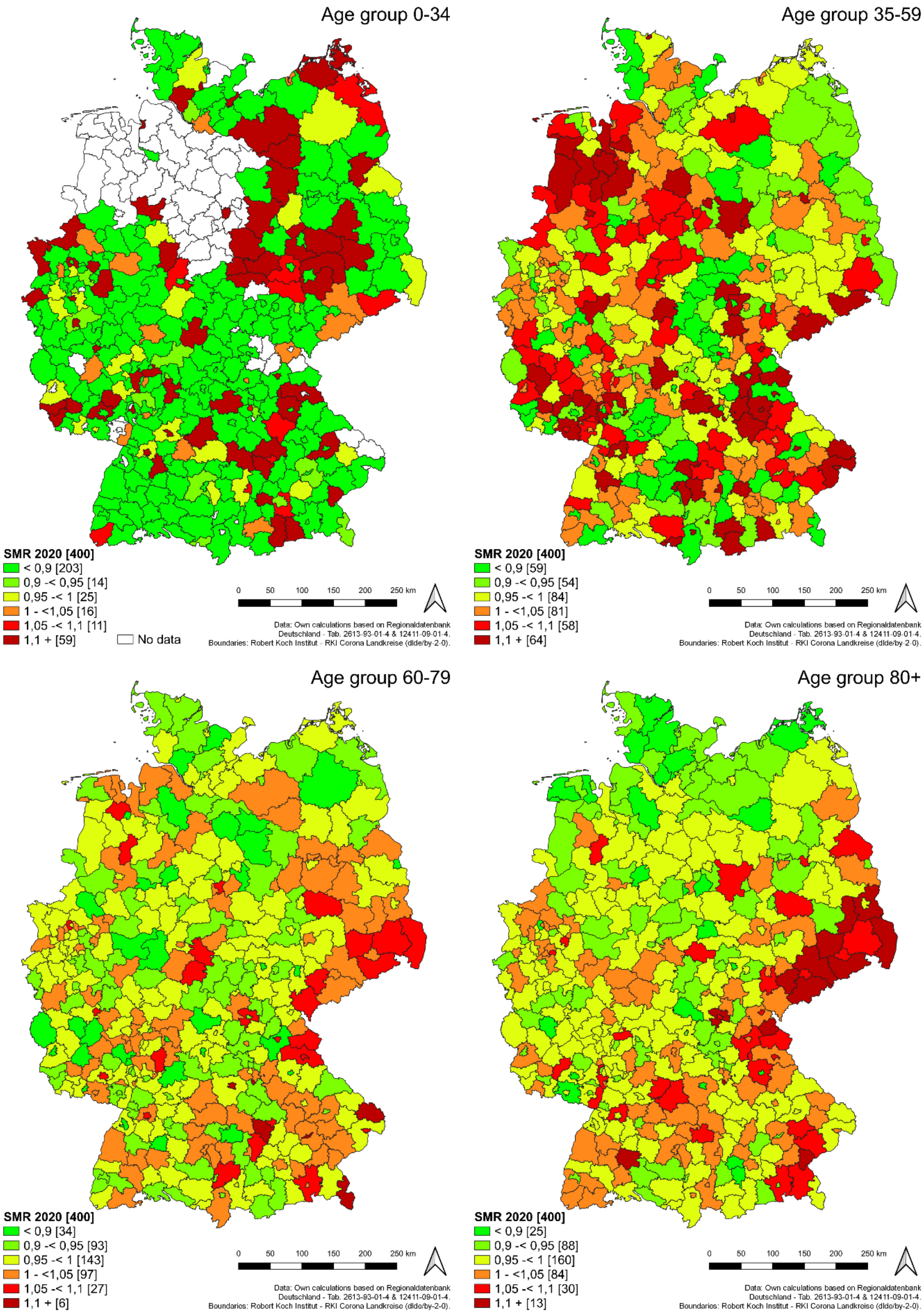
In all significance tests, the significance level was set to 95% ($p < 0.05$). All analyses were conducted in *R* (R Core Team, 2021), while using the packages *spdep* (Bivand & Wong, 2018), and *corrplot* (Wei & Simko, 2021). Map visualization was done in *QGIS* (QGIS Development Team, 2021).

## 3. RESULTS

Standardized Mortality Ratios (SMRs) for all four age groups at the county level are shown in the maps in figure 1. In the maps, the SMRs are classified in steps of 0.05 (5%) with values above one reveal that the observed mortality is above the expected mortality (excess mortality). As there is no (complete) data for 72 counties with respect to the first age group (0-34), all subsequent statistics were calculated for the remaining 328 counties. Figure 2 presents regional COVID-19-related deaths per 100,000pop based on the RKI data and classified by quantiles (except for the first age group as there are no COVID-19 fatalities in most counties). In figure 3, the Spearman correlations between the indicators are visualized. Non-significant correlation coefficients ($p > 0.05$) are crossed out.

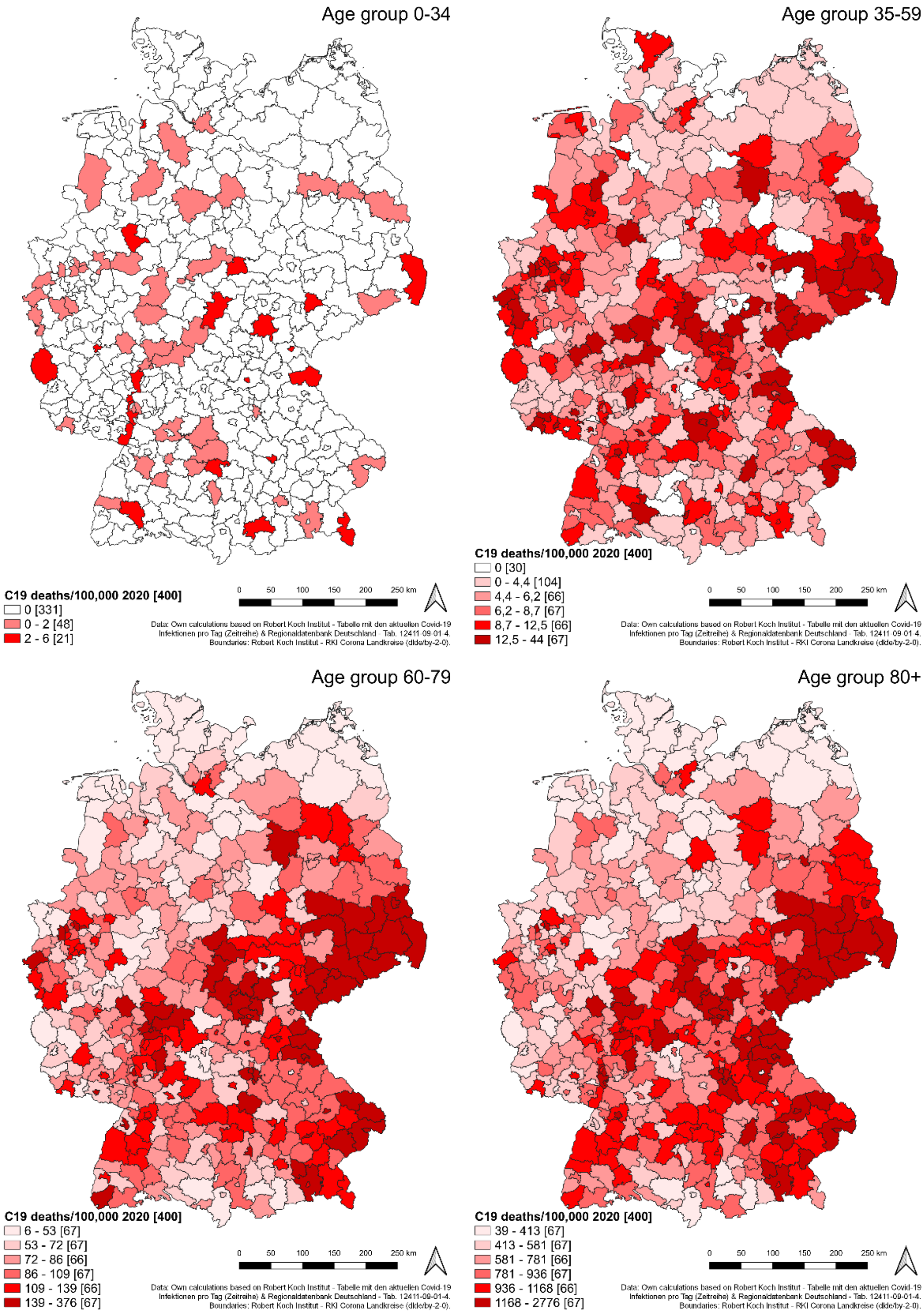
The SMRs for the age group 0-34 (mean = 0.850, sd = 0.301, median = 0.869) are distributed as follows. In most counties (242; 73.78%), the observed mortality in 2020 is below the expected value (*SMR* < 1), while there is excess mortality (*SMR* > 1) in the remaining 86 counties (26.22%). In 59 counties (17.99%), excess mortality is equal to 10% or higher (*SMR* ≥ 1,1). Because of the lack of data, which is obviously unevenly distributed over space, no Moran's I coefficient was estimated for the first age group. For age group 35-59, the coefficient for spatial autocorrelation, Moran's I, is equal to $I$ = 0.020 with $p$ = 0.25, and, thus, not significant above the expected value of *E(I)* = -0.003 (which is equal for all age groups due to the same number of spatial units). Looking at the values of all counties (mean = 1.004, sd = 0.102, median = 0.999) shows that 203 counties (50.75%) reach values of *SMR* > 1, which means that there is excess mortality in a narrow majority of counties for this age group. This is different from the *SMR* of the third age group, 60-79 (mean = 0.977, sd = 0.053, median = 0.975). In 132 counties (33.00%), the SMRs are above one, with an excess mortality of 10% or above (*SMR* ≥ 1,1) in six counties (1.50%). The estimate of spatial dependence is $I$ = 0.085, which is significantly higher than the expected value ($p < 0.01$). This result is similar with respect to the age group of 80 and above (mean = 0.981, sd = 0.055, median = 0.977). Here, Moran's I has the value of $I$ = 0.350 ($p$ < 0.01). *SMR* values above one are found in 127 of 400 counties (31.75%), which means that excess mortality occurs in a minority of German counties. In 13 counties (3.25%), excess mortality reaches 10% or more.

**Figure 1.** Standardized mortality ratios (SMRs) at the county level 2020.




Taking a look at the maps in figure 2, there are obvious spatial differences in the cumulative COVID-19 fatalities (COVID-19-related deaths per 100,000 pop) in 2020. In the age group 0-34 (mean = 0.301, sd = 0.817, median = 0.000), there are 331 counties without COVID-19-related deaths in 2020. The indicator for spatial dependence, Moran's I, is equal to $I = 0.0005$, and not significant ($p = 0.46$). In contrast, COVID-19-related deaths in the age group of 30-59 (mean = 7.488, sd = 5.785, median = 6.240) is spatially autocorrelated ($I = 0.132$, $p < 0.01$). The same can be found for the age groups 60-79 (mean = 97.095, sd = 52.865, median = 86.438) with $I = 0.503$ ($p < 0.01$) and 80+ (mean = 817.790, sd = 444.788, median = 781.434) with $I = 0.519$ ($p < 0.01$). COVID-19-related deaths are, thus, spatially autocorrelated with respect to the age groups 30-59, 60-70, and 80+.

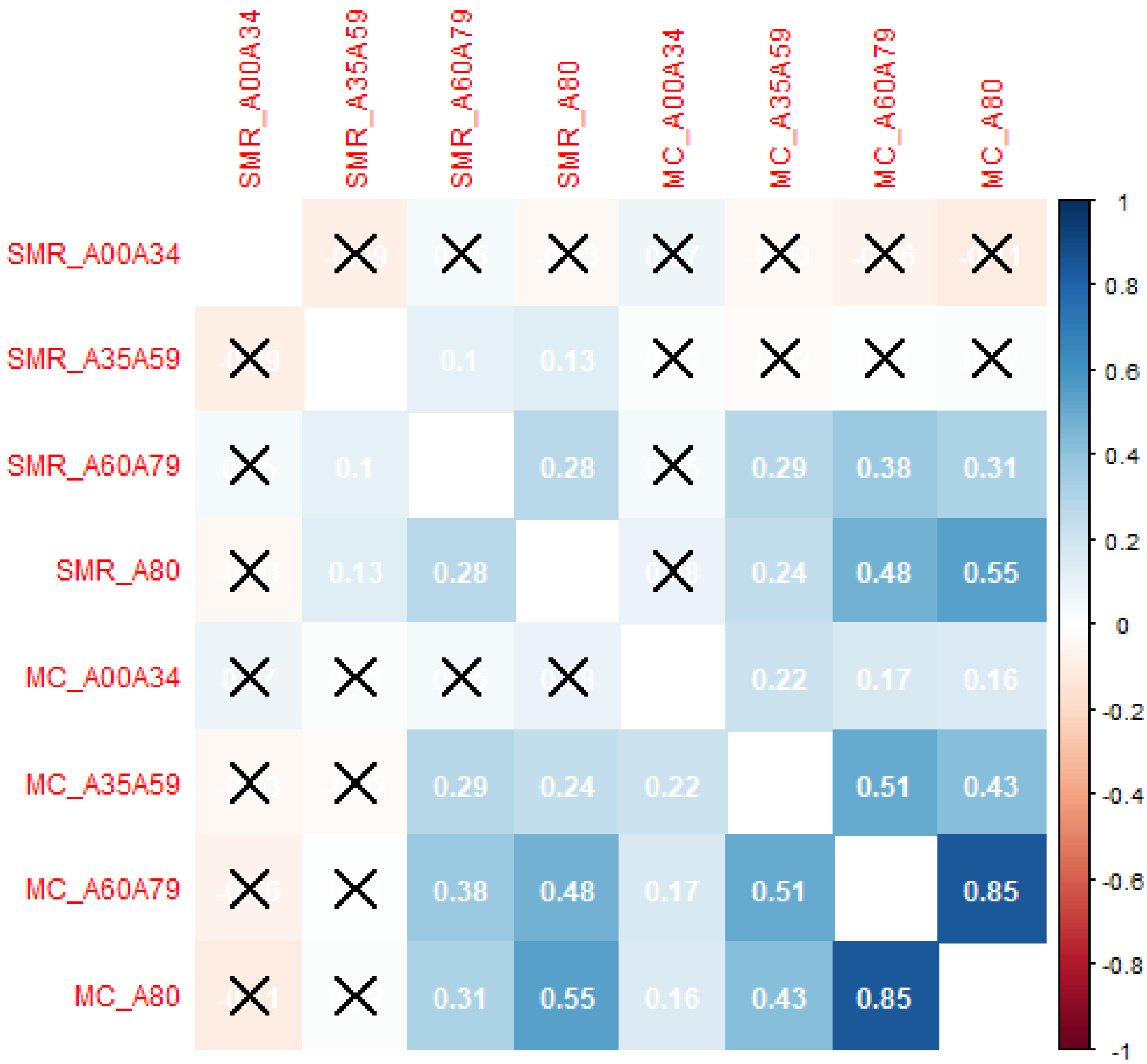
**Figure 2.** COVID-19-related deaths at the county level 2020.




All in all, excess mortality can only be identified in a minority of counties, except for one age group. Mortality is spatially autocorrelated for elder age groups (60-79, 80+) with a geographical emphasis in the east and southeast of Germany (states Saxony and Bavaria), but not for younger age groups. Spatial clustering of COVID-19-related deaths can be identified especially in the east and southeast of Germany as well.

It is, thus, not surprising that COVID-19-related deaths in the elder age groups (60-79, 80+) correlate strongly and positively, with a Spearman correlation coefficient of $r_{Sp}$ = 0.85 (p < 0.01). Regional COVID-19 deaths in the other age groups show weak to moderate positive correlations ($r_{Sp}$ = 0.16 to $r_{Sp}$ = 0.51, $p$ < 0.01) (see figure 3). Whilst the *SMR* and death numbers are not significantly correlated in younger age groups (0-34, 35-59), there are significant correlations between SMRs and COVID-19 deaths for the age groups 60-79 ($r_{Sp}$ = 0.38, $p$ < 0.01), and 80+ ($r_{Sp}$ = 0.55, $p$ < 0.01). Thus, there is, at least to a certain degree, an association between regional COVID-19-related deaths and regional all-cause mortality in older age groups, but this correlation cannot be confirmed for younger age groups.

**Figure 3.** Spearman rank correlation coefficients for SMRs and COVID-19 deaths.




## 4. DISCUSSION

Whilst taking into account demographic changes, Kowall et al. (2021) have found that there has been no excess mortality at the national level in Germany in the first pandemic year. In principle, the current results confirm these findings, as regional excess mortality occurred only in a minority of counties, with most of them showing mortality values below the expected mortality instead. These findings are clear with respect to young (0-34) and older age groups (60-70, 80+), but there is a balance of counties with and without excess mortality for the middle age group (35-59).

However, this result does not rule out excess mortality due to COVID-19 per se. There are regions with mortality clearly above the expected value in all age groups. Both excess mortality and COVID-19-related deaths in the older age groups (60-79, 80+) tend to be spatially clustered ("hotspots"). Especially counties in the east of Saxony and Bavaria have experienced excess mortality of 10% or more in the age group 80+. At least a part of regional excess mortality in the older groups (especially 80+) is statistically associated with COVID-19 deaths. Thus, it is likely that COVID-19 has contributed substantially to excess mortality in the age-specific COVID-19 "risk group". In contrast, regional (excess) mortality of people below 60 years cannot be explained by COVID-19, as there is (a) no such spatial pattern in mortality, and (b) no correlation between COVID-19-related deaths and all-cause mortality.

The analysis of spatial autocorrelation has shown spatial dependence of both regional mortality and COVID-19-related deaths, at least for the older age groups. This can be explained by a spatially clustered occurrence of infections in combination with interregional virus transmission due to interregional mobility. As there are more spatial interactions between nearby regions, also infection levels of nearby regions are more similar than distant ones. The influence of mobility (especially commuting) on virus transmission was outlined several times for infectious diseases such as influenza (Charaudeau et al., 2014; Charu et al., 2017, Dalziel et al., 2013, Viboud et al., 2006). With respect to SARS-CoV-2, Mitze & Kosfeld (2021) outline the enhancing effect of commuting to work on regional infections in the first pandemic wave in Germany. Regarding the same time period, Wieland (2020) shows that, all other things being equal, growth rates of SARS-CoV-2 infections in German counties increase with increasing intensity of commuting. Bourdin et al. (2021) find that the regions most affected by COVID-19 in the first wave in Italy are also those with the highest level of connectivity to the rest of the world. The present results towards regional mortality and COVID-19-related deaths are in line with studies which have found spatial dependence of SARS-CoV-2 infections and/or COVID-19 deaths at the small-scale level in the initial phase of the pandemic, such as in Italy (Bourdin et al., 2021), USA (Saffary et al., 2020), Germany (Wieland, 2020), and China (Wang et al., 2021). However, the results contrast with the results of Doukissas et al. (2018), which have not found spatial dependence of SMR in the context of the swine flu in Greece.

The occurring of spatial clusters ("hotspots") of (COVID-associated) excess mortality and COVID-19 fatalities can be caused by both interregional and intraregional disease transmission. Regional disparities of infections and deaths have been confirmed for many epidemics, regardless of the pathogen. The main reason is population heterogeneity, which means that individuals do not have the same probability of being infected and/or infecting others, especially because of heterogeneous networks of social contacts. Network connectivity may differ between regions. There are "super-spreading events" at the local level, at which many people get infected at once. These reasons lead to spatial heterogeneity in infectious disease epidemics with strong differences in regional infections or deaths (Chowell et al., 2015; Thomas et al., 2020). The study cannot examine the reasons for the hotspots found in the analysis directly but could provide possible interpretations. Some regional hotspots in the first wave of infections are attributed to specific super-spreading events, such as indoor public large-scale events (Brandl et al., 2021; Streeck et al., 2020). There have also been outbreaks in nursing homes across Germany in 2020, resulting in many COVID-19-related deaths (Kohl et al., 2021; Wieland, 2020).

Clusters of excess mortality and COVID-19 deaths were especially found in the east and southeast of Germany. As these counties are located at the Czech and Polish border, commuting from these countries might explain a higher level of infections, since their border regions were themselves hotspots at times. Many of these cross-border commuters work in hospitals, nursing homes and home care, and are, thus, in contact with people of the age-specific risk group (Ärzteblatt, 2020a,b; Unger, 2021). It is therefore possible that this could explain the increased mortality in these regions. This cannot be proven, as most chains of infection are not traceable. However, such cross-border transmission has been confirmed for the first care home outbreak in the Netherlands, which was traced back to mobility from Germany (van Hensbergen, 2021).

There is a possible indication of population heterogeneity in the results. Except for the age groups 60-79 and 80+, regional COVID-19 deaths show only weak to moderate correlations between the four regarded age groups. This means that the number of COVID-related deaths within one age group in a given region is hardly associated with COVID-related deaths within another age group in the same region. The further apart the age groups are, the smaller the correlations are. This might be an indication that virus transmission between people of different age groups within the regions was rather low. These results may be explained by a strong age assortativity, which means that individuals tend to have more social contacts with people of similar age. This fact is well-known in epidemiology and proven by many studies on social mixing patterns (e.g., Leung et al., 2017; Mossong et al., 2008; Read et al., 2014).

## 5. CONCLUSIONS AND LIMITATIONS

In the present study, mortality for Germany in 2020 at the county level ($N$ = 400 spatial units) was estimated, whilst taking into account demographic changes from 2016 to 2020. Regional excess mortality was tested for spatial dependence and for correlation with regional COVID-19-related deaths. It was shown that excess mortality only occurred in a minority of counties, which is consistent with results of previous studies at the national level. There are large regional disparities of all-cause mortality and COVID-19-related deaths. In older age groups, both indicators show spatial dependence. (Excess) mortality in older age groups is impacted by COVID-19, but this association is not found for young and middle age groups.

The present results lead to two main conclusions: 1) Epidemics (and pandemics) have to be regarded as spatial phenomena. The spread of a pathogen or disease is a spatial diffusion process with strong regional disparities and spatial dependence. Transmission varies within and between regions, which results from population heterogeneity and interregional mobility. Any kind of analysis or forecast should be conducted at a small-scale spatial level. Indicators such as incidence, deaths or excess mortality are not very meaningful at national or at a roughly delineated sub-national level such as federal states. 2) COVID-19 in 2020 has had the potential to increase mortality in older age groups well above the expected mortality. In contrast, this effect has not been determined for people of age groups below 60 years (although it can be assumed that such pathogens spread faster in younger age groups due to their higher contact rate and mobility). Consequently, *if* preventing COVID-related deaths is defined as the primary goal of governmental interventions, then protective measures (*Nonpharmaceutical interventions*, *NPI*) should preferably address the COVID-19 risk group, especially older people. Thus, prioritizing vaccination (which started at the end of December 2020) by age and protective measures for nursing homes can be considered useful.

This study shows that excess mortality may be caused by COVID-19 in a hotspot-specific manner, but that no such effects have occurred nationwide. The study's methodology is suitable for identifying hotspots and for distinguishing between pandemic-related effects and expected mortality. It turns out that looking *only* at excess mortality or *only* fatalities may be not enough. However, the analysis faces some limitations: Although spatial clusters and spatial dependence of excess mortality and COVID-19 deaths were revealed, the study cannot identify *why* these regional disparities occur. Possible explanations that have been formulated are just conjectures rather than evidence. This is because the context of infection is unknown for the most confirmed SARS-CoV-2 infections and COVID-19-related deaths in Germany. Hotspots at a regional level are based to a large extent on region-specific singularities, and it will be an important task for future studies in health geography and spatial epidemiology to find out why certain regions have been hit so hard by COVID-19 and others not.

Moreover, the interpretation of (excess) mortality in 2020 is difficult due to specific circumstances in Germany in this year. For example, the wave of seasonal influenza in the winter season 2019/2020 was extraordinarily mild and stopped at the beginning of March 2020 (Buchholz et al., 2020). Additionally, the reduction of social contacts and mobility might have had positive side effects in terms of a reduction of all-cause mortality. For example, in 2020, traffic accident fatalities were 10.6% lower than in 2019 (Statistisches Bundesamt, 2021b). There might have also been negative side effects ("collateral damages"). For example, Kortüm et al. (2020) have found excess mortality in the German county Waldshut in April 2020, with only 55% of this can be attributed to COVID-19 deaths. As the number of patients in emergency care declined strongly during this period, the authors assume that the remaining 45% can be attributed to missed treatments of other severe diseases. Furthermore, there is the question whether NPIs have impacted (excess) mortality and COVID-19 deaths. Previous studies with respect to Germany have stated that this effect cannot be assessed on the basis of excess mortality (Morfeld et al., 2021, Stang et al., 2020). As there are large regional disparities of both mortality and COVID-related deaths, it remains unclear whether and, if so, by how much COVID-19 deaths were reduced by the interventions. This question has also been raised in an international context in terms of empirical studies involving many countries. While many studies have found an impact of specific NPIs on infections and their growth rates or effective reproduction numbers, other studies have analysed COVID-related deaths instead. As a result, there were no or hardly any significant effects of the interventions on COVID-related deaths (Chaudry et al., 2020; Mader & Rüttenauer, 2022). However, Mader & Rüttenauer (2022) found an effect of COVID vaccinations, namely that they significantly reduced COVID deaths. For 2020, Kowall et al. (2021) find no excess mortality in Germany, little excess mortality in Sweden, but strong excess mortality in Spain, with Spain having the strictest interventions.

It is important for the interpretation to remember that the spatial scale has a substantial impact on the result of such an analysis. Like with many other variables, variance of mortality and disease fatalities increases with the resolution of the spatial units, and, thus, the more small-scale the analysis is, the more heterogeneous is the overall picture. This is a part of the *Modifiable Areal Unit Problem* (*MAUP*), which is well-known in the spatial sciences (Elliott & Wartenberg, 2004; Manley, 2014). Moreover, regional disparities in all-cause mortality can be attributed to many reasons (e.g., health-related behaviour, living conditions, local climate) and have been determined before (e.g., Gavalas, 2018; Robert Koch Institut, 2011). Thus, an explanation of spatial mortality patterns in general is outside the scope of this study.

Apart from the interpretation, the study also has methodological limitations: In contrast to previous studies, the present analysis does not investigate mortality over time, as the data provided by the German Regionaldatenbank is limited at this spatial scale (counties). E.g., there is monthly (not weekly) data, but not disaggregated by age groups. Apart from that, it is questionable whether the results of such an analysis with 400 spatial units would still be comprehensible. Another limitation is that mortality data for some age groups is incomplete at the county level, which has led to leaving out these counties from the mortality analysis for the first age group. Moreover, one must keep in mind that the present results relate to cumulative mortality in one year, which does not rule out excess mortality within a specific time period. In fact, it is unknown how many people died from (or with) COVID-19 at the county level within a given time period. Thus, county-level COVID deaths had to be estimated based on the best match for a specific confirmation date. This can lead to inaccuracies in determining regional COVID deaths.

Finally, it must be reiterated that the analysis conducted here is aimed at the societal impact of the COVID-19 pandemic (like any other study towards excess mortality), not the risk to the individual. The presence or absence of excess mortality does not say anything about how dangerous the infection with a virus or the disease it causes is for a person. Once mortality data for 2021 are available at the county level, this analysis should be repeated for the second year of the pandemic. The general conditions have changed significantly because vaccination started at the end of December 2020, where older age groups were prioritized. Furthermore, a SARS-CoV-2 testing strategy in nursing homes was established around the same time. Additionally, new virus variants emerged in 2021, which has influenced COVID-related deaths as well.

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