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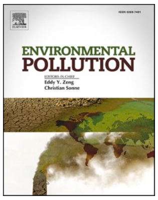

Impacts of changes in environmental exposures and health behaviours due to the COVID-19 pandemic on cardiovascular and mental health: A comparison of Barcelona, Vienna, and Stockholm☆

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ABSTRACT

Responses to COVID-19 altered environmental exposures and health behaviours associated with non-communicable diseases. We aimed to (1) quantify changes in nitrogen dioxide (NO_2), noise, physical activity, and greenspace visits associated with COVID-19 policies in the spring of 2020 in Barcelona (Spain), Vienna (Austria), and Stockholm (Sweden), and (2) estimated the number of additional and prevented diagnoses of myocardial infarction (MI), stroke, depression, and anxiety based on these changes. We calculated differences in NO_2, noise, physical activity, and greenspace visits between pre-pandemic (baseline) and pandemic (counterfactual) levels. With two counterfactual scenarios, we distinguished between Acute Period (March 15th – April 26th, 2020) and Deconfinement Period (May 2nd – June 30th’ 2020) assuming counterfactual scenarios were extended for 12 months. Relative risks for each exposure difference were estimated with exposure-risk functions. In the Acute Period, reductions in NO_2 (range of change from -16.9 μg/m^3 to -1.1 μg/m^3), noise (from -5 dB(A) to -2 dB(A)), physical activity (from -659 MET*min/wk to -183 MET*min/wk) and greenspace visits (from -20.2 h/m to 1.1 h/m) were largest in Barcelona and smallest in Stockholm. In the Deconfinement Period, NO_2 (from -13.9 μg/m^3 to -3.1 μg/m^3), noise (from -3 dB(A) to -1 dB(A)), and physical activity levels (from -524 MET*min/wk to -83 MET*min/wk) remained below pre-pandemic levels in all cities. Greatest impacts were caused by physical activity reductions. If physical activity levels in Barcelona remained at Acute Period levels, increases in annual diagnoses for MI (mean: 572 (95% CI: 224, 943)), stroke (585 (6, 1156)), depression (7903 (5202, 10,936)), and anxiety (16,677 (926, 27,002)) would be anticipated. To decrease cardiovascular and mental health impacts, reductions in NO_2 and noise from the first COVID-19 surge should be sustained, but without reducing physical activity. Focusing on cities’ connectivity that promotes active transportation and reduces motor vehicle use assists in achieving this goal.

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1. Introduction

After the outbreak of the SARS-CoV-2 virus in 2019, governments implemented non-pharmacological interventions (NPIs) to decelerate infection rates (European Centre for Disease Prevention and Control, 2020a). Hand hygiene and coughing etiquette, surface cleaning and space ventilation, border closures and limited travel, and physical distancing and confinement were recommended by the European Centre for Disease Prevention and Control (2020b). Varying combinations of NPIs, with large differences for confinement measures, were enforced by governments. While these NPIs reduced daily coronavirus disease (COVID-19) diagnoses (Flaxman et al., 2020), their impact on other, non-COVID-19 disease related health outcomes, such as cardiovascular diseases (CVDs) and mental disorders (MDs) and their associated risk factors, have not yet been sufficiently assessed.

Prior to the COVID-19 pandemic, CVDs and MDs were already key contributors to global mortality and morbidity (Rehm and Shield, 2019; Roth et al., 2020). Among the main environmental and health behaviour risk factors of both CVDs and MDs are air (Braithwaite et al., 2019; Rajagopalan et al., 2018) and noise pollution (Guski et al., 2017; Münzel et al., 2018), physical inactivity (Lavie et al., 2019; Rebar et al., 2015), and insufficient greenspace exposures (Dalton and Jones, 2020; Gascon et al., 2018). Due to the unprecedented impacts of COVID-19 related governmental responses on global industry, mobility, and individuals' day-to-day lives, environmental exposures and health behaviours were altered (Rumpler et al., 2020; Venter et al., 2020). However, the extent of these measures on a combination of environmental exposures and health behaviours have not yet been quantified. Additionally, comparisons of different COVID-19 responses implemented in cities, which are generally considered COVID-19 hotspots, are lacking.

The purpose of this study was to leverage this global natural experiment to generate evidence for policymakers, urban planners, medical professionals, and citizens of how environmental exposures and health behaviours can be optimized to reduce the burden of non-communicable diseases from CVDs and MDs. Accordingly, we aimed to estimate and compare the impact of governmental COVID-19 responses implemented by Spain, Austria, and Sweden on environmental exposures and health behaviours in Barcelona, Vienna, and Stockholm, respectively. Secondly, we aimed to quantify the annual CVD and MD diagnoses that would be prevented or added if NPIs from the first COVID-19 surge were extended for at least one year, and changes in environmental exposures and health behaviours were sustained long-term. Specifically, we assessed the effects of country-specific NPI variations on nitrogen dioxide (NO_2) and noise pollution, physical activity levels and greenspace visits during March 15th – June 30th, 2020 and quantified the annual myocardial infarctions (MI), stroke, depression and anxiety diagnoses that would be prevented or added if the COVID-19 related changes in exposures were sustained for at least one year.

2. Methods

2.1. Cities and population

We selected Barcelona (Spain), Vienna (Austria) and Stockholm (Sweden) for our analyses because the range of responses from their national governments to COVID-19 differed vastly. While Spain ordered a strict, law-enforced home confinement, Sweden relied on general recommendations without confinement, and Austria took an intermediate route with softer confinement measures (Fig. S1 of the Supplementary Material). Fig. S2 of the Supplementary Material shows the Government Stringency Index for Spain, Austria, and Sweden, a composite score defining the severity of the implemented NPIs. Further relevant information describing Barcelona, Vienna, and Stockholm are summarized in Table S1 of the Supplementary Material.

2.2. Health impact modelling methodology

With the Urban and Transport Planning Health Impact Assessment (UTOPHIA) tool (Mueller et al., 2017a, 2017b), we used a systematic approach to look across sectors by estimating the consequences of COVID-19 NPIs on environmental exposures and health behaviours, and subsequently on CVD and MD diagnoses in cities. Based on our modelling results, we propose policy recommendations on how to minimize CVD and MD diagnoses during crisis times and beyond by generating more active, cleaner, and greener cities.

UTOPHIA uses a comparative risk assessment approach in which environmental exposure and health behaviour levels at baseline (i.e., pre-COVID-19 pandemic exposures) are compared against levels in a counterfactual scenario (i.e., implemented governmental NPIs during the first COVID-19 surge). Concretely, we first (Fig. 1– *step 1*) determined pre-pandemic exposure levels for NO_2, road traffic noise, physical activity, and greenspace visits as baseline. Next, we assessed exposure concentrations for two counterfactual periods (*steps 2 & 3*) for each of these four exposures. We divided the overall assessment period from March 15th – June 30th, 2020 into two counterfactual periods: the Acute Period from March 15th – April 26th, 2020, during the first surge of the COVID-19 pandemic with the strictest NPIs, and the Deconfinement Period from May 2nd – June 30th, 2020, characterized by the relaxation of the NPIs. The weeks between March 8th – March 14th, 2020 and April 26th – May 2nd, 2020 were considered transition periods, and were excluded from all analyses due to general uncertainties around the first reported COVID-19 infections in Europe and new measures implemented during deconfinement. For impact modelling purposes, we simulated what would have happened if the NPIs and corresponding changes in environmental exposures and health behaviours were sustained for 12 months. The exposure differences between the Acute Period and baseline *(step 4a)* and the Deconfinement Period and baseline *(step 4b)* were calculated. In Table S2 of the Supplementary Material, the exact timeframes and aggregation levels used for each exposure are presented. Next *(step 5)*, we retrieved exposure response functions (ERFs) from the literature that quantify the strength of the association between the exposures and CVD (myocardial infarctions (MI) and stroke) and MD (depression and anxiety) diagnoses. Then, *(step 6)* we scaled the relative risk (RR) to the exposure level differences and *(step 7)* calculated the population attributable fractions (PAFs) for each exposure level difference.

Uncertainties in the ERFs and exposure levels at baseline and in the counterfactual scenarios were considered to calculate the point estimates and 95% confidence intervals (CIs). To propagate the uncertainties, we used Monte Carlo simulations (Harrison, 2010) (Text S1 of the Supplementary Material).

All calculations were performed for both counterfactual scenarios *(step 8)* on a city level for the adult population of the three cities to finally estimate the annual number and percent of preventable and additional MI, stroke, depression, and anxiety diagnoses if environmental exposures and health behaviours during the Acute and Deconfinement Periods were prolonged for one year or more. We were unable to quantify the number of prevented or excess anxiety diagnoses in response to changes in NO_2 due to the absence of reliable ERFs. Similarly, no ERFs were available for greenspace visits and depression and anxiety diagnoses; however, the ERF by Van den Berg et al. (2016) allowed us to report the scaled RR for greenspace visits and general mental health and vitality.

2.3. Pre-pandemic and pandemic environmental and health behaviour exposures

2.3.1. Nitrogen dioxide

Baseline: Due to limited data of multiple pollutants at the required temporal resolution for all three cities, we focussed on NO_2. Daily NO_2 concentrations from background stations from January 1st, 2016–June

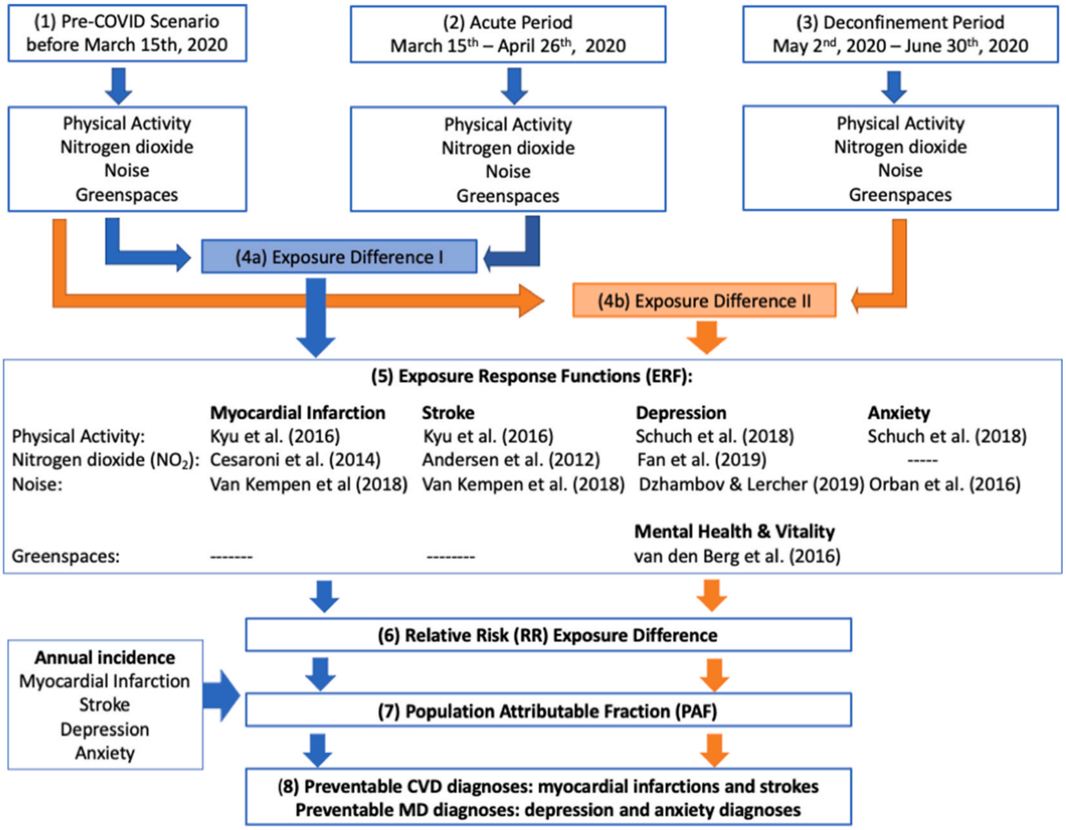

Fig. 1. Conceptual framework of the Urban and Transport Planning Health Impact Assessment Tool (UTOPHIA) (1) Pre-Pandemic Exposure setting (averages based on data from 2016/2017 to 2019); (2) Acute Period (March 15th’ 2020–April 26th’ 2020); (3) Deconfinement Period (May 2nd’ 2020–June 30th’ 2020), (4a) Exposure difference between pre-pandemic exposure and the Acute Period, (4 b) exposure difference between pre-pandemic exposure and the Deconfinement Period, (5) exposure response function (ERF) to quantify the association between exposure and incidence rate, (6) relative risk (RR) corresponding to the exposure difference, (7) population attributable fraction (PAF) corresponding to the exposure difference; (8) preventable cardiovascular disease (CVD) and mental disorder (MD) diagnoses. – Figure adapted after Mueller et al. (2017b).

30th, 2020 were obtained from local air pollution assessment agencies (Text S2, Tables S3 and S4 of the Supplementary Material). Baseline pre-pandemic exposure to NO_2 concentrations was established as the annual mean exposure for 2016–2019 for Barcelona, and 2017–2019 for Vienna and Stockholm.

Counterfactual periods: To estimate exposure differences in NO_2 between baseline and the Acute and Deconfinement Periods, respectively, we constructed a random-forest model for each city and applied a meteorological normalization (Grange and Carslaw, 2019) to NO_2 daily time series data to estimate the expected NO_2 concentrations in the counterfactual period. The number of trees for the random forest models was set at 300 and the minimal node size was five (Table S4 of the Supplementary Material). We calculated the average percent reduction in NO_2 for the Acute and Deconfinement Periods based on the difference between the measured and expected NO_2 concentrations. These percentages were applied to baseline concentrations to estimate the average annual counterfactual NO_2 exposure if these reductions were maintained long-term. Finally, we quantified the association between NO_2 and MI (Cesaroni et al., 2014), stroke (Andersen et al., 2012), and depression (Fan et al., 2020). An overview of all ERFs for all exposures and CVDs and MDs outcomes is provided in Fig. 1.

2.3.2. Noise

Baseline: Noise exposure was assessed using the 24 h day-evening-night noise level indicator (L_{den}). L_{den} was retrieved from European Union-commissioned road-traffic noise maps from 2017 for Barcelona and Vienna, and 2016 for Stockholm. All maps represent annual mean L_{den} noise exposure levels in A-weighted decibels (dB(A)) and were used as pre-pandemic baseline levels. We focussed on road-traffic noise because it is the most dominant noise source in European cities (EEA, 2014).

Counterfactual periods: For Barcelona, we calculated differences in noise between baseline and the counterfactual periods by combining the baseline noise map with a traffic map from 2018 (Ajuntament de Barcelona and Departament de Mobilitat, 2018; Ajuntament de Barcelona Ecologia Urbana, 2020). We obtained counterfactual weekly noise estimates by applying weekly percent changes in traffic categories (intense, moderate, low). For Vienna, noise estimates were modelled via counts of changes in traffic categories for the period of March 16th to April 14th, 2020. For the period between April 15th – June 30th, 2020, no direct measurements of changes in traffic categories were conducted; however, other markers of traffic volume indicate that this period is comparable to identical weeks of previous years (Stadt Wien,). For Stockholm, weekly variations in L_{den} were obtained from the interpolation of strategic noise maps on the basis of monitored noise levels at two locations: one representative of a dense traffic configuration at a busy crossing, the other representative of a residential area. These interpolated noise maps were used to calculate counterfactual period noise exposures. For both Vienna and Stockholm a specific noise map for the pandemic period was retrieved. To estimate noise in the baseline and counterfactual periods for Vienna and Stockholm, we used a residential building map (EEA, 2015) to assess the exposure to road traffic noise by aggregating the median L_{den} value for each building. Then the mean noise value at city level was derived. For Vienna, baseline maps showed aggregated noise levels that were below the WHO threshold of 55 dB(A), meaning that these areas could not be included in the assessment of noise for the counterfactual periods due to unavailability of data. Thus, all noise estimates for Vienna were completed only for those areas with baseline exposure levels of 55 dB(A) or higher. The noise estimates for Barcelona and Stockholm were not affected by this limitation. Due to the logarithmic scale for decibels, all changes between baseline and the counterfactual periods are expressed in absolute values and not in percent change. Finally, we quantified the association between road traffic noise and MI (van Kempen et al., 2018), stroke (van Kempen et al., 2018), depression (Orban et al., 2016), and anxiety (Lan et al., 2020).

2.3.3. *Physical activity*

Baseline: Objectively measured overall physical activity levels during the COVID-19 pandemic were not available at the time of analysis; therefore, self-reported walking-related physical activity at baseline (Bundesministerium für Soziales, Gesundheit, 2019;Generalitat de Catalunya. Departament de Territori i Sostenibilitat, 2020; Socialstyrelsen, 2021), and Apple Mobility Mobility Reports (Apple, 2020) for the counterfactual periods were used as a proxy for overall physical activity levels. Baseline self-reported physical activity levels were assessed using the international physical activity questionnaire (IPAQ) in a sample of randomly selected adults of Barcelona, Vienna, and Stockholm (IPAQ International Physical Activity Questionnaire Group, 2015). To match the physical activity exposure metric used in the ERFs, minutes of walking-related physical activity per week were translated to weekly metabolic equivalent of task-minutes (MET*min) by multiplying the median weekly minutes by a factor of 3.3 METs (IPAQ International Physical Activity Questionnaire Group, 2015). The average MET*min per week was considered representative of a regular week for adult residents (Text S3 and Table S5 of the Supplementary Material).

Counterfactual periods: To determine changes in walking-related physical activity for the Acute and Deconfinement Periods, city-specific percent differences reported in the Mobility Trends Reports by Apple (2020) were applied to the baseline weekly MET*min. We calculated exposure differences in MET*min per week between pre-pandemic baseline levels and the Acute and Deconfinement Periods, respectively. We quantified the associations between physical activity and MI (Kyu et al., 2016), stroke (Kyu et al., 2016), depression (Schuch et al., 2018), and anxiety (Schuch et al., 2019) in a final step. Based on a meta-analysis on the effect of non-vigorous physical activity on all-cause mortality that showed a non-linear relationship (Woodcock et al., 2011), we applied a 0.375 power transformation to physical activity exposures assuming that changes in physical activity at the lower end of the distribution have greater effects on CVDs and MDs compared to changes in physical activity levels at the higher end of the spectrum.

2.3.4. *Greenspace visits*

Baseline: Greenspace exposure was assessed by the average time spent in greenspaces per week. For Barcelona, baseline greenspace exposure was taken as reported in the PHENOTYPE project (Van den Berg et al., 2016). There was no equivalent assessment of greenspace visits available for Vienna. After assessing the normalised difference vegetation index (NDVI) and percentage of green area (%GA) from a study on greenspace and mortality study in 49 greater European cities (Barboza et al., 2021), we deemed it adequate to report the average greenspace exposure measured for Barcelona (Spain), Stoke-on-Trent (UK), Doetinchem (Netherlands), and Kaunas (Lithuania), four cities included in PHENOTYPE (Van den Berg et al., 2016) as a proxy for greenspace visits in Vienna (Table S6 of the Supplementary Material). Greenspace exposure for Stockholm was derived from data of the “Where is your Stockholm?” project (Giusti et al., 2017). Baseline exposures were established in hours per week spent in greenspace and considered representative of a typical week for adult residents of Barcelona, Vienna, and Stockholm.

Counterfactual Periods: We used the variable called “Parks” from the COVID-19 Community Mobility Reports to determine changes in greenspace exposure during the counterfactual periods (Google, 2020). For each city, weekly percent changes in greenspace visits based on Google’s “Parks” variable were calculated with respect to the baseline period. Next, the corresponding percent change in greenspace visits was applied to pre-pandemic baseline values in hours per week, and the exposure differences were calculated.

As previously mentioned, to date, no ERFs are available quantifying the association between weekly time spent in greenspaces and MI, stroke, depression, and anxiety diagnoses. In PHENOTYPE, time spent in greenspaces was associated with mental health and vitality using subscales from the Medical Outcome Study Short Form (SF-36) general health survey (Van den Berg et al., 2016; Ware and Sherbourne, 1993). Using these ERFs, we quantified the impact of weekly time spent in greenspaces on mental health and vitality and expressed the results as scaled risk ratio corresponding to the exposure difference in both counterfactual periods. The scaled risk ratio can be interpreted as the increased or reduced risk of reporting worse mental health and vitality due to the changes in greenspace visits during the Acute and Deconfinement Periods.

2.4. *City-specific data on cardiovascular disease and mental disorders*

For Barcelona, the annual incidence of physician-diagnosed MIs, strokes, depression, and anxiety was taken from the 2019 Catalonia Health Survey (Generalitat de Catalunya. Departament de Territori i Sostenibilitat, 2020). For Vienna, the mean annual MI and stroke diagnoses between 2017 and 2019 for residents were calculated based on data from the Austrian Ministry of Health and the Austrian National Public Health Institute (Gesundheit Österreich GmbH, 2019). Annual physician-diagnosed depressions were derived from the 2019 Austrian Health Interview Survey (Bundesministerium für Soziales und Gesundheit, 2019). Anxiety diagnoses in Vienna were estimated based on a 2011 report on chronic health conditions (Statistik Austria, 2011). For Stockholm, annual incidences of all four health outcomes were obtained using the following ICD-10 codes: MI (I21), stroke (I60–I64), depression (F32), anxiety (F40–F43) from the Swedish National Board of Health and Welfare (Socialstyrelsen, 2021) for the years 2017–2019. Average values for the 3-year period were used for the analyses (Table S1 of the Supplementary Material).

2.5. *Sensitivity analyses*

We conducted three sensitivity analyses. In the first two, we accounted for seasonal effects on physical activity levels and greenspace visits. In the third sensitivity analysis, we modelled the health impacts of changes in overall physical activity behaviours, assuming that reported changes in walking-related physical activity in the Apple Mobility Reports (2020) are representative of changes in overall physical activity levels (Text S4 of the Supplementary Material).

3. Results

In Table 1 and Fig. S5 of the Supplementary Material, absolute values and percent changes from pre-pandemic baseline to the Acute and Deconfinement Periods, respectively, for all four assessed environmental exposures and health behaviours are presented. Additional and prevented CVD and MD diagnoses, and effects on mental health and vitality for greenspace visits, if observed changes were sustained long-term for the Acute and Deconfinement Periods are presented in Table 2, Table 3, and Table 4. To show the overall health impact, cumulative prevented and additional diagnoses per 1000 adult citizens by city and environmental exposure or health behaviour are shown in Fig. 2.

3.1. *Nitrogen dioxide*

Pre-pandemic concentrations of NO_2 were nearly twice as high in

Table 1

Changes in nitrogen dioxide, noise, physical activity, and greenspace exposures in Barcelona, Vienna, and Stockholm during the COVID-19 Acute and Deconfinement Periods.

Exposure	Baseline	Acute Period March 15th – April 26th, 2020		Deconfinement Period May 2nd – June 30th, 2020	
	Absolute Values Mean ± SD	Absolute Values Mean ± SD	% Change to BL Mean ± SD[a]	Absolute Values Mean ± SD	% Change to BL Mean ± SD[a]
NO_2 (μg/m^3)					
Barcelona	33.9 ± 12.5	17.0 ± 2.4	−50% ± 14%	20.0 ± 3.8	−41% ± 19%
Vienna	18.2 ± 7.9	14.2 ± 1.5	−22% ± 10%	14.0 ± 2.8	−23% ± 20%
Stockholm	12.3 ± 6.1	11.2 ± 1.1	−9% ± 10%	9.2 ± 1.1	−25% ± 12%
Noise (dB(A) L_{den})[a]					
Barcelona	62 ± 8	57 ± 2	−5 ± 2 dB(A)	59 ± 1	−3 ± 1 dB(A)
Vienna	59 ± 5	58 ± 7	−1 ± 5 dB(A)	59 ± 5	0 ± 5 dB(A)
Stockholm	56 ± 10	54 ± 0	−2 ± 0 dB(A)	55 ± 1	1 ± 1 dB(A)
Physical Activity (MET min/week)					
Barcelona	693 ± 79	34 ± 8	−95% ± 25%	169 ± 55	−76% ± 23%
Vienna	462 ± 39	112 ± 25	−76% ± 23%	272 ± 62	−41% ± 23%
Stockholm	436 ± 24	253 ± 27	−42% ± 11%	352 ± 58	−19% ± 17%
Greenspace (hrs/m)					
Barcelona	23.9 ± 1.0	3.7 ± 0.6	−85% ± 16%	20.5 ± 4.7	−14% ± 23%
Vienna	28.4 ± 3.0	17.9 ± 5.4	−37% ± 30%	27.6 ± 4.3	−3% ± 15%
Stockholm	33.3 ± 2.8	34.4 ± 6.0	3% ± 18%	50.2 ± 10.2	51% ± 20%

Abbreviations: BL: baseline; NO_2: nitrogen dioxide; L_{den}: day-evening-night noise indicator; dB(A): A-weighted decibel; MET min/week: metabolic equivalent of task – minutes per week; hrs/m: hours per month; SD: standard deviation.

[a] Due to the use of a logarithmic scale when expressing dB(A), the difference in noise between baseline and the Acute and Deconfinement Periods, respectively, are expressed in dB(A) and not in percent.

Barcelona (mean ± standard deviation = 33.9 ± 12.5 μg/m^3) compared to Vienna (18.2 ± 7.9 μg/m^3) and Stockholm (12.3 ± 6.1 μg/m^3; Table 1 and Fig. S3 of the Supplementary Material). Comparing observed with expected NO_2 concentrations resulted in the largest decreases in Barcelona (−50 ± 14%), followed by Vienna (−22 ± 10%), and Stockholm (−9 ± 10%) in the Acute Period. In the Deconfinement Period, NO_2 concentrations remained below baseline concentrations in all three cities. As shown in Tables 2 and 4, a long-term reduction in NO_2 at the concentrations reported during the Acute and Deconfinement Periods would result in reductions of annual MI, stroke, and depression diagnoses in all three cities. The largest decreases in CVDs and MDs would be observed in Barcelona (prevented annual diagnoses of MI and strokes between −6 and −5%; prevented annual diagnoses of depression of about −11%) at approximately five to six times the magnitude of Vienna and Stockholm (mean decrease for prevented MI and stroke diagnoses of −1%, respectively).

3.2. Noise

At the city level, mean noise levels at baseline were highest in Barcelona (62 ± 8 dB(A) L_{den}), followed by Vienna (59 ± 5 dB(A) L_{den}) and Stockholm (56 ± 10 dB(A) L_{den}; Fig. S4 of the Supplementary Material)). In the Acute Period, mean noise levels decreased or remained close to baseline, with reductions in Barcelona by 5 ± 2 dB, in Stockholm by 2 ± 0 dB(A), and in Vienna by 1 ± 5 dB(A). In the Deconfinement Period, noise levels increased when compared to the Acute Period, and stayed below or at baseline. If noise decreases during the Acute Period in all three cities were sustained, prevented annual diagnoses would range for MI from −4 to −1%, for stroke from −7 to −1%, and for depression and anxiety from −4 to −1%, respectively.

3.3. Physical activity

Compared to baseline, physical activity levels decreased in the Acute Period by 95 ± 25% in Barcelona, by 76 ± 23% in Vienna, and by 42 ± 11% in Stockholm (Fig. S6, Panel A of the Supplementary Material). Subsequently, a long-term reduction in physical activity at Acute Period levels would result in increases in CVDs and MDs in all three cities with additional annual diagnoses ranging between 2% and 12% (95% CIs between 1 and 16%), with the largest increases observed in Barcelona. In the Deconfinement Period, physical activity levels remained below pre-pandemic levels with decreases of 76 ± 23% in Barcelona, 41 ± 23% in Vienna, and 19 ± 17% in Stockholm. In Barcelona, a sustained decrease of physical activity at Deconfinement Period levels would result in 8% (95% CI: 3, 14%) additional MIs, 8% (0, 16%) additional strokes, 6% (95% CI: 4, 9%) more depression, and 10% (95% CI: 4, 16%) additional anxiety diagnoses.

Seasonal adjustment had the greatest impact on changes in physical activity levels in Stockholm during the Acute Period, where instead of a decrease of 42 ± 11%, a decrease of 48 ± 11% was observed (Fig. S6 Panel B and Tables S7, S8, and S9 of the Supplementary Material). As a consequence, annual CVD and MD diagnoses increased by an extra 1–2% when compared to not adjusting.

In our third sensitivity analysis, we assessed the adverse health effects of reductions in overall physical activity. While Barcelona residents accumulated most physical activity from walking, Vienna residents engaged in greater proportions of moderate-, and vigorous-intensity physical activities besides walking (Table S11 of the Supplementary Material). As a result, adverse health impacts of decreases in overall physical activity in Vienna double and exceed those observed in Barcelona when compared to focusing on walking-related physical activity only (Tables S12 and S13 of the Supplementary Material).

3.4. Greenspace visits

Compared to baseline, greenspace visits decreased in the Acute and Deconfinement Periods in Barcelona (−85 ± 16%) and Vienna (−37 ± 30%) but increased in Stockholm (3 ± 18%; Fig. S6 Panel C of the Supplementary Material). If the increase in greenspace exposure in Stockholm were of longer duration, the general risk of having worse mental health and vitality would decrease by 3% (CIs: 43%, 35%) for Stockholm adult residents. In contrast, if the drastic decrease in greenspace exposure in Barcelona were of longer duration, the risk of worse general mental health and vitality in Barcelona adult residents would increase by 82%. Seasonal adjustment resulted in the greatest impacts in Stockholm, with a decrease in greenspace visits of −12 ± 18% during the Acute Period instead of the aforementioned 3% ± 18% increase without seasonal adjustment. In the Deconfinement Period, seasonal adjustment of greenspace visits resulted in greater changes in Barcelona (35 ± 22% decrease instead of 14 ± 23% decrease) and in Stockholm

Table 2

Changes in nitrogen dioxide, noise, and physical activity exposures during the Acute Period and their effects on the anticipated annual incidence of myocardial infarctions, strokes, depression, and anxiety diagnoses.

	Prevented/Additional Myocardial Infarction Diagnoses			Prevented/Additional Stroke Diagnoses			Prevented/Additional Depression Diagnoses			Prevented/Additional Anxiety Diagnoses		
	Cases		% Change	Cases		% Change	Cases		% Change	Cases		% Change
Exposure	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)
NO_2 – (µg/m^3)												
Barcelona	−304 (−881,-235)	−299	−5 (−15, 4)	−344 (−771, 63)	−341	−6 (−13,1)	−11658 (−66273, 29,232)	−9392	−11 (−63,28)			
Vienna	−67 (−202, −54)	−64	−1 (−4, 1)	−75 (−178, 13)	−72	−1 (−3,0)	−2396 (−14459, 8577)	−2222	−2 (-13,8)			
Stockholm	−8 (−30, 7)	−6	0 (−1, 0)	−12 (−39, 3)	−10	0 (−1,0)	−86 (−684, 401)	−55	−1 (−4,3)			
Noise – (L_{den})												
Barcelona	−239 (−1313,546)	−175	−4 (−23, 9)	−448 (−2410, 917)	−327	−7 (−40, 15)	−2165 (−15455, 6642)	−1041	−4 (−23,9)	−5858 (−35683, 14,123)	−3625	−4 (−26, 10)
Vienna	−35 (−946, 771)	−12	−1 (−17, 14)	−77 (−1685, 1246)	−24	−1 (−30, 22)	−333 (−12399, 10,225)	−68	−1 (−17,14)	−282 (−7988, 6277)	−67	−1 (−19, 15)
Stockholm	−45 (−488, 320)	−29	−2 (−21, 14)	−126 (−1255, 741)	−79	−4 (−37,22)	- 149 (−2157, 431)	−48	−2 (−21,14)	−1358 (−15934, 10,059)	−625	−2 (−23, 15)
Physical activity – (MET*min/wk)												
Barcelona	572 (224, 943)	569	10 (4, 16)	585 (6, 1156)	584	10 (0, 19)	7903 (5202, 10,936)	7849	8 (5,10)	16,677 (6926, 27,002)	16,609	12 (5, 19)
Vienna	302 (115, 508)	298	5 (2, 9)	305 (8, 617)	302	5 (0,11)	4603 (2942, 6499)	4567	4 (3,6)	2777 (1109, 4602)	2746	7 (3, 11)
Stockholm	67 (23, 119)	65	3 (1, 5)	97 (2, 206)	94	3 (0,6)	342 (189, 520)	337	2 (1,3)	2381 (874, 4216)	2326	3 (1, 6)

Abbreviations: % change: percent change from baseline; CI: confidence interval; NO_2: nitrogen dioxide; MET*min/week: metabolic equivalent of task – minutes per week.

Table 3

Changes in greenspace visits exposures during the Acute and Deconfinement Periods and their effects on mental health and vitality.

	Acute Period Mental Health and Vitality		Deconfinement Period Mental Health and Vitality	
	Risk Ratios		Risk Ratios	
Exposure	Mean (CI)	Median	Mean (CI)	Median
Greenspace Visits (hrs/m)				
Barcelona	1.82 (1.48, 2.27)	1.81	1.11 (0.84, 1.49)	1.10
Vienna	1.37 (0.96, 2.03)	1.35	1.02 (0.75, 1.40)	1.02
Stockholm	0.97 (0.65, 1.43)	0.97	0.61 (0.30, 1.12)	0.62

Abbreviation: CI: confidence interval, hrs/m: hours per month.

(19 ± 20% increase instead of 51 ± 20% increase; Fig. S6 Panel D of the Supplementary Material). Subsequently, if changes in greenspace visits while accounting for seasonal variability were maintained, the risk of reporting decreased mental health and vitality during the Deconfinement Period in Barcelona would increase by 34% and decrease in Stockholm by 20% (Table S10 of the Supplementary Material).

4. Discussion

This study shows that different NPIs in response to COVID-19 altered environmental exposures and health behaviours in Barcelona, Vienna and Stockholm. All three cities experienced reductions in NO_2, noise, and physical activity and greenspace exposures during the Acute Period when accounting for seasonal variability. Additional CVD and MD diagnoses estimated to occur due to decreases in physical activity exceed the prevented CVD and MD diagnoses of NO_2 and noise reductions, if changes in environmental exposures and health behaviours were of longer duration. The estimated changes in mental health and vitality due to decreases in greenspace visits in Barcelona and increases in Stockholm in the Deconfinement Period are indicative of the importance of accessible green and public spaces in urban centres. Thus, policies that focus on maintaining air pollution and noise reductions observed during the first surge of the COVID-19 pandemic while promoting and facilitating access to physical activity and public greenspaces are needed (Fig. 3).

4.1. Nitrogen dioxide

Our estimated changes in NO_2 are in accordance with estimates by the European Environmental Agency (2021) and other researchers (Baldasano, 2020; Barré et al., 2020; Tobías et al., 2020; Venter et al., 2020). Despite drastic decreases in Barcelona, NO_2 concentrations remained above current annual WHO recommendations (World Health Organization, 2021) for both counterfactual periods. Main sources of urban NO_2 are combustion processes associated with road traffic, industry, power generation and shipping (Tobías et al., 2020). Border, school, and non-essential business closures with obligatory home-office, mobility restrictions, home confinement and near-zero tourism resulted in a near-complete standstill of economic and leisure-time activities in many countries (Venter et al., 2020, OECD, 2020). Therefore, the globally-observed decreases in NO_2 during the first COVID-19 surge have been linked to drastic vehicle transportation declines (Baldasano, 2020; Tobías et al., 2020; Venter et al., 2020). Not surprisingly, strict home confinement resulted in the greatest reductions of NO_2 in Barcelona; however, such drastic regulations are impossible to maintain as a viable solution to keep NO_2 below pre-pandemic concentrations. Our study provides empirical evidence that more modest NPIs with associated mobility decreases led to considerable reductions in NO_2, as shown for Vienna and Stockholm. Importantly, reductions in NO_2 in cities with pre-pandemic concentrations approaching WHO annual limits still yield considerable health benefits. In the case of Vienna, prolonged reductions in NO_2 by 22%, as seen in the Acute Period, would contribute to the

Table 4

Changes in nitrogen dioxide, noise, and physical activity during the Deconfinement Period and their effects on the anticipated annual incidence of myocardial infarction, stroke, depression, and anxiety diagnoses.

	Prevented/Additional Myocardial Infarction Diagnoses			Prevented/Additional Stroke Diagnoses			Prevented/Additional Depression Diagnoses			Prevented/Additional Anxiety Diagnoses		
	Cases		% Change	Cases		% Change	Cases		% Change	Cases		% Change
Exposure	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)	Mean (CI)	Median	Mean (CI)
NO_2 – (µg/m^3)												
Barcelona	−247 (−717, 192)	−244	−4 (−12, 3)	−280 (−632, 50)	−277	−5 (−11, 1)	−9122 ((-52316, 24,724)	−7589	−9 (−50, 24)			
Vienna	−70 (−222, 256)	−65	−1 (−4, 1)	−79 (−196, 13)	−74	−1 (−3, 0)	−2523 (−15702, 9124)	−2238	−2 (−14, 8)			
Stockholm	−21 (−64, 18)	−21	−1 (−3, 1)	−34 (−80, 6)	−33	−1 (−2, 3)	−247 (−1562, 931)	−228	−2 (−10, 6)			
Noise – (L_{den})												
Barcelona	−126 (−1092, 650)	−85	−2 (−19, 11)	−241 (−1980, 1980)	−163	−4 (−33, 18)	−1125 (−112,731, 7742)	−410	−1 (−12, 7)	−3089 (−29267, 16,942)	−1583	−2 (−21, 12)
Vienna	−12 (−701, 625)	−2	0 (−13, 11)	−30 (−1235, 1025)	−30	−1 (−22, 18)	−106 (−9056, 835,305)	−14	0 (−8, 7)	−100 (−5811, 5059)	−13	0 (−14, 12)
Stockholm	−27 (−456, 339)	−15	−1 (−20, 15)	−79 (−1170, 782)	−79	−2 (−34, 23)	−86 (−1996, 15)	−24	−1 (−13, 10)	−813 (−14961, 10,737)	−335	−1 (−22, 16)
Physical activity –(MET*min/wk)												
Barcelona	460 (167, 800)	453	8 (3, 14)	471 (13, 971)	463	8 (0, 16)	6340 (3688, 9363)	6273	6 (4, 9)	13,450 (5149, 22,999)	13,239	10 (4, 16)
Vienna	165 (30, 349)	157	3 (1, 6)	167 (−1, 412)	154	3 (0, 7)	2516 (607, 4683)	2458	2 (1, 4)	1526 (288, 3184)	1457	4 (1, 8)
Stockholm	31 (−14, 88)	28	1 (−1, 4)	45 (−22, 145)	38	1 (−1, 4)	157 (−72, 403)	153	1 (0, 3)	1100 (−499, 3112)	1007	2 (−2, 5)

Abbreviations: % change: percent change from baseline; CI: confidence interval; NO_2: nitrogen dioxide; MET*min/wk: metabolic equivalent of task – minutes per week.

annual prevention of ~1% of MI and stroke diagnoses, respectively, and ~2% depression diagnoses. Therefore, action is not only warranted in cities where air pollution concentrations largely exceed WHO guidelines, but also in cities where pollution concentrations are generally considered low.

4.2. Noise

Drastic reductions in vehicle traffic, transportation, and general mobility manifested in reduced noise levels in several European cities (Basu et al., 2021; Rumpler et al., 2020). In our study, the highest decreases in noise levels were observed in Barcelona during the Acute Period, where baseline noise exposures were highest at 62 ± 8 dB(A) L_{den} and NPIs strictest. Several limitations affected the quality of noise data that we used for our study. For example, in Vienna, noise levels were derived from changes in traffic categories and not via direct daily noise measures. Furthermore, all analyses were conducted on a city level, which does not account variations specific to different neighbourhoods. Despite these limitations, our analyses resulted in noise changes that are comparable to those reported in other studies (Basu et al., 2021; Rumpler et al., 2020), and would result in considerable reductions in annual MI (−4 to −1%), stroke (−7 to −1), depression, and anxiety diagnoses (−4 to −1%), if noise level reductions were maintained long-term. Policies that reduce vehicle traffic, speed limits in urban centres, and promotions of active transportation and the generation of greenspaces add more quiet zones in cities.

4.3. Physical activity

Pre-pandemic walking-related physical activity levels were below or within the lower half of current physical activity recommendations in all three cities (Bull et al., 2020), and thus symbolic of the global "physical inactivity pandemic" described in the literature (Ding et al., 2016; Guthold et al., 2018, Andersen et al., 2016). Uncertainty of what was legally permitted following changes to initial COVID-19 restrictions (for example, Barcelona assigned time-windows when residents were allowed to leave their homes for physical activity according to age groups), and general insecurity on the transmission of the SARS-CoV-2 virus and protection guidelines likely affected individuals' physical activity levels further. Living in densely populated cities, where the size of apartments and space to exercise is limited, makes physical activity at home difficult and likely resulted in large differences between those with and without access to private greenspaces from their homes. Increased body weight is only one mechanism of how reduced physical activity levels can trigger a cascade of downstream health effects, for example also through impaired inflammatory and other metabolic responses, and sleep. Health benefits gained from physical activity are also important for mental and social health (Warburton et al., 2006) through enhanced stress management, self-perceived health and quality of life, resilience and social connectedness. Regular physical activity has become a key component in the prevention and treatment of anxiety and depression, which have increasingly affected adults during the COVID-19 pandemic (Xiong et al., 2020). Therefore, generating opportunities to safely engage in physical activity in times of crisis, can offset negative non-COVID-19 health impacts.

4.4. Greenspace visits

When accounting for seasonal variations, we found a decrease in greenspace visits in all three cities. This finding conflicts with those from another study conducted in Stockholm, where the number of greenspace visits was increased by 13% during the COVID-19 pandemic compared to before (Lõhmus et al., 2021). It is possible that our reliance on the "Parks" variable from the Google Mobility Reports (2021) while Lõhmus et al. (2021) used online surveys can explain these opposing findings. Public greenspaces were recognized as significant sources of welfare and

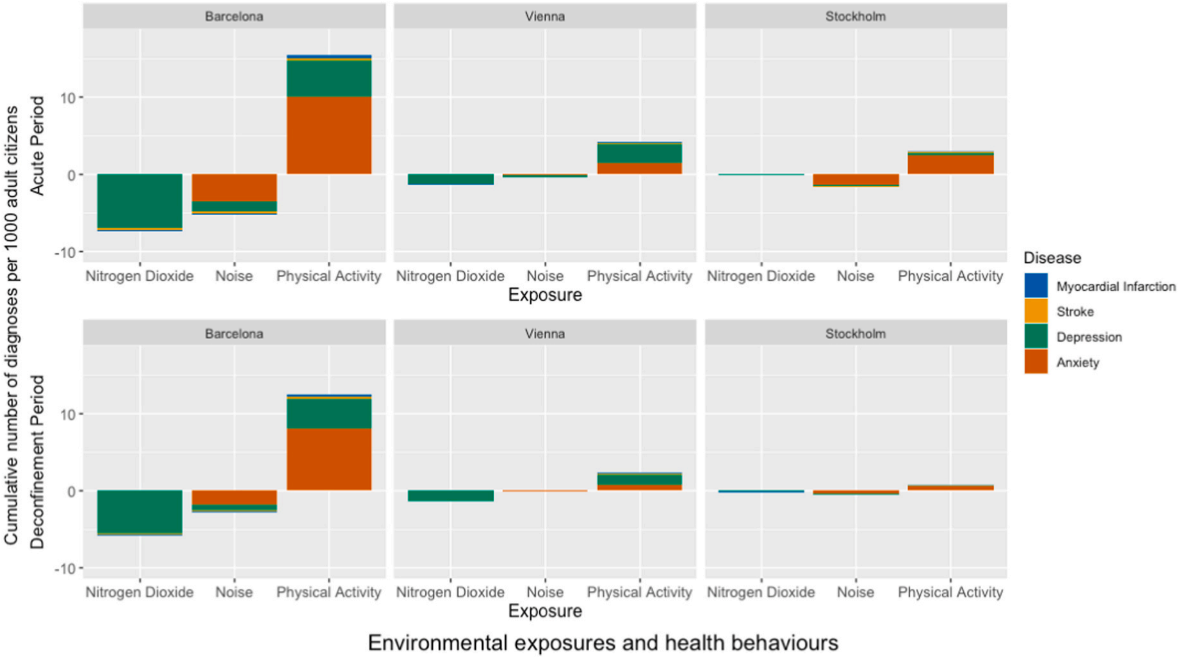

Fig. 2. Cumulative prevented and additional diagnoses per 1000 adult citizens by city and environmental exposure or health behaviour. Abbreviations: MI: myocardial infarction.

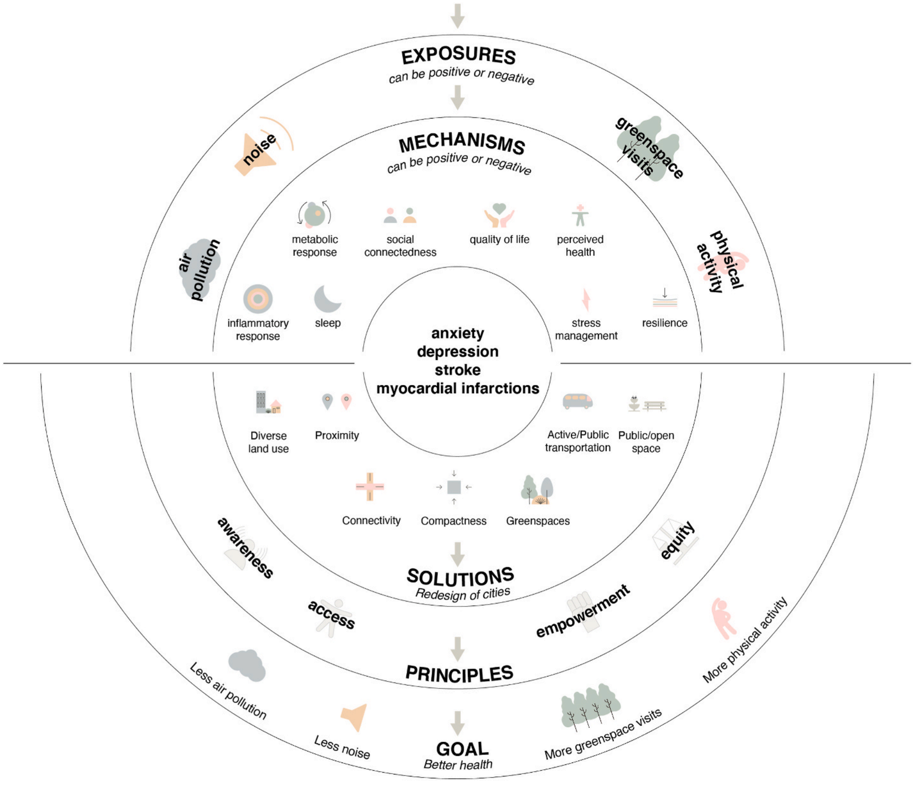

Fig. 3. Conceptual framework for the interplay of cardiovascular disease and mental health disorders with environmental exposures and health behaviours - An overview of potential urban planning solutions that shift underlying mechanisms to improve cardiovascular and mental health.

wellbeing during the COVID-19 pandemic (Day, 2020). Participants of an online survey from Croatia, Israel, Italy, Lithuania, Slovenia, and Spain reported that they normally use accessible urban greenspaces for physical activity, relaxing and observing nature. When asked what they missed most about greenspaces during the pandemic, “spending time outdoors” and “meeting people,” were the most common responses, indicating that greenspaces serve as places of solace and restoration, to engage in physical activity, and to relax and socially connect with others (Ugolini et al., 2020).

5. Strengths and limitations

A strength of this study is the integration of uncertainty analyses. We took the variation of all environmental and health behaviour exposures at baseline and both counterfactual scenarios into account. We believe that this study provides an overview of the magnitude to which the COVID-19 pandemic affected environmental exposures and health behaviours, and how long-term exposures at counterfactual levels could affect CVDs and MDs.

Limitations of our study include the analysis on a city level without considering neighbourhood-specific variations. Furthermore, we did not stratify our estimates of CVD and MD diagnoses by sex, gender, or age. Due to the complexity of collecting and integrating environmental exposure, health behaviour, and health outcome data from various sources at various temporal and spatial scales, analyses at this detailed level were not possible. Socio-economic status, ethnicity and cultural background have also been reported as factors resulting in disproportional health outcomes (for both COVID-19 infections and secondary health effects) in the COVID-19 pandemic (Razai et al., 2021), that we were not able to account for, but consider an important research gap that needs to be filled. We did not assess the combined or interaction effects of the environmental exposures and health behaviours on our health outcomes. While we did include four exposures, there are likely additional exposures (e.g. diet, reorganization of health services, access to health care and other contributors to environmental and health inequalities) that affect CVDs and MDs. Additionally, we did not account for possible effects of the assessed CVDs and MDs on each other.

The two periods of the counterfactual scenarios in this study matched the timeline of the home confinement in Barcelona. Larger percent changes in environmental and health behaviour changes and thus greater impacts on prevented or additional CVDs or MDs would have resulted for Vienna and Stockholm if the assessed periods had matched their country-specific restriction timelines. When this study was started a linear trajectory of Acute and Deconfinement Periods appeared plausible. In practice we have seen multiple periods of restrictions of various intensity. As of February 20th, 2022, COVID-19 cases currently remain extremely high in Europe with the Omicron variant, even with highly vaccinated populations, yet restrictions are being lifted such as in the United Kingdom (Wise, 2022; European Centre for Prevention and Disease Control, 2022). Thus, for many people behaviours and activities have changed over a two-year period. Given the uncertain nature of the pandemic, and differential individual responses to risk, these changes in behaviours and activities could be expected to continue for some time to come. Using the timeframe of one year of sustained environmental exposure and health behaviour changes at the level of the Acute and Deconfinement Periods was arbitrary, and it could be possible that a longer period is needed to observe the true long-term health impacts of such changes in environmental exposure and health behaviour changes. Further limitations are explained in Text S5 of the Supplementary Material.

6. Moving forward – lessons learned from the COVID-19 pandemic to tackle global health threats

To reduce CVDs and MDs in cities through reductions in air and noise pollution and increased physical activity and greenspace visits, various mechanisms, solutions and principles need to be considered. In Fig. 3, we present a framework to illustrate the connections among these aspects. The environmental exposures and health behaviours that we modelled share biological, mental, and social mechanisms. For example, the direction of impacts on metabolic and inflammatory responses, perception of one's own health, quality of life, stress management, and resilience depend on the direction and magnitude of changes in environmental exposures and health behaviours. Thus to promote health, a mixed land use approach can increase connectivity to generate compact cities where essential services are within proximity and reachable through active or public transportation and reduce fossil-fuelled vehicle traffic (Nieuwenhuijsen, 2018). We showed that governmental restrictions in response to the COVID-19 pandemic successfully reduce NO_2 concentrations and noise levels in urban centres. Joining Venter et al. (2020) and Baldasano (2020), our results support the adoption of active and public transportation initiatives as response for improving health during and after the pandemic. Active transportation concomitantly increase physical activity levels, which considerably reduces the burden of non-communicable diseases, particularly from CVDs and MDs, and make cities more liveable and sustainable (Nieuwenhuijsen, 2020). Reducing private vehicle traffic in cities frees up public space for alternative use such as greenspaces to socialize and connect with neighbours, extra bike lanes and walking paths, playgrounds or open-air gymnasiums, among others.

The COVID-19 pandemic has resulted in a major set-back in the use of public transportation. Enhancing space ventilation and social distancing, and implementing future preventative measures for COVID-19 infections is a challenge that needs to be tackled in regaining individuals' confidence in the safe use of public transit. Many cities observed a spike in bike sales and ridership numbers in 2020 (Kraus and Koch, 2021). Via tactical urbanism, bike and walking lanes were added, access to green and blue spaces facilitated, roads closed during specific hours to generate public space for leisure-time activities. These temporary interventions could be made permanent to ensure longer lasting impacts but will require further political discussions as countries lift COVID-19 restrictions and transition from a pandemic into an endemic. Guiding principles to redesign cities include awareness of inequalities, striving for equity that provides easy access, for example to green and public spaces for all, and educational and information services to empower all to adopt healthier lifestyles leading to less polluted, greener, and more active cities.

Conclusions

In the first COVID-19 surge, NO_2, noise, physical activity and greenspace exposures decreased in Barcelona, Vienna, and Stockholm despite different governmental COVID-19 responses. If altered environmental and health behaviour exposures were maintained long-term, greatest estimated increases in CVD and MD diagnoses would be due to the drastic decreases in physical activity levels. In terms of policy implications, sustainable solutions to keep NO_2 and noise reduced, while increasing physical activity and greenspace visits, should focus on the transformation of cities to enhance active transportation and increase public open and greenspaces should be leveraged with an effort to reduce fossil-fuelled vehicles in urban centres. Although prevented and additional CVDs and MDs in response to greenspace visits could not be estimated in this study, promoting access to and additional generation of public greenspaces in cities should be a key element of urban planning. In addition to acting as public spaces with reduced air pollution and noise exposures, they facilitate health promoting behaviours such as physical activity and connections with others and nature.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Dr. Wellenius previously served as a visiting scientist at Google, LLC (Mountain View, CA). This work of Dr. Wellenius with Google did not affect the analyses or interpretations presented in this manuscript in any way. All other 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 A. Supplementary data

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