MobiliSense cohort study protocol: do air pollution and noise exposure related to transport behaviour have short-term and longer-term health effects in Paris, France?

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Basile Chaix ,[1] Sanjeev Bista,[1] Limin Wang,[1] Tarik Benmarhnia,[2] Clélie Dureau,[1] Dustin T Duncan[3]

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[1]Institut Pierre Louis d'Epidémiologie et de Santé Publique IPLESP, Nemesis team, INSERM, Paris, France
[2]Department of Family Medicine and Public Health & Scripps Institution of Oceanography, University of California San Diego, La Jolla, California, USA
[3]Department of Epidemiology, Columbia University Mailman School of Public Health, New York, New York, USA

Correspondence to
Professor Basile Chaix;
basile.chaix@iplesp.upmc.fr

ABSTRACT

Introduction MobiliSense explores effects of air pollution and noise related to personal transport habits on respiratory and cardiovascular health. Its objectives are to quantify the contribution of personal transport/mobility to air pollution and noise exposures of individuals; to compare exposures in different transport modes; and to investigate whether total and transport-related personal exposures are associated with short-term and longer-term changes in respiratory and cardiovascular health.

Methods and analysis MobiliSense uses sensors of location, behaviour, environmental nuisances and health in 290 census-sampled participants followed-up after 1/2 years with an identical sensor-based strategy. It addresses knowledge gaps by: (1) assessing transport behaviour over 6 days with GPS receivers and GPS-based mobility surveys; (2) considering personal exposures to both air pollution and noise and improving their characterisation (inhaled doses, noise frequency components, etc); (3) measuring respiratory and cardiovascular outcomes (smartphone-assessed respiratory symptoms, lung function with spirometry, resting blood pressure, ambulatory brachial/central blood pressure, arterial stiffness and heart rate variability) and (4) investigating short-term and longer-term (over 1–2 years) effects of transport.

Ethics and dissemination The sampling and data collection protocol was approved by the National Council for Statistical Information, the French Data Protection Authority and the Ethical Committee of Inserm. Our final aim is to determine, for communicating with policy-makers, how scenarios of changes in personal transport behaviour affect individual exposure and health.

Strengths and limitations of this study

- While assessing transport behaviour with GPS receivers and GPS-based mobility surveys, we develop a multiexposure perspective considering the personal dynamic exposure to both air pollution and noise using wearable sensors, because road traffic is a shared source of the two and thus provides a basis for major reciprocal confounding.
- In order to improve the characterisation of environmental exposures, sensor-based heart rate, respiratory rate and accelerometry data are considered for estimating inhaled doses of air pollutants, and we distinguish between noise frequency components (ie, low and high pitch sounds) through frequency spectrum analysis.
- MobiliSense assesses through smartphone surveys behaviours that could confound the relationships of interest, and it measures respiratory and cardiovascular outcomes (smartphone-assessed respiratory symptoms, lung function with spirometry, resting blood pressure, ambulatory brachial/central blood pressure, arterial stiffness and heart rate variability).
- MobiliSense aims to investigate both the short-term health effects of transport-related environmental exposures and longer-term effects, with a second sensor-based assessment after 1–2 years.
- Limitations of the study include the small sample of participants, the short monitoring period that may not represent participants' regular behaviour, a potential Hawthorne effect, the partial assessment of cardiovascular and respiratory functions, and the follow-up between 1 and 2 years that may be too short to capture changes in these functions.

INTRODUCTION

Societal background

There is accumulating evidence on the health impacts of environmental emissions (including air pollutants and noise) from motorised transport. It is estimated that in France 31 700 deaths per year in adults≥30 years are attributable to outdoor particulate matter with an aerodynamic diameter of 10 µm or less (PM_{10}), of which 17 600 would be related to traffic related PM_{10}.[1] As a separate calculation (not to be added to the previous one), it was also shown that in 2015 in France ambient particulate matter with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$)

resulted in 20 000 deaths, of which 6400 were of transport origin (corresponding to a transport-attributable fraction of 32%).[2] Of the latter transport attributable deaths, 66% were estimated to be related to on-road diesel vehicles and 5% to on-road non-diesel vehicles.

Regarding noise, an evaluation published in 2013 showed that around 66 000 healthy life years were lost every year in the Paris Metropolitan area due to noise exposure, and that traffic noise represented about 87% of the disability-adjusted life-years loss.[3] Another study reported that inhabitants of Greater Paris Metropolis suffer an 8-month loss of life in good health over lifetime because of their transport-related noise exposure and that such a loss would reach 18 months in some municipalities.[4]

Scientific background

Literature assessment

The MobiliSense project was developed on the basis of a literature review that is reported in online supplemental appendix 1. We examined studies investigating associations of air pollution and noise exposure with respiratory symptoms, lung function, heart rate variability and blood pressure.

One of our conclusions is that numerous studies have focused on the health impacts of environmental exposures resulting from transport infrastructures and flows (eg, road traffic, air traffic). However, much less studies have investigated the health effects of exposures incurred during personal trips with different transport modes, as it is methodologically challenging in terms of exposure assessment. Thus the present study focuses on personal mobility/transport behaviour, as Paris residents spend a substantial time in their daily travels.[5] Some studies dealing with this issue are scripted exposure studies where the same participants are asked to perform 'exposed' and 'unexposed' trips along predefined itineraries.[6 7] Although strong from a causal perspective, these experimental studies collect data for a very limited number of trips and with a limited number of modes, thus have a very poor generalisability. MobiliSense addresses this gap in order to elaborate a comprehensive picture taking into account benefits (eg, physical activity) but also hazards (air pollution, noise, stress) associated with the personal use of transport modes in free-living individuals across a large diversity of trips.

Second, most previous cardiovascular studies have focused either on air pollution or noise exposure, but few have developed a multi-exposure perspective considering both air pollutants and noise, and very few based on personal monitoring. For example, two studies used personal monitors to perform a simultaneous assessment of noise and particle number concentration,[8] and of noise, $PM_{2.5}$, CO and black carbon.[9] However, heart rate variability, but not blood pressure, was considered in these studies. Simultaneous monitoring of air pollutants and noise is critical (1) because road traffic is a shared source of the two and thus provides a basis for major reciprocal confounding and (2) in order to investigate amplification effects (interaction between these exposures).

Third, our literature review assessed both short-term effects and longer-term effects of air pollutants and noise. Studies have either focused on the former or on the latter, but not on both due to incompatibilities of design. We aimed to address this gap by deriving estimates of short-term effects and medium-term effects (over a period of 1/2 years) from our population sample.

The development of Public health policies using levers for action related to transport systems and the simultaneous development of transport policies that are aware of health issues need accurate data on the physical activity performed and environmental exposures incurred during trips in the multiple transport microenvironments across a variety of modes. Policy-makers also need a better knowledge of hotpots of exposure in the urban and transport system. MobiliSense aims to provide objective sensor-based data on transport behaviours, environmental exposures and health status to support analyses of the health impacts of policies and interventions related to urban and transport systems.

Assessment of overall and transport-related environmental exposures

While a major challenge is to assign an individual exposure to participants while minimising measurement error, methods for assessing exposures typically differ between short-term and longer-term exposure studies. Regarding air pollution, studies have often assigned to participants outdoor concentrations of pollutants measured at the closest monitoring station, have averaged or interpolated measures at different stations, or have relied on residential estimates of outdoor concentrations from air dispersion models or land use regression models.[10–12] Noise studies have often relied on modelled noise maps from land use regression or simpler approaches.[13 14] Assessing individual environmental exposures with these approaches has a limited validity.[15 16] First, such exposure data either ignore or only imperfectly account for proximity sources of exposure or other determinants of exposure at the residence, or they ignore the true circumstances of exposure at the residence (eg, noise assessed on the most exposed façade of buildings). Second, these approaches neglect that people spend a different fraction of their time at their residence rather than in other places visited during their daily activities. Finally, this exposure assessment ignores that people spend a different amount of time inside rather than outside buildings. Combining precise locational information obtained from Global Positioning System (GPS) tracking with maps of outdoor pollutants, as studies have done but often without concomitant measurement of health outcomes,[17] only partially addresses these limitations, especially because a fraction of the exposures during trips occurs indoor (eg, in underground settings, in cars or buses).

There is a large consensus that wearable monitors are key to improve the assessment of personal exposures.[18–20]

Weak longitudinal correlations in concentrations of suspended particles have been reported for certain participants in studies following participants with wearable monitors and fixed monitoring stations.[15 21 22] Thus, it is assumed that wearable monitors more closely reflect personal dynamic exposure. While personal mobile measurement may be a gold standard for air pollution exposure assessment, it must be emphasised that the accuracy of new sensors cannot be taken for granted, and that studies with personal measurement have often included small samples and are typically unable to collect data continuously over the time period needed to capture chronic effects.[23]

Most studies based on personal monitors captured air pollution or noise exposure aggregated for entire periods (eg, over 24 hours in analyses of short-term effects) without discriminating between subperiods of space-time budgets. Accurately quantifying levels of exposure to air pollutants and noise in the multiple microenvironments, especially with the different transport modes, would represent a significant advance.[6 18 24] Many people receive a significant fraction of their exposure to certain pollutants when commuting to work or during trips.[7 19 25] Thus, personal monitoring is particularly useful if deployed with novel methodologies accurately capturing time use or space-time budgets.

Travel diaries filled by participants are a common strategy to collect data on transport modes and visited places.[26] However, such reporting is imprecise, while accurate timestamps are needed to match information on transport modes with exposure data from the wearable environmental sensors. Moreover, the quality of reporting in diaries has been shown to decline as soon as after the first day.[27] Another option is to automatically predict transport modes, for example, at the minute level, from algorithms applied to GPS data.[28] However, such algorithms may lack accuracy in the predicted transport modes (while we need to distinguish personal car from motorbike, bus, and train) to establish correspondence between minute-level information on transport modes and environmental exposures measured by personal sensors. As described below, we address these concerns through a so-called GPS-based mobility survey[29 30] where algorithm-processed GPS data provide a basis for a phone survey of participants that permits to correct or complement information on trip schedules and modes of participants. This approach, although costly to implement, yields time-stamped information on the transport behaviour of participants at a reasonable level of accuracy for matching with environmental data from wearable sensors.[31 32]

There are specific additional challenges. Regarding air pollution, first, it is a priority to perform a personal monitoring of black carbon: (1) because black carbon is an excellent marker of road traffic particulate pollution (tire wear particles, diesel vehicle exhaust),[33] a recent study demonstrating that transport episodes represented 6% of participants' time but 21% of their exposure to black carbon and 30% of inhaled doses[18] and (2) because there is evidence that black carbon is more strongly associated (eg, than $PM_{2.5}$) with some of the respiratory and cardiovascular outcomes.[7 20 34–36] Second, only few studies of short-term effects of air pollutants have accounted for estimates of inhaled doses.[18 24] Regarding noise exposure, studies of cardiovascular outcomes in real-life settings have assessed the overall sound pressure but have not distinguished between noise frequency components[37] (eg, low and high pitch sounds) through frequency spectrum analysis. This is a limitation because the different organs are susceptible to different acoustic frequencies.

Objectives

The MobiliSense study aims to conduct a comprehensive investigation of the relationships between transport-related exposures and selected health outcomes. It addresses gaps in knowledge: (1) by focusing on both short-term and longer-term effects of personal transport behaviour on health, based on a repeated assessment of transport behaviour and health 1/2 years apart; (2) by considering two distinct environmental exposures (air pollution and noise) related to the transport activity that were often investigated separately and (3) by deriving reliable measures of exposures, confounders, and respiratory and cardiovascular outcomes using passive and active sensors and innovative electronic survey methods.

Regarding specific objectives, first, we aim to assess the contribution of personal transport behaviour to the overall air pollution ($PM_{2.5}$, black carbon, nitrogen dioxide (NO_2) and ozone (O_3)) and noise exposure of individuals; and our goal is to compare the air pollution and noise exposure across transport modes (walking, biking, two-wheel or four-wheel personal motorised vehicle, public transport modes), to better understand source-specific impacts and critical exposure periods. Our detailed assessment protocol permits to quantify exposures by types of public transport mode; by names of public transport line; and by brands and other characteristics of private motorised vehicles.

Second, we aim to investigate whether (1) profiles of transport behaviour, (2) total personal exposure to selected air pollutants and noise, and (3) transport-related personal exposure to air pollutants and noise are associated with short-term respiratory and cardiovascular outcomes and with longer-term (1/2 years) changes in respiratory and cardiovascular outcomes.

As secondary objectives, in estimating these associations, we aim to compare (1) exposures measured by personal sensors with those estimated by combining participants' GPS tracks (corrected and complemented through the electronic mobility survey) and model-based maps of exposures; (2) concentrations of air pollutants with inhaled doses of pollutants; (3) overall sound pressure exposure with noise frequency components; (4) noise effects in time segments where participants are annoyed by noise versus not and (5) effects in individuals who describe themselves as sensitive to noise versus not.

METHODS AND ANALYSIS

Sampling and recruitment

Participants were recruited through a two-stage stratified sampling design. The neighbourhood sampling phase involved the random selection of local neighbourhoods in the Metropolitan area of Paris (so called Grand Paris), stratified by quartiles of area-level household income and quartiles of road traffic density (traffic model of the Ministry of Infrastructures). Within each area income stratum, we randomly selected 30 neighbourhoods in each of the two extreme quartiles of traffic density (60 neighbourhoods in each area income quartile, ie, 240 neighbourhoods overall).

At the second stage, based on the allowance of the National Council for Statistical Information (CNIS), the Population census was used by the National Institute of Statistics and Economic Studies to sample dwelling units in each of the selected neighbourhoods. Overall, 33 501 dwellings were selected in the 240 neighbourhoods. We accessed to the demographic and socioeconomic data on the occupants of these dwellings in the 2013–2014 censuses. Each dwelling was contacted twice by postal mail. Our eligible participants were people aged 30–64 years on January 1 2016, who either were residing in the dwelling in 2013–2014 or arrived later.

The sampling and data collection protocol was approved by the National Council for Statistical Information, the French Data Protection Authority, and the Ethical Committee of Inserm. Access to MobiliSense data is possible through scientific collaborations. The first wave of the study was conducted between May 2018 and March 2020. The second wave started in March 2020 but was delayed due to the COVID-19 pandemics and will last until March 2022.

Participants are recruited at home after signing an informed consent letter, and are managed from a computer application. At their home, we collected data on body weight, body height, waist circumference and arm circumference, and on fat mass through bioelectrical impedance analysis. The overview of the data collection is reported in figure 1.

Patient and public involvement

Participants or residents were not involved in the development of hypotheses or construction of the protocol. Participants receive personalised reports on their environmental exposures and health from their own sensor data after the follow-up, and will be able to access to the global findings of the study on the MobiliSense website.

Standard questionnaires

Before the sensor-based assessment, research assistants guide participants through a standard computerised questionnaire on the following dimensions: health status; health-related behaviour (physical activity, smoking, alcohol consumption, sleep); country of citizenship and country of birth of the participant and her/his parents; socioeconomic status; occupational history over 2 years;

(Time)

	Before	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	After
Questionnaires								
Standard questionnaire	X							
VERITAS questionnaire	X							
Post-questionnaire								X
GPS-based mobility survey								X
Sensors								
BT-Q1000XT (GPS receiver)		X	X	X	X	X	X	
wGT3X+ (accelerometer)		X	X	X	X	X	X	
AE51 (black carbon)								
PAQM 520 (multi-pollutants)		X	X			X	X	
SV 104A (noise)				X	X	X	X	
AG24 (ambulatory blood pressure)		X		X				
Biopatch (heart & respiratory rates)			X		X	X	X	
Withings (blood pressure at rest)			X		X	X	X	
Spirotel 2 (spirometry)		X	X	X				
Smartphone surveys								
Respiratory questionnaires		X	X	X				
Post-blood pressure at rest					X	X	X	
Alcohol consumption		X	X	X	X	X	X	
Tea consumption		X	X	X	X	X	X	
Coffee consumption		X	X	X	X	X	X	
Food consumption		X		X				
Passive smoking		X	X	X	X	X	X	
Antihypertensive medications		X	X	X	X	X	X	
Respiratory medications		X	X	X	X	X	X	

Figure 1 Overview of the MobiliSense data collection. GPS, Global Positioning System.

perception of the residential environment; resources for transport (driving licence, motorised and non-motorised vehicle ownership, access to parking, public transport pass, etc) and detailed perceptions and attitudes related to transport; perceptions related to air pollution and noise; and characteristics of and exposures related to the dwelling (cooking and heating equipment, air conditioned, humidity, furniture, animals and plants, double/triple-glazed windows in the dwelling).

At the end of the sensor-based assessment, participants are asked to answer a postquestionnaire during a phone call which asks about their sleep, alcohol consumption, sport participation, perceived consequences of air pollution and noise exposure, and mental health over the specific days where the sensors were worn.

Sensor and smartphone-based strategy

As depicted in figure 1, participants are followed with sensors over 6 days (thus encompassing week and weekend days). Over these days, they alternate between different configurations of sensors. The sensors used in this study are represented in figure 2. On all days, participants carry a GPS receiver and an accelerometer. Participants carry every day two of the three following monitors: a monitor of black carbon concentration, a wearable monitor for gases and particles, and a monitor for sound pressure. Participants report annoyance by noise and air pollution in trips and stress in trips in a paper travel diary. Participants undergo ambulatory blood pressure monitoring for two sessions of 24 hours; they measure their blood pressure at rest in the morning and evening over 4 days; and their heart rate is measured continuously over 4 days. Finally, participants perform a spirometry test in the morning and evening over 3 days; and they are surveyed on their respiratory symptoms with a smartphone over

Figure 2 Sensors and devices used in the MobiliSense data collection.

the same days. The smartphone survey application also permits to report other relevant health behaviours.

Participants wear all devices from wakeup to bedtime. They are instructed to not deviate from their usual routine during the data collection. They receive a strong support during the follow-up and detailed personalised reports on their health status and exposures afterwards. Devices are brought back by a courier service. Quality control and cleaning procedures related to each particular sensor will be published in our forthcoming articles using the corresponding data.

Ambulatory and resting blood pressure

On days 1 and 3, participants wear an Arteriograph 24 ambulatory blood pressure monitor (TensioMed, Budapest, Hungary) from wakeup to bedtime. The device measures, as few studies have done, in addition to brachial (peripheral) systolic and diastolic blood pressure and pulse pressure, central systolic blood pressure and pulse pressure, and aortic pulse wave velocity and the so-called augmentation index as markers of arterial stiffness. The device takes a measure every 30 min during the day.

On days 2, 4, 5 and 6, participants are asked to measure their blood pressure at rest 3 successive times in the morning and in the evening, while sitting and relaxing, with their non-dominant arm resting on a table (according to the self-measurement protocol of the European Society of Hypertension), before taking potential medications. Self-measurement of blood pressure for several days is thought to be as reliable as measurement at the physician's office.[38] Participants use a certified blood pressure monitor (Nokia Health / Withings, Issy-les-Moulineaux, France) that permits a real-time transmission of measurements to a distant server through a connection to the smartphone provided to participants. Participants answer each morning and evening on the smartphone to a very short survey on the circumstances of measurement of blood pressure (medications taken, time spent at rest, social interactions, ambient noise).

Heart rate variability

On days 2, 4, 5 and 6, a monitoring of heart rate is performed with the BioPatch (Medtronic Zephyr, Boulder, Colorado, USA), an electrocardiographic device with two electrodes which was validated against a 12-lead device.[39] The BioPatch is worn on the left below the pectoral muscle. RR intervals are determined from an ECG sampled at 250 Hz. The RHRV R package[40] will be used to determine heart rate variability parameters related to the time domain and to the frequency domain (the latter decomposes periodical oscillations of heart rate at different frequencies) for 5 min, 1 hour and 24 hours intervals.

Spirometry

On days 1, 2 and 3, a spirometry test is performed by participants before taking potential medications each morning and each evening using Spirotel 2 (MIR, Langlade, France), a device that meets the ATS and ISO standards. Spirotel 2 measures the peak expiratory flow, the forced expiratory volume in 1 s, the forced vital capacity, the forced expiratory flow between 25% and 75% of vital capacity, and the forced expiratory volume in 6 s. Spirotel 2 automatically sends the information to a distant server through a connection to the smartphone provided to participants.

Our research assistants received an extensive training. At the participants' homes, they perform a demonstration and then ask participants to perform measurements, while explaining them carefully how to do and encouraging them to provide maximal efforts when expiring. After participants perform up to eight measurements, they are invited to examine the resulting spirometry curves, and are explained which curves are acceptable and which are not. Spirometer curves are remotely checked every day, and in case they are of insufficient quality, participants are called on their phone to fix the problem.

Smartphone survey

On days where participants perform spirometry tests, they are surveyed on their respiratory symptoms: asthma attack, loose or hacking cough, shortness of breath, wheezing, phlegm, runny nose and stuffed nose (absent, mild, or severe). Participants report symptoms in the morning and evening as well as two additional times during the day if they have asthma or chronic obstructive pulmonary disease (after receiving an alert at random times on the smartphone provided for the study). Participants also report alcohol, coffee, tea and medication consumption with the smartphone. These surveys are implemented with our Eco-emo tracker web and smartphone platform that

we develop for collaborative purpose. It permits a real-time follow-up of each participant's response rate from the web platform, and thereby to intervene to encourage participation if needed.

Location and physical activity

Participants carry a BT-Q1000XT GPS receiver (Qstarz, Taipei, Taiwan) collecting location information every 5 s and a wGT3X+tri-axial accelerometer (ActiGraph, Pensacola, Florida, USA) on an inelastic belt over the 6 days.

Air pollution and noise

Participants also wear the AE51 Aethalometer (AethLabs, San Francisco, California, USA) on days 1, 2, 3 and 4 of the follow-up for measuring concentrations of black carbon, whose significance for health has been emphasised in the review reported in online supplemental appendix 1. This device has been successfully used in previous studies.[6 18 41] Devices are calibrated before each participant's recruitment. Measurements are taken every 10 s. Participants recruited in winter have to change the filter on the second day at 20:00 hour.

On days 1, 2, 5 and 6, participants carry the Personal Air Quality Monitor, PAQM 520 (Atmospheric Sensors, Bedfordshire, United Kingdom), which measures concentrations of gases (O_3, NO_2, nitrogen monoxide and carbon monoxide (CO)) and particles. We performed a calibration of each of the PAQM monitors against reference instruments for gases and particles and use the equations derived from this calibration to correct the values measured with the sensors. Measurement of gases is averaged over 10 s epochs. Electrochemical sensors measure gases quite well with static temperature and humidity, but are influenced by rapid changes in temperature and relative humidity from one microenvironment to the other. Measurement of temperature and relative humidity by PAQM 520 is useful to address these artefacts in the measurement of gases. Measurement of particles is conducted over 5 s every minute across 16 segments of particle size between 0.38 and 17 µm, which is important to distinguish between particles from different sources. The device also includes a GPS receiver, an accelerometer, a low-cost noise sensor and a mobile phone Subscriber Identity Module (SIM card for the automatic transmission of data to a distant server (even if data are stored as well on an internal memory card).

Several approaches are used to estimate the inhaled doses of pollutants. In these approaches, the ventilation rate in litre/minute for each minute of the follow-up is multiplied by the corresponding exposure concentrations. This 1 min ventilation rate is calculated for each subject: (1) using a stochastic equation according to age, sex, and the corresponding 1 min metabolic equivalent estimated from the accelerometer[17 42] or (2) with exponential equations for men and women based on heart rate or (3) using comparable equations based on breathing rate.[43]

On days 3, 4, 5 and 6, the SV 104A dosimeter (Svantek, Warszawa, Poland) fixed at the belt, with a microphone attached to the participant's collar close to the ear, is used for a personal monitoring of noise. This dosimeter integrates a one-third octave band filter, permitting to divide noise into its frequency components (frequency spectrum analysis). It allows us to assess in an innovative way the effects of noise frequency components,[37] and of noise containing discrete frequencies or marked tones (higher level in a one-third octave band than in the adjacent frequency bands, more likely to be perceived as a nuisance).

Participants are instructed to place the air pollution and noise monitors as close as possible from them when they do not wear them (eg, when sleeping or bathing).

Spatial mobility and transport behaviour

During the recruitment, participants are surveyed with the VERITAS web mapping application, to geocode the regular places where they perform a list of predefined activities.[44] Survey technicians ask participants how often they went to each of these regular places (per week, month or year) over the previous year and collect information on the most regular transport modes used to travel to these destinations.

Based on a methodology that we have developed in our previous work,[31 32 45] after the follow-up, GPS data are uploaded in the TripBuilder application where they are automatically analysed with algorithms.[46] On the basis of GPS data and external data sources (survey questions on transport habits, VERITAS data on regular visited places, geographic data on points of interest and public transport stations), these algorithms identify the places visited by participants and the trips (with their unimodal components) between these places. They also automatically impute information on the nature of visited places and on the transport modes in each trip stage.[46] The preprocessed GPS tracks and imputed information are shown in the web mapping interface of the TripBuilder application. We use this application to survey participants by phone on their visited places and transport modes in each trip stage over 6 days (we validate, correct or complement the imputed information). The application is also used to edit the GPS tracks, by eliminating artefacts and by graphically reporting missing trips or portions of trips. Compared with our previous projects,[31] it includes a novel tool to retrieve the correct itinerary of public transport trips in the General Transit Feed Specification data, which is useful for underground trips; for each trip stage with a personal motorised vehicle, we collect the id of the vehicle (that can be matched to relevant characteristics of vehicles of the household, including the brand, the model year, and various motorisation and emission characteristics, surveyed in the main computerised questionnaire from the id card of the vehicle); finally, this mobility survey is used to assess the level of stress experienced in each of the trips. The final output over 6 days comprises the cleaned GPS tracks; the location of, arrival time to,

and departure time from each visited place; and the location and time of each point of change of mode during trips. This information permits to ascribe data collected with behavioural, environmental and health sensors to each trip stage or visited place of the mobility survey, for example, to calculate transport-related environmental exposures.

The 6-day transport behaviour and VERITAS assessment of regularly visited places and associated transport modes will permit to distinguish casual transport behaviour from *regular* transport behaviour, to investigate short-term and longer-term effects of transport on health.

Estimation of exposure from modelled maps

Apart from personal environmental monitoring, we will approximate air pollution and noise exposures with model-based maps of air pollutants (hourly maps) and noise (annual means) at the residence and along the corrected and cleaned GPS tracks over 6 days (the different exposure assessment methods will be compared). We will extract the air pollutant or noise exposure value from the model-based map at each GPS point. Adjustments will be made for indoor locations (by applying an average coefficient related to the impermeability of buildings to air or to acoustic insulation) and for underground transport stages (by applying average values from previous measurement campaigns).

Longer-term exposures to air pollutants and noise will be determined by considering places regularly visited over the past 12 months and usual transport modes to these places from the VERITAS survey, linked to data from exposure maps and knowledge on exposure in indoor and transport microenvironments from subject monitoring.

Follow-up

Participants are invited to perform the same data collection (locational, behavioural, environmental and health sensors and full questionnaire assessment) between 1 year and 2 years after the first wave (allowing for differential changes between exposure groups to occur).

Statistical analyses

Descriptive analyses

Taking into account the exact time segments devoted to trips over 6 days, we will compare the exposure to air pollutants and noise between the different transport modes at the trip stage level (walking, cycling, wo-wheel motor vehicle, car and the different public transport modes). We will determine the percentage of exposure to air pollutants and noise over 6 days that is attributable to the transport activity and to each transport mode.

Analyses of short-term effects

Analytical designs will be developed for each outcome. For example, ambulatory blood pressure measurements as repeated outcomes will be modelled according to air pollutant and noise levels in the preceding 1 or 2 hours. Differently, changes in resting blood pressure and lung function between the morning and evening measurements will be modelled against air pollution and noise exposure in the 1 or 2 hours preceding the evening measurement or against exposures accumulated over the day.

For each outcome variable, models taking into account repeated outcome measures will be used. In addition to sampling design and non-response weights, regression models will incorporate a random effect at the individual level and a temporal autocorrelation structure,[47 48] and will account for spatial autocorrelation if present in the data.[49 50] We will specify random slopes to determine whether an exposure—outcome association is only documented in few susceptible individuals or among most participants.[36] Multiexposure models (different air pollutants, noise) will be estimated, using quantile-based g-computation and Bayesian kernel machine regression. Time length of exposure windows and time lags in the effects (with distributed lag models) will be investigated in sensitivity analyses.

The anticipated list of confounders that will be accounted for is reported in online supplemental appendix 2. Whenever appropriate, we will account for the different periods of the COVID-19 crisis (partial lockdown, restrictions of movement, etc) through adjustment (no recruitment of participants was conducted during the full lockdown). Quadratic or cubic terms, piecewise regression analyses, or smoothing terms will be used to take into account humidity or temperature in the models for air pollution effects, and to test the hypothesis of nonlinear associations between air pollutants or noise and health. Interactions between the effects of air pollutants and noise will be tested for cardiovascular outcomes.[9]

Analyses of longer-term effects

A two-stage model will be used to investigate determinants of changes in health status between wave 1 and wave 2. Stage 1 will model the short-term association between the exposure and the repeated outcome. Pooling the data of the two waves (baseline and after 1/2 years), we will add to the model: a dummy variable for the second wave (as opposed to the first); an interaction between this dummy and the short-term exposure effect; and an individual-level random slope for the latter effect. This model will indicate how the health sensitivity to short-term exposures changed between waves 1 and 2 and how this change varies among participants. From this model, a prediction of the outcome will be derived for each of the two measurement waves for each participant, considering an average short-term exposure level. The second stage of the model will estimate the association between longer-term exposures and change in the predicted level of the outcome between waves 1 and 2. The two stages of the model will be estimated jointly through a Markov chain Monte Carlo approach. Biases in the analyses of changes over time related to attrition (participants failing to be involved in the second wave of data collection) will be addressed through inverse probability weighting.

Summary of study strengths and limitations

A key strength of the MobiliSense project is that it relies on objective and dynamic measurement of exposures, confounders and health outcomes. The protocol uses passive and active wearable monitors of location, behaviour, environmental conditions and health. Strengths of the study include the simultaneous monitoring of air pollution and noise with personal devices; the evaluation of inhaled concentrations of air pollutants and noise frequency components; the combination of personal environmental monitoring with an accurate assessment of transport behaviour using methods from Transport sciences; and the assessment of short-term effect and longer-term effects of environmental exposures. From an analytical viewpoint, the project develops a momentary perspective, that is, analyses repeated health measurements for each individual in function of immediately preceding and local environmental exposures and circumstances preceding measurement. The ambition of this work, complementing our previous work focusing on physical activity in trips,[5 31 45] is to build a comprehensive picture of the health benefits and hazards associated with each transport mode, and to derive accurate data to model the health impacts of urban and transport policies.

The main limitations of the study pertain to the small sample of individuals to capture the transport behaviour of a background population of several millions, to the short monitoring period (6 days) that may not represent participants' regular behaviour, to a potential Hawthorne effect through which our burdensome observation protocol could have modified people's transport behaviour, to the complex structure of data resulting from the fact that participants could not carry all sensors on the same days, to the partial assessment of cardiovascular and respiratory functions, and to the follow-up between 1 and 2 years that may be too short and sample size that may be too small to capture environmentally induced changes in these functions.

ETHICS AND DISSEMINATION

The sampling and data collection protocol was approved by the National Council for Statistical Information. Based on this allowance, the French National Institute for Statistics and Economic Studies drew a sample of potential participants from the population census. The MobiliSense project also received the appropriate allowances from the French Data Protection Authority and from the Ethical Committee of Inserm.

Participants are recruited at home after signing an informed consent letter. During the sensor-based study, they receive the support they need from the research assistants. They are welcome to call on a hotline at any time, should they need any technical help during the data collection. After the data collection, participants receive a personalised report describing their exposures to noise and air pollutants in the different places where they went and in the different transport modes that they used. They also receive reports pertaining to their blood pressure and spirometry measurements.

Regarding dissemination, in addition to standard scientific publications, our final aim is to determine, for our communication with policy-makers, how scenarios of changes in personal transport behaviour would affect individual exposure and health, and how urban and transport policies shifting the shares of trips with the different transport modes would influence population health.

Contributors BC conceived the MobiliSense protocol, obtained funding, and is the principal investigator of the project. CD supervised the data collection team and was involved in the data collection. CD, SB, ALW, TB and DD are involved in the project and revised the manuscript for important intellectual content.

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ORCID iD

Basile Chaix http://orcid.org/0000-0003-1631-8630

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Short- and longer-term health effects of air pollution and noise exposure related to transport behaviour: the MobiliSense Study

Web Appendix

Web appendix 1: Literature review of air pollution and noise effects on selected health outcomes

Respiratory symptoms

Studies of long-term exposure to air pollutants in adults have usually documented associations with respiratory symptoms.[1] A Swiss study documented positive associations between annual concentrations of nitrogen dioxide (NO_2) or particulate matter with an aerodynamic diameter of 10 µm or less (PM_{10}) and chronic phlegm production, chronic cough, breathlessness at rest, and dyspnea.[2]

Regarding studies of short-term effects, a work conducted in different European cities based on background concentrations over 24 hours measured from a central site and on a daily respiratory questionnaire completed over 6 months concluded that a high concentration of particulate matter with an aerodynamic diameter between 2.5 and 10 µm was positively associated with shortness of breath and wheezing.[3] As another example relevant to the present project devoted to exposures during trips, a Dutch study of 489 adults found that the exposure to black smoke over 24 hours (as an indicator of black carbon emitted by diesel engines) was associated with upper respiratory symptoms, in a more consistent way than the exposure to sulphate and PM_{10}.[4]

Several studies have focused on the effects of air pollutants on the exacerbation of symptoms among asthmatics or chronic obstructive pulmonary disease (COPD) patients. For example, a study of 75 asthmatic or COPD patients from the United Kingdom reported that high concentrations of NO_2 and ozone (O_3) over 24 hours were associated with wheezing or dyspnea within one or two days.[5] As another example, a study suggested that a higher concentration of PM_{10} was associated with dyspnea one day after.[6] However, certain studies also reported negative findings. Paradoxically, a study of 16 COPD patients that analysed, in

addition to the background concentrations of particulate matter with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$), data from a personal monitoring of the exposure to $PM_{2.5}$ did not identify an association with any of the respiratory symptoms examined,[7] perhaps because of the weak number of participants.

A limitation of these studies is that paper questionnaires referring to relatively long recall periods (e.g., 24 hours, one week, one month) were used, implying reporting biases in the symptoms.

Lung function

A relatively weak number of studies have focused on the relationships between the long-term exposure to air pollutants and lung function. For example, a Swiss study showed that elevated annual concentrations of sulfur dioxide (SO_2), NO_2, and PM_{10} were associated with a lower forced vital capacity (FVC) and forced expiratory volume in one second (FEV_1), with stronger relationships observed for PM_{10}.[8] A longitudinal analysis from the same study subsequently documented that a decrease in the concentration of PM_{10} was associated with a lower decrease of lung function over time.[9] More recently, a French study reported that a higher concentration of PM_{10} over the preceding 12 months was associated with a lower FVC and FEV_1.[10] However, it is important to emphasize that, comparing different exposure areas with each other, these studies of the long-term effects of air pollutants are vulnerable to residual confounding.[11]

Apart from investigations of long-term exposure effects, studies of the effects of short-term exposure to air pollutants were conducted[12] based on repeated spirometry measurements. For example, an Italian study of 29 participants found that a higher daily concentration of NO_2 was related to a decrease in FEV_1 among asthmatics but not among coronary patients.[13] The strength of the associations identified in studies seemed to depend on the average concentration of pollutants over the territory, with stronger associations at higher average

concentrations. In a study of 16 COPD patients in Vancouver where the average concentration of PM_{10} was of 18 µg/m^3, each 10 µg/m^3 increase in the concentration of PM_{10} measured over one day was associated with a 3% larger decrease in FEV_1 between the morning and the evening measure.[7] In a study in which the average concentration of PM_{10} over 24 hours was above 150 µg/m^3, a 10 µg/m^3 increase in the concentration was related to a decrease of up to 7% in FEV_1.[14] However, a recent study also emphasized that even a "moderate" (compared to a "good") range of exposure to $PM_{2.5}$, NO_2, and O_3 over 24 hours according to the classification of the US Environmental Protection Agency was associated with a decreased FEV_1.[15]

Some studies of short-term effects of air pollutants have focused on the size of the time window to consider to better identify associations with lung function. A Korean study that compared different strategies to proxy the individual residential exposure from measures performed at fixed monitoring stations showed that a high concentration of PM_{10} was associated with a reduced FVC, especially when concentrations were assessed over 24 hours two days before the spirometry test.[16] This finding is coherent with another study that reported that an elevated concentration of PM_{10} over the 37–60 hours preceding the spirometry assessment was associated with a decreased FVC and FEV_1.[17] However, it must be emphasized that certain studies did not observe a relationship between the exposure to air pollutants and lung function.[18]

Very few studies have established a direct link with the transport activity. One experimental (thus poorly generalizable) study of 60 participants demonstrated that walking for two hours in Oxford Street was associated with more important reductions in FVC and FEV_1 than that observed in the same participants when walking through Hyde Park.[12] Such an effect was particularly attributable to the higher exposure to ultrafine particles and black carbon (as markers of road traffic with diesel engines) in Oxford Street.

Limitation of these repeated measure studies of lung function is that they were often based on a low sample size.

Blood pressure

Air pollution effects: Relatively few studies investigated associations between the chronic exposure to air pollutants and blood pressure or the prevalence / incidence of hypertension. For example, in a US study, a higher exposure to nitrogen oxides (NO_x) but not to $PM_{2.5}$ was associated with a slight increase in the incidence of hypertension over 10 years.[19] Similarly, a German study reported that higher concentrations of $PM_{2.5}$ were associated with an increased blood pressure, which association persisted after adjustment for road traffic noise.[20]

A larger number of blood pressure studies considered short-term exposures to air pollutants. Transient elevations of blood pressure repeated daily over years could lead to chronic blood pressure increase; moreover, a transient increase in blood pressure can trigger cardiovascular events in vulnerable individuals[21] (as a potential explanation of the increased incidence of cardiovascular events during pollution episodes[22]). As an example, a US study reported that an increase of 10 $\mu g/m^3$ in the daily concentration of $PM_{2.5}$ was associated with a 3.2 mmHg higher systolic blood pressure, with still stronger effects in the area where the average concentration of PM2.5 was the highest.[22] However, certain studies did not observe such positive short-term association, or even documented negative associations.[23] These incoherent patterns may be attributable to the fact that blood pressure depends on both vascular resistance and the cardiac output, while the main hypothesis for air pollution effects is related to the first aspect (air pollution increases peripheral resistance and decreases elasticity of arterial walls). This is why our MobiliSense study also focuses on markers of arterial stiffness. Other sources of inconsistency include varying sources and composition of

suspended particles from one place to the other, differences in the susceptibility of populations, etc.[23]

Two studies found that the positive relationship between the short-term exposure to $PM_{2.5}$ and blood pressure was stronger in areas where road traffic was dense.[22, 24] An experimental study demonstrated that the effects documented on blood pressure were attributable to the organic carbon fraction of $PM_{2.5}$, mainly to fossil fuel combustion products of traffic sources.[25] Another study that relied on repeated measures did not find any association between the concentration of $PM_{2.5}$ and blood pressure but reported that a higher exposure to black carbon over the previous 7 days was related to an increased blood pressure.[26]

Aforementioned studies on blood pressure have assessed air pollutants with fixed monitoring stations, while very few studies were able to measure personal exposure.[27, 28] One study that measured concentrations of $PM_{2.5}$, organic carbon, and black carbon directly outside the residence showed that the strongest positive associations with blood pressure were documented for organic carbon, and for periods where the participants were at home and where measurement error was consequently the weakest.[29] However, some studies that relied on wearable monitors of $PM_{2.5}$ (carried in a backpack) did not permit to conclude that personal exposure was more strongly associated with blood pressure than background concentrations.[30, 31] One study[27] however showed that exposure to $PM_{2.5}$ measured with a wearable monitor was more strongly associated with blood pressure than the concentration of $PM_{2.5}$ measured outside each participant's residence; but that the concentration of black carbon outside the residence showed a still stronger association with blood pressure, suggesting that a priority for future research is to perform a personal monitoring of black carbon (which was not done in this study).

Noise effects: Regarding long-term effects, according to the World Health Organisation,[32] associations were consistently documented between the residential exposure to road traffic noise and hypertension. Most studies relied on noise maps derived from noise dispersion models. For example, a Swedish study of 1953 participants showed a positive association between road traffic noise (at the residence, from noise maps) and self-reported physician-diagnosed hypertension, with a stronger association documented with incidence than with prevalence (based on a retrospective questionnaire), and with a stronger association when the analyses were restricted to individuals who had lived for a long time at their residence.[33] A Swedish cross-sectional study of 667 subjects found that the adjusted odds of self-reported physician-diagnosed hypertension were 1.38 times larger for each 5 dB(A) increase in road traffic noise exposure (dispersion model and expert classification) at lower overall noise levels than in other studies.[34] Interestingly, the association was stronger among participants who had lived at the address for >10 years and among those not having triple-glazed windows, living in an old house, and having the bedroom facing a street. Other studies performed direct noise measurements in selected study sites to assess long-term exposures. For example, a cross-sectional study conducted in Taiwan among 321 males and 499 females residing nearby four main roads of Taichung along which measurements were performed reported an adjusted dose-response increase across noise exposure groups in the prevalence of self-reported physician-diagnosed hypertension.[35]

Regarding other sources than road traffic, certain studies have documented relationships between air traffic noise and hypertension or blood pressure,[36-38] while few were able to take into account railway traffic noise or the multi-exposure to noise of different transport modes. For example, a Swiss study of 6450 participants found that a cross-sectional measure of systolic blood pressure increased by 0.6 or 0.8 mmHg for each 10 dB(A) increase in daytime or night-time exposure to railway noise, while associations with road traffic noise were only

documented among participants with diabetes.[39] Of interest for the present project interested in the multi-exposure to noise and air pollutants, the adjustment for outdoor annual concentrations of NO_2 and PM_{10} did not result in weaker associations of road or railway traffic noise with blood pressure. Also of interest for the innovative joint assessment of objective and subjective noise levels in the present project, the European HYENA study found that the positive association between aircraft noise and the prevalence of hypertension was stronger among participants who reported being annoyed by aircraft noise.[40]

Only few studies in real-life, non-occupational settings have relied on wearable noise sensors. Pointing to the limitations of resting blood pressure, a study of 60 young adults in Taiwan that simultaneously measured ambulatory blood pressure and personal noise exposure over 24 hours found that each 5 dB(A) increase in noise exposure was associated with a transient increase of 1.15 and 1.16 mmHg in systolic and diastolic blood pressure during daytime and of 0.74 and 0.77 mmHg during night-time.[41] A German study of 632 adolescents and 482 adults documented an association between night-time noise exposure (personal dosimetry over 24 hours) and hypertension (measured blood pressure), but did not report any association with the subjective assessment of noise from a diary (the study, however, did not examine interactions between objective and subjective noise assessments).[42]

Regarding limitations, first, most studies of long-term effects of noise have used a cross-sectional design (no incidence data on hypertension) and relied on self-reports of physician-diagnosed hypertension. Second, few studies of air pollution effects were based on repeated measures of resting blood pressure,[43] and repeated measure studies have either recruited a small number of participants (much smaller than 100) or collected a limited number of measures per individual ($n \approx 3$[22, 26]). Third, among repeated measure studies, extremely few have relied on ambulatory monitoring of blood pressure,[29, 41, 44] and none has examined both

resting and ambulatory blood pressure as we do (while each assessment may have its own strengths). Fourth, few studies have examined pulse pressure, central rather than brachial blood pressure (as more predictive of target organ damage and morbidity / mortality), and aortic pulse wave velocity or the augmentation index (as markers of arterial stiffness[45]) in relation to air pollutants.[23, 46] Finally, the air pollution and noise studies that compared participants with each other (rather than repeated measures with each other) have insufficiently controlled for confounding factors related to individual and environmental characteristics.[47]

Heart rate variability

Researchers focus on heart rate variability to investigate how the sympathetic and parasympathetic branches of the autonomous nervous system modulate heart rate. An alteration of the autonomous regulation of heart rate may be one of the pathophysiological mechanisms through which air pollution[48, 49] (as also confirmed by toxicological studies[50]) and noise[51, 52] increase cardiovascular mortality. Indeed, studies have shown that reduced heart rate variability may be associated with an increased incidence of myocardial infarction in the general population, and with a poor prognosis in heart disease patients.[53-55]

Air pollution effects: The strongest evidence for a relationship between an increased exposure to air pollutants and reduced heart rate variability has been reported for particulate matter.[43] A meta-analysis (18667 participants from 29 studies) of the relationship between particulate matter and heart rate variability suggests that an increased concentration of $PM_{2.5}$ is associated with a reduced heart rate variability, as demonstrated by indicators of both the time domain and the frequency domain.[56] Even if certain studies have reported stronger air pollution effects among people with cardiovascular diseases,[57] this meta-analysis did not observe that

the association became weaker when studies with cardiovascular disease patients were excluded. Studies have often measured air pollutant exposure over 24 hours. For example, a work that assessed the concentration of $PM_{2.5}$ from a fixed monitoring station reported that considering exposure windows of 1 hour to 4 hours did not yield a stronger association than an exposure window of 24 hours.[58] It should be noted, however, that certain studies did not identify associations between an increased exposure to air pollutants and reduced heart rate variability, or even reported associations in the opposite direction.[59-61]

Regarding air pollutants from traffic sources, a study of 28 elderly subjects reported that a high concentration of $PM_{2.5}$ (assessed from fixed monitoring stations) was associated with reduced heart rate variability, but that the concentration of black carbon (used as a marker of particles from road traffic) resulted in stronger associations and with a larger number of indicators of heart rate variability.[62] A high concentration of carbon monoxide (CO) was also associated with reduced heart rate variability, but the association with CO had entirely disappeared after adjustment for black carbon, a marker of particles from road traffic.

Noise effects: The literature on heart rate variability is scarcer for noise than for air pollution effects. A German study of 110 individuals (326 electrocardiogram recordings) observed that increases in sound pressure below 65 dB(A) were associated with changes in heart rate variability suggestive of an elevation in sympathetic tone and parasympathetic withdrawal, while elevations in sound pressure above 65 dB(A) were primarily associated with increased sympathetic activity.[51] Of relevance for the present project is a Chinese randomised crossover study of participants successively spending time in a traffic centre and in a park. These participants underwent personal monitoring of noise and traffic-related air pollutants ($PM_{2.5}$, CO, and black carbon).[52] The study found that higher noise levels were associated with reduced heart rate variability, resulting from an increased sympathetic activation and a

decreased parasympathetic modulation. It also reported that noise levels modified the relationships between air pollutants and heart rate variability.

Regarding limitations, first, previous repeated measure studies of heart rate variability have relied on small sample sizes. For example, of the 25 repeated measure studies identified in the aforementioned meta-analysis of air pollution effects,[56] one study included 100 participants, 3 studies between 50 and 100 participants, and 21 studies less than 50 participants. Second, a number of studies did not combine indicators of heart rate variability from both the time domain and the frequency domain, although certain did.[56, 63]

Web appendix 2: List of confounders for the regression analyses

On the basis of our precise literature review for each exposure–outcome relationship, we will take into account – to adjust for confounding or as modifying factors – the following variables into the models (varying or not over time; list of factors to be adapted to the exposure and health variables examined): demographic characteristics (age, sex, country of birth, cohabitation, etc.); socioeconomic characteristics (education, employment status, occupation, income, wealth, etc.); health characteristics (body mass index, waist circumference, heart rate,[51, 64] personal history of diseases, medication use,[22] etc.); health behaviour (physical activity and body posture assessed with accelerometry,[29, 51, 64] tobacco and alcohol consumption, etc.); contextual characteristics defined at the residence, at the different places visited over the observation period, and along trip itineraries (socioeconomic level, building density, population density, traffic density,[22, 24] etc.); detailed characteristics of the dwelling; temperature, relative humidity or apparent temperature,[23] and atmospheric pressure[58, 63]; estimated incidence of influenza or influenza-like illness[4]; pollen and mould in the air (French Aerobiology Network); hour, day of the week, and season of measurement; and conditions of measurement of blood pressure at rest.

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