SMART-WORKING VS OFFICE WORK: HOW DOES PERSONAL EXPOSURE TO DIFFERENT AIR POLLUTANTS CHANGE?

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ABSTRACT

The COVID-19 pandemic is raging all over the world, with possible structural effects on the work: the smart-working (WFH - Working From Home) role is therefore emphasized by the fact that it could become a traditional way of working in many work sectors.
Several scientific papers have recently analyzed the WFH phenomenon under different aspects, but scientific studies have not yet been conducted considering the differences between WFH and WFO (Working From Office), in terms of evaluation of personal exposure assessment to selected airborne pollutants.
This study, therefore, aims to evaluate, using portable monitors, the differences in terms of personal exposure to selected airborne pollutants, during different working conditions (WFO vs WFH), over long periods of time (from days to weeks), extending the results to even longer periods (years), to adhere to the approach proposed by the concept of the exposome.
The preliminary results of this study refer to three separate phases of the work (i) re-analyses of literature data via Monte Carlo simulation, and assessment of personal exposure to different air pollutants during different working conditions, during (ii) "long term" campaign and (iii) a "short term" monitoring campaign. During the two different measurement campaigns, portable instrumentation was used, because of the ability of these kinds of instruments to obtain data characterized by a high spatial and temperature resolution.
The re-elaborations of the data obtained from the literature show how, under different conditions, the exposure concentrations to different PM fractions are statistically lower in WFH working conditions, compared to WFO conditions. These results are in contrast with the preliminary results obtained from exploratory monitoring (both for the "long term" and for the "short term" campaigns). The results obtained from these exploratory monitoring show that the WFH condition has a greater impact on the daily exposure of the monitored subjects, compared to the WFO condition.

INTRODUCTION

The COVID-19 pandemic is raging around the world and is likely not to end in the short term, with possible structural effects on the labor market in many countries (Baert et al., 2020). In order to limit the number of deaths and hospital admissions due to the novel coronavirus, most governments of developed countries have decided to suspend many economic activities and limit people's freedom of mobility (Brodeur et al., 2020a, b; Qiu et al., 2020): millions of workers around the world were suddenly forced to work in smart-working mode, due to the implementations of various levels of restrictions (de Klerk et al., 2021).
In this context, the opportunity to work in this way – smart-working (WFH - Working From Home), already governed by Law no. 81/2017, has become of great importance (Acemoglu et al., 2020) as it allows (i) employees to continue working and (ii) employers to continue producing services and revenues, (iii) limiting the spread of COVID-19 and the recessive impacts of the pandemic are complex. Due to the uncertainty regarding the duration of the pandemic and future waves of contagion, the role of WFH in the labor market is further emphasized by the fact that this could become a traditional way of working in many economic sectors.

WFH is not a completely new way of working: in a research conducted in the USA and Europe (Barrot et al., 2020; Boeri et al., 2020) in fact, the results show that 40% of all work activities could be carried out from your home. Furthermore, this way of working appears to be on the rise: the annual rate of smart-workers in the United States has increased, from 9% in 1995 to 37% in 2015 (Jones et al., 2015). As reported by Birimoglu Okuyan and Begen (2020), in Europe, 5.2% of people aged 15-64 worked regularly from home in 2018 and this rate was even higher in certain countries (for example 14 % in the Netherlands, 13% in Finland, 11% in Luxembourg and 10% in Austria) (Messenger et al., 2019; Vilhelmson et al., 2016).

Problem definition and aims of the study

Due to the sudden importance and growth of WFH, several studies have recently investigated this phenomenon, in particular with the intention of identifying the number of works that can be carried out in smart-working mode (Adams-Prassl et al., 2020; Dingel and Neiman, 2020; Koren and Peto, 2020; Leibovici et al., 2020; Mongey et al., 2020), analyzing various aspects such as, but not limited to: its implications (i) on physical activity of workers (Koohsari et al., 2021), (ii) at the psychological level (Conroy et al., 2021; Wang et al., 2021) and (iii) concerning problems related to ergonomics (Reznik et al., 2021). Other studies have been conducted to (iv) analyze the advantages and disadvantages of this way of working: from the literature it emerges that organizational benefits are mainly related to the improvement of employee performance (Conradie and De Klerk, 2019; Lee, 2018; Rudolph and Baltes, 2017), the reduction of absenteeism (Schaufeli, 2013), the improvement of financial returns and the organizational effectiveness of workers (Khodakarami and Dirani, 2020). The disadvantages are related, for example, to social isolation and reduced employee involvement (Vander Elst et al., 2017; Sardeshmukh, Sharma and Golden, 2012).

To date, to the knowledge of the authors, no studies have yet been conducted that consider the differences between the conditions of WFH and WFO (Working From Office), in terms of assessing personal exposure to different air pollutants. This aspect should be of particular interest as exposure to selected air pollutants in the domestic context represents a significant proportion of the total personal exposure of the population (Raw et al., 2004).
In particular, for a comprehensive and fully representative health impact assessment, human exposure to air pollutants should ideally be assessed as a whole, following the concept of the exposome. The concept of exposome concerns the assessment of exposure in its entirety, deriving from a variety of both internal and external sources (chemical and biological agents) (Wild, 2005).
In recent years, several technological developments have been recognized as useful enhancements for personal exposure studies. For example, portable and real-time monitors, increasingly miniaturized, can provide data concentration to selected pollutants characterized by high spatial and temporal resolution (Borghi et al., 2017). Thanks to this instrumentation it is therefore possible to investigate, in addition to the concentrations of personal exposure to a given pollutant, also other useful aspects in the context of exposomics, such as (i) the position of the monitored subject at a given time, (ii) his daily activities and his (iii) lifestyle.

This study therefore aims to evaluate, through portable and real-time monitors, personal exposure to selected atmospheric pollutants (different fractions of PM – particulate matter), during different working conditions (WFO and WFH), for relatively long periods of time (days and weeks), with the assumption of extending the results to even longer periods of time (months, seasons, years), in order to adhere to the approach proposed by the concept of the exposome.

MATERIALS AND METHODS

Study design

To investigate the differences, in terms of personal exposure to selected atmospheric pollutants in different working conditions, two different measurement campaigns are planned, a “long term” and a “short term” campaign. The “long-term” campaign involves the measurement of different PM fractions (PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP - total suspended particles), through the use of portable direct-reading instruments (Aerocet 831, Met One Instruments - 1 data per minute). The measurements will be performed in two different seasons (summer and winter) for two consecutive weeks. The data relating to exposure concentrations will be acquired simultaneously from one subject in WFH conditions for 24 hours a day, and from a second subject in WFO conditions for 8 working hours, including in the monitoring period also the important moment of commuting from home to work and back.

The “short-term” campaign involves the analysis of different concentrations of PM (PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP), using the same instrumentation previously described. In this case, at least 50 subjects will be enrolled, who will carry out two consecutive monitoring days (one in WFO conditions and one in WFH conditions).
The “short term” campaign will last 12 months, in order to carry out monitoring during different seasons and environmental conditions. In both campaigns, the various subjects will be provided with an activity diary, with the aim of correlating the activities carried out by the enrolled subjects (e.g., meal preparation, commuting, exposure to passive smoking) with the measured exposure concentrations.

Data quality

The data obtained from direct-reading instruments are characterized by an intrinsic error of the measurement (Spinazzè et al., 2017). For this reason, data quality verification campaigns are programmed, to (i) quantify the error associated with the instrumentation used and (ii) correct the data obtained from the instrumentation. In particular, during the two weeks of monitoring of the “long-term” campaign, for one day a week (10 h/day), the direct-reading instruments will be placed side by side with a reference gravimetric instrument (Harvard Impactor - HI; operating at a flow rate of 10 L/min). The $PM_{2.5}$ mass sampled by the gravimetric technique will be collected on a PTFE substrate, diameter: 37 mm; porosity: 2 µm (Marple et al., 1987)): in this way it will be possible to calculate a ratio between the concentrations of $PM_{2.5}$ measured by the two different techniques (gravimetric and direct-reading), applicable as a posterior correction factor on the data acquired continuously by the direct-reading instrument. The correction factors will be calculated separately for the two environments under study (home and office), in order to apply an *ad hoc* a posteriori correction factor (Spinazzè et al., 2017). This procedure will also be performed monthly during the “short term” monitoring campaign: during this measurement campaign, instrumentation precision tests will also be carried out on a monthly basis.

Statistical analysis

After a first descriptive analysis, the data will be analyzed with appropriate statistical tests to (i) quantitatively evaluate the differences in terms of personal exposure between the two working conditions (Student’s T-test/Mann Whitney’s U-test) and for (ii) assess which activities contribute most to the daily exposure of the two types of workers (e.g., commuting, meal preparation), through a sensitivity analysis.
The daily data obtained from the “long-term” and “short-term” monitoring campaigns will then be used

Study	Execution	Completed analyzes	Future analyzes	Preliminary results
Literature elaborations	March 2021	Monte Carlo simulation	Sensitivity analysis	Expo. WFO > Expo. WFH
"Long term" monitoring campaign	June 2021; November 2021	Evaluation of the differences between exposure in WFO and WFH conditions (summer campaign; June 2021).	Evaluation of the differences between exposure in WFO and WFH conditions (winter campaign; November 2021); Evaluation of the contribution of the different activities to the total daily exposure, during WFO and WFH; Monte Carlo simulation; Calculation of the daily intake, for the different PM fractions considered.	Expo. WFO < Expo. WFH
"Short term" monitoring campaign	June 2021 – June 2022	Evaluation of the differences between exposure in WFO and WFH conditions (N = 5 subjects).	Evaluation of the differences between exposure in WFO and WFH conditions (> 50 subjects); Evaluation of the contribution of the different activities to the total daily exposure, during WFO and WFH; Monte Carlo simulation; Calculation of the daily intake, for the different PM fractions considered.	Expo. WFO < Expo. WFH

Tab. 1 - *Summary of the preliminary analyzes performed (and reported in this work) and those planned. Expo.: exposure to different fractions of PM.*

in a (iii) Monte Carlo simulation, following what is reported by the scientific literature (Spinazzè et al., 2014). Finally, for each subject recruited in the "short-term" campaign, the daily intake (CDI - Chronic Daily Intake, mg/kg day) of each pollutant will be calculated, such as:

CDI=Mean exposure concentration ×Inhalation rate ×Absorption fractionBody weight

where the inhalation rate and body weight are commonly assumed to be 20 m^3/day and 70 kg (Morawska et al., 2013).

Problems and solutions

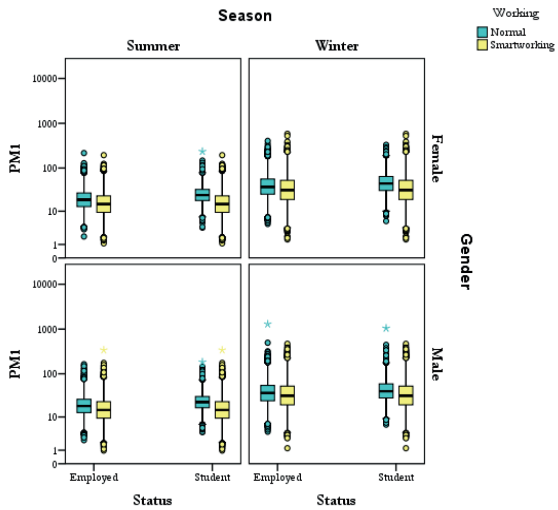
As mentioned, a problem encountered within this project mainly concerns the quality of the data obtained from the direct-reading instrumentation that will be used for the assessment of personal exposure. This problem can be solved by using (i) a correction factor applied *a posteriori* on the entire dataset, calculated *ad hoc* within the instruments comparison/validation sessions and (ii) by performing regular (monthly) precision tests between the different instruments used.
Another problem could be related to the large amount of data needed to obtain robust results, especially for the "short term" campaign. In fact, from a statistical power analysis performed *a priori*, the number of subjects to be enrolled should vary between 73 and 53, respectively for a power of 0.90 and 0.80 (1-β err. Prob.). For this reason, the recruitment phase of the subjects will be carefully planned, to foresee personal measures in the different seasons of the year. If the expected subjects are not reached, the subjects enrolled in the early stages of the project (summer 2021) can be asked to repeat the monitoring in the following months (winter 2021-22).

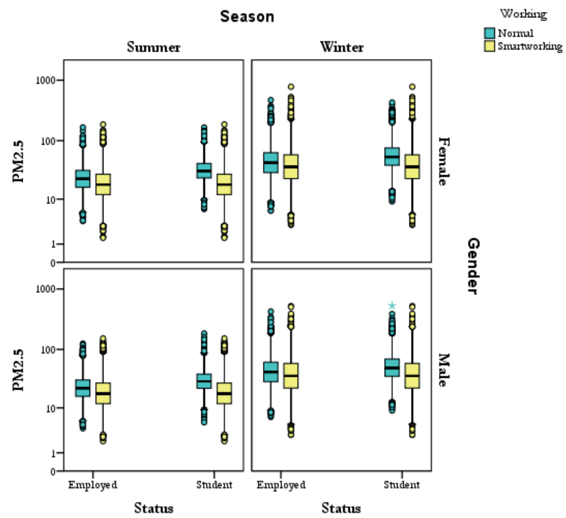
Preliminary Results and Discussions

Some exploratory analyzes and measurements were carried out: the main preliminary results are reported below. Firstly, the data obtained from the literature were reviewed (Paragraph 3.1.): these data seem to be in contrast with the preliminary measurements carried out according to the study design previously described (Paragraphs 3.2. and 3.3.). For this reason, the aforementioned monitoring campaigns should be conducted (i) in a structured and in-depth way, as described above and (ii) on a large number of cases (N> 50). Table 1 summarizes the preliminary analyzes carried out (reported in this work) and those planned.

Literature analysis

Using the literature data concerning (i) the use of time





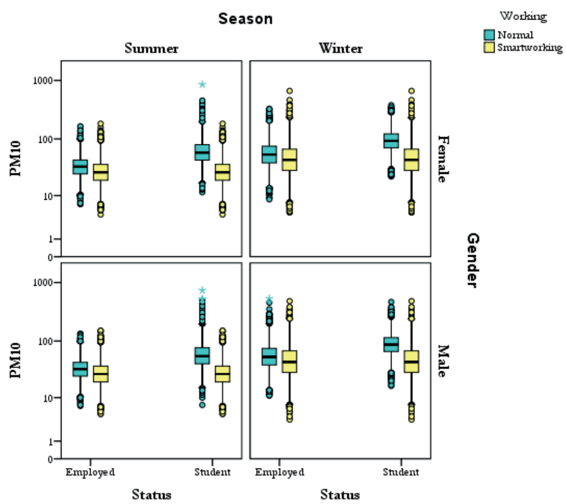


Fig. 1 - *Boxplot concerning the average daily exposure concentrations (µg/m³) estimated for PM_1, $PM_{2.5}$ and PM_{10} in different situations. The data obtained during the WFH condition are shown in yellow, the data obtained during the WFO condition in blue, divided by status (employee/student), season (summer/winter) and gender (male/female). The extremes of the boxplots represent the first and third quartiles, the black line the median.*

of different categories of subjects (males/females and employed/students) (Spinazzè et al., 2014) and (ii) the exposure concentration levels to different fractions of PM (PM_1, $PM_{2.5}$ and PM_{10}) in different environments (office, home and means of transport) in different seasons (summer/winter) (Borghi et al., 2020; Mandin et al., 2017; Rovelli et al., 2014), through a Monte Carlo simulation (Spinazzè et al., 2014) the daily exposure was calculated for the different categories of subjects investigated in different working conditions (WFO and WFH).

The main results of this work show how, in all WFO situations (in terms of season, gender and type of worker - employee or student), the median values of the concentrations of the various PM fractions considered are significantly higher than those associated with a WFH situation (via Mann-Whitney test) (Figure I). The results of this preliminary study show that working from home exposes, probably due to the lack of exposure to traffic-related pollutants during commuting, to PM concentrations lower than those found in a typical office working day. However, it is impor-

Working mode	Pollutant	N	Min.	Mean	Median	Max.	S.D.	5th percentile	95th percentile
WFO *Office*	PM_1	3455	0.3	3.0	2.1	28.9	2.9	0.6	8.6
	$PM_{2.5}$	3455	0.4	5.2	3.2	179.1	6.4	0.9	15.5
	PM_4	3455	0.4	8.2	5.2	344.7	10.3	2.0	24.7
	PM_{10}	3455	0.4	21.3	11.7	1604.0	40.2	4.2	61.3
	TSP	3455	0.5	36.2	15.9	2156.4	72.6	5.1	126.5
WFH *Home*	PM_1	3396	<0.1	5.5	4.9	89.3	4.4	0.2	12.4
	$PM_{2.5}$	3396	<0.1	10.1	8.3	333.1	16.1	0.3	20.3
	PM_4	3396	<0.1	16.6	13.1	569.9	31.9	0.6	30.7
	PM_{10}	3396	<0.1	35.3	26.4	1042.8	60.0	4.3	72.3
	TSP	3396	<0.1	52.1	34.4	1085.9	75.0	13.1	128.2

Tab. 2 - *Descriptive statistics of the exposure concentrations (µg/m³) to the different PM fractions measured during the WFO and WFH condition. Min.: minimum; Max.: maximum; S.D.: standard deviation.*

Working mode	Pollutant	N	Min.	Mean	Median	Max.	S.D.	5th percentile	95th percentile
WFO *Office*	PM_1	8240	0.7	6.7	5.3	194.3	7.2	1.6	20.2
	$PM_{2.5}$	8240	0.7	8.2	6.1	446.2	10.6	1.9	25.9
	PM_4	8240	1.3	10.3	7.3	450.8	12.6	2.4	34.0
	PM_{10}	8240	1.8	16.8	10.3	512.6	22.1	3.5	54.7
	TSP	8240	1.9	23.8	12.8	870.7	41.3	4.2	72.1
WFH *Home*	PM_1	21688	0.8	11.6	10.0	71.0	7.8	2.1	24.9
	$PM_{2.5}$	21688	0.9	15.9	15.0	105.1	9.1	3.3	31.0
	PM_4	21688	1.4	21.6	20.7	173.7	11.7	5.1	40.2
	PM_{10}	21688	2.2	32.9	30.0	378.7	20.6	8.2	69.9
	TSP	21688	2.2	37.9	33.2	479.2	26.1	9.4	84.1

Tab. 3 - *Descriptive statistics of the exposure concentrations (µg/m³) to the different PM fractions measured during the WFO and WFH condition. Min.: minimum; Max.: maximum; S.D.: standard deviation.*

tant to underline that this analysis is to be considered purely indicative as it is characterized by an intrinsic error. As mentioned, in fact, for the purposes of the simulation simplifications and assumptions were necessarily introduced, and the concentration data used for the simulation were obtained from different studies, conducted in a non-contextual manner, therefore not directly comparable with each other.

Short-term campaign

Preliminary results conducted on a limited number of subjects (N = 5) enrolled in the "short term" campaign indicate that, on average, the levels of exposure to the different PM fractions are higher during the WFH work mode (Table 2). In particular, the WFH/WFO ratios calculated on the different PM fractions are on average equal to 2.4, thus indicating concentrations measured in smart-working conditions twice higher than those measured in the office. Furthermore, the differences in terms of median exposure concentrations measured during the two working conditions are statistically significant (Mann-Whitney U test; $p < 0.001$ for all PM fractions).

Long-term campaign

The preliminary results of the first "long-term" monitoring campaign, conducted in June 2021 (N days WFO = 10; N days WFH = 14; N WFO data > 8,000; N WFH data > 20,000), show how, on average, the exposure levels to the different PM fractions are higher during the WFH work mode (Table 3 and Figure II). More in detail, the ratio between the exposure concentrations measured at home and those measured in the office was equal to 1.87 (min.: 1.6; max.: 2.1), indicating a higher concentration of exposure in the domestic environment. The differences in terms of median exposure concentrations measured during the two working conditions are statistically significant (Mann Whitney's U test; $p < 0.001$ for all PM fractions).

CONCLUSIONS

Advantages and disadvantages

The strengths of this project mainly relate to the fact that, to the knowledge of the authors, no studies have yet been carried out that consider the differences between WFO and WFH conditions, in terms of exposure assessment to different airborne pollutants. This aspect could become of particular interest as, as mentioned, the way of working from home will probably become more and more widespread: the assessment of personal exposure to selected air pollutants could therefore be used to support the choice of the best remote workplace. A second strength of this study refers to the assessment of "long-term" exposure (days/weeks) to air pollutants, intending to extend the results to even longer periods of time (months, seasons, years), to comply to the approach proposed by the concept of exposome.

The limitations of this study are mainly related to the quality of the data obtained through direct-reading instruments, characterized by an intrinsic error of the measurement and by the large number of data necessary to obtain robust results.

Future developments

As described, the monitoring campaigns will mainly be based on the measurement and assessment of personal exposure to different PM fractions, as particulate matter is considered (i) ubiquitous in urban and indoor environments and (ii) identified as one of the "criteria pollutants", pollutants of great interest for their effects on human health and the environment (EPA).

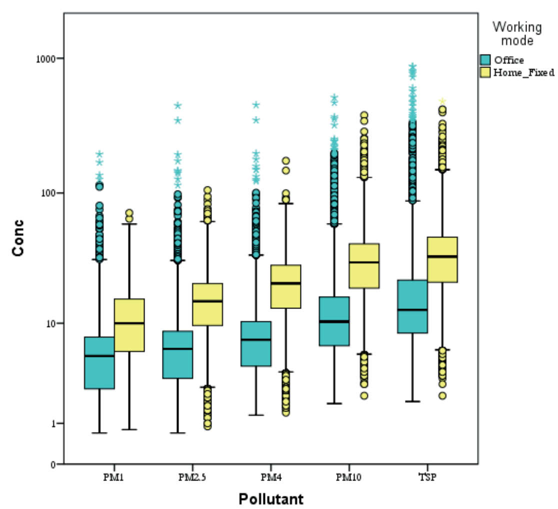


Fig. 2 - *Boxplot concerning the exposure concentrations (µg/m³) measured for PM_1, $PM_{2.5}$, PM_4, PM_{10} and TSP in different situations. The data obtained during the WFH condition are shown in yellow, the data obtained during the WFO condition in blue. The extremes of the boxplots represent the first and third quartiles, the black line the median.*

However, as widely described in the scientific literature (Nandan et al., 2021), other airborne pollutants can come from very different sources: some of the pollution sources can be related, for example to (i) building materials, (ii) sealants, (iii) cleaning products, (iv) tobacco smoke, (v) household activities, such as preparing meals and (vi) issuing certain appliances such as printers and copiers, as well as (vii) various external sources (such as vehicular traffic, etc.).

For these reasons, further developments of this study could concern the analysis of other pollutants. Particular attention should be paid to the measurement and assessment of personal exposure to ozone, carbon and sulfur oxides and heavy metals, as well as semi-volatile organic compounds (SVOCs) and volatile organic compounds (VOCs) such as benzene, toluene, xylene and formaldehyde.

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