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Daily Exposure to Air Pollution in Indoor, Outdoor, and In-vehicle Micro-environments: A Pilot Study in Delhi

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Abstract

The study aims at characterizing human exposure to air pollution in an urban setting in India. Integrated daily exposure to respirable suspended particulates (RSP) and carbon monoxide (CO) was assessed by personal and area sampling of air of six major micro-environments defined with respect to space and time. The selected micro-environments included those for which data did not exist in India prior to this study, for example: traveling, schools and offices. Time budget survey was conducted to determine how much time six population groups spend in these micro-environments. A sample of 1100 households (4311 individuals) was chosen randomly from 32 localities in Delhi for an activity patterns survey.

Mean levels of RSP during traveling ranged between 370 - 2860 $\mu g\ m^{-3}$ depending on the mode of travel. CO levels during traveling ranged from 8 - 19 ppm. The weighted average of RSP daily exposure due to all micro-environments was found to be 12.7 $mg\ h\ m^{-3}$, with housewives and female workers being the most exposed groups. The mean CO exposure was found to be 30 ppm h; workers being the most exposed category. We estimated that the assumption that people are exposed only to outdoor levels of RSP for all the 24 hours caused the true exposure to be underestimated by a factor of 1.7 – 2.7. Indoor background RSP levels were found to be higher than expected. Determining the sources of particulate matter within these micro-environments is an important and urgent area of research.

Key work index: Micro-environments, offices, schools, time budget, in-vehicle exposure, cookstoves, personal sampling, RSP, CO, daily integrated exposure, Delhi.

Introduction

Industrialization and urbanization have lead to increased levels of air pollution. Currently policy researchers and decision makers believe that vehicles and industries are the main source of this pollution and this is reflected, for example, in India's National Environment Action Programme (MoEF, 1993). In an attempt to set priorities for actions, researchers have attempted to apportion the emissions across various sources (Bose, 1990; TERI, 1992) at various spatial scales.

However, the practice of using emission inventories to prioritize air pollution problems completely ignores the role of factors such as meteorology which determines the actual concentration of ambient concentration; the specific population at risk and their activity patterns which determines the actual exposure. In reality, health-effects are not solely dependent on emissions and outdoor concentrations, rather they are dependent on doses received by individual. Doses, in turn, depend on the outdoor and indoor concentrations and the duration the individual experiences it. Focus on exposure has three important implications (Smith, 1993): less relevance of outdoor pollution, greater significance of small and local sources (specially indoor sources) in developing countries and larger set of management options.

In India most of the previous studies related to exposure characterization focused on biofuel combustion for cooking in rural and slum areas (e.g. Saksena et al., 1992; Smith et al., 1994). Very few studies (Kulkarni and Patil, 1999) have attempted to characterize exposures in general urban populations. The aim of this study is to estimate daily integrated exposure of urban residents to RSP and CO.

Description of the region

Delhi, the capital city of India, is situated in the north of India, 160 km south of the Himalayas. Delhi has the Thar desert of Rajasthan to the west, the central hot planes to the south and cooler hilly region to the north and east. It is located at 28°35 N latitude and 77°17 E longitude. The total area is 1483 km^2, at an altitude of 216 m above mean sea level.

Delhi has a tropical semi-arid climate with extremely hot summers and moderately cold winters. July to September is the typical monsoon season. Maximum rainfall occurs during July. Wind speed higher during summer and monsoon months and calms are frequent in winter. Average temperature range is 14-34° C while annual mean precipitation is 715 mm.

Delhi is the fourth most polluted mega-city of the world vis-a-vis air quality. More than three-quarters of the emissions of air pollutants are caused by vehicles. The total number of vehicles in 1991 was 1.9 million (22 percent cars and 67 percent two-wheelers). This is a nine-fold increase over the total number of vehicles in 1971. Delhi has three big thermal power stations—all coal based. While two of these are located within the city, the third is on the outskirts.

Delhi is not as industrialized as other mega cities like Mumbai or Kolkata. Factories are mainly located in west, northwest or east Delhi. There are certain non-polluting industrial estates in south Delhi. Industrial air pollution in Delhi is mainly due to the very large number of small-scale industries. Delhi has many satellite towns which are industrialized to a large extent. Major infrastructural units and large-scale industries are located in this region. Delhi and its satellite towns form the National Capital

Region—a large area source of pollution. It is estimated that there are about 93,000 industries in Delhi, of which 9000 are significantly polluting. Eighty-one thousand five-hundred industries are located in residential and non-conforming areas.

Methodology

Zartarian et al. (1997) have defined exposure to be the contact between an agent and a target. They further define instantaneous point exposure as contact between an agent and a target at a single point in space and at a single instant in time. There are major methods for estimating exposure of a person (or a population) to air pollution: a) direct methods, and b) indirect methods. Direct methods involve monitoring pollution concentrations using portable equipment worn by the subjects to assess 'personal' exposure. Indirect methods, on the other hand, involve measurement of pollutant concentration at established sites/environments/locations and the time spent by the subject in these locations/environments to assess the 'total' exposure. The concept of integrated exposure incorporates the duration of the exposure by integrating the concentration with the duration of exposure. Duan (1982) introduced the term 'micro-environment type' to compute exposure over any time period. He also suggested that a micro-environment should be defined with sufficient resolution to be homogeneous, i.e. the concentration coefficients should not vary appreciably from one individual to another, in other words variance of individual exposures within a micro-environment should be smaller than the variance of exposures from one micro-environment to another. On the other hand, a micro-environment type has to be somewhat broad so that the analyst does not have too many types to assess.

The study attempts to estimate an individual's daily-integrated exposure using Duan’s definition.

The following assessment procedure was used:

$$E_i = \sum_{j=1}^{m} C_{ij} t_{ij}$$

where, E_i is the exposure of the ith individual, C_{ij} is the concentration of the pollutant measured in the jth micro-environment of the ith individual, t_{ij} is the time spent by the ith individual in the jth micro-environment. The total number of micro-environments is m such that:

$$\sum_{j=1}^{m} t_{ij} = 24h$$

An attempt has been made to estimate exposure for various population sub-groups. This involved consideration of six activity based population groups, i.e., workers, housewives, unemployed people, infants (0-4 years), school & college going children and elders (>65 years). Population groups were further divided into sub-groups based on cooking fuel and mode of travel. The four fuel groups considered were: a) cow-dung, charcoal and wood; b) coal, coke and lignite; c) kerosene; and d) LPG and biogas.

For each population sub-group, main micro-environments of relevance were identified. The number of micro-environments ranged from three (as for the elderly male—indoors at home, outdoors and sleeping) to six (as for working females—workplace, traveling, indoors at home, cooking, outdoor and sleeping).

Micro-environments and time budget survey

A time-budget survey was conducted in 1,100 households spread all over Delhi. For this, a close-ended questionnaire based on the method of recall was designed which included information at the household level, e.g., family size, family income, type and quantity of cooking fuel used, etc. At the individual level information was obtained on activity patterns, education, employment, etc. The sample consisted of 4,311 individuals. Houses were chosen using a stratified random sampling design from 32 different localities in Delhi. These locations had earlier been selected for outdoor air quality monitoring by the National Environmental Engineering Research Institute (NEERI, 1995), and hence these outdoor data served as a secondary source of information. The selection of these sites was based on the land-use pattern of the area, i.e., residential, commercial and industrial.

The questionnaire was pre-tested in 100 households by seven trained enumerators for. A limitation of the questionnaire was that it did not differentiate between time allocation on weekdays, weekends and holidays.

The exposure assessment involved measuring concentrations of Respirable Particulate Matter (RSP) and carbon monoxide (CO) in the more important micro-environments. These are six in number—the kitchen during cooking sessions, the drawing room during non-cooking and the living room during sleeping, school during class, offices during work, shops during normal business, in-vehicle commuting (two-wheelers, three-wheelers, buses and cars). Micro-environments in urban India settings that had been adequately characterized by previous studies (Raiyani et al., 1993; Saksena, 1999) were not sampled in this one. RSP and CO concentrations in micro-environments were measured using stationary samplers. The only exception was personal sampling of RSP and CO during commuting; for this, the samplers were strapped to the commuter's body as close as possible to the breathing zone. Pollutants concentrations were monitored during the three cooking sessions (breakfast, lunch and dinner). In commuting micro-environment, monitoring was done twice a day—morning and evening. In the other micro-environments once in a day (including night). Monitoring was carried out during February-March, 1997.

Material and methods

A personal air sampler (SKC make) was used for RSP monitoring which had a servo control to adjust for pressure drops. The sampler was fitted with a cyclone ($d_{50} = 5\mu m$). A portable electrochemical cell based (OLDHAM, TX12, make), monitor was used for CO monitoring. At the time of cooking the pumps of the RSP sampler and CO monitor were kept half meter away from the stove. Height of the filter and the CO monitor were kept at the nose height. The flow rate of the RSP sampler was set to 2 liter per minute. The RSP sampler and CO monitor were switched on 1-2 minutes before the cooking started and 1-2 minutes after the cooking ended.

For the commuting micro-environments, samplers were attached to the body of the driver/passenger. For the office, school and shop places, the RSP sampler and CO monitor were kept on a table.

All samplers were checked and calibrated before and after every experiment. An electronic calibrator was used to measure the flow rate of RSP samplers. If the difference between the initial and final flow rates was more than ±10% then the RSP sample was rejected. A span gas of 99 ppm was used to calibrate the CO monitor.

Millipore depth filters of 1 μm pore size and 37 mm diameter were used. Filters were desiccated for 24 hours with silica gel before weighing them in an electronic balance with an accuracy of 10 μg. As many filter cassette holders were taken to the field as the number of experiments to be performed, to avoid the risk of the dusty environment contaminating the filters if they were to be transferred from a container to the cassettes in the field. One in every 20 filters was used as a field blank.

Special attention was given to designing a protocol for the monitoring of indoor cooking sessions, especially because the participants were not in a position to operate the instruments themselves.

Nine houses were selected for monitoring the levels of RSP and CO in the kitchen, living room and bedroom. Nine offices/shops were also selected for the purpose. For commuting micro-environment, nine routes were selected and in each route four modes of travel were considered. Field experiments were conducted in the month of January-April, 1997 to measure level of RSP and CO in different micro-environments.

Results and discussion

Time budget survey

The time spent by various population groups in the six micro-environments is shown in Table 1. It was observed that children and elders spent the most time outdoors (approximately two hours), presumably in recreational activities. The time spent traveling across various modes of transport is shown in Table 2. We observed that the city bus is the most preferred mode of travel for students followed by walking. But irrespective of mode of travel the time spent traveling to school and back is same across modes. Workers too prefer the city bus, followed by 2-wheelers. Here, too the variation in time spent traveling across modes of travel is not significant.

Air quality

The concentration of RSP and CO measured in various micro-environments is shown Table 3. It was observed that the concentration of RSP and CO was maximum during traveling two-wheelers while RSP was minimum in cars and CO in buses. We are unable to explain why levels of RSP during cooking with LPG are higher than that when cooking with kerosene. Indoor background levels of RSP are higher than expected. This phenomenon has also been observed by others (Kumar, 2002; Sabapathy, 1998). It is speculated that this could be due to smoking, natural dust and re-suspension. The levels of RSP observed in offices is higher than that observed by Prasad et al. (2002) in a clean air-conditioned building, which is logical. But our results are very similar to those observed by Kulkarni and Patil (1999) in Mumbai for outdoor workers The unusually high levels of RSP at night in the bedroom have also been observed in slum houses of Delhi by Saksena (1999).

Exposure

Figures 1 and 2 show the personal integrated exposure during commuting to RSP and CO respectively in the sample of 36 people. Exposure here has been computed as the concentration of pollutant multiplied by time spent traveling. We observed that the route chosen affects RSP exposure more than it does the CO levels. Also, cars and buses are better at shielding passengers and drivers against RSP than against CO.

Daily-integrated exposure due to all micro-environments is shown in Table 4. The weighted average of RSP daily exposure was found to be 12.7 mg h m^{-3}, with housewives and female workers being the most exposed groups. The mean CO exposure was found to be 30 ppm h; workers being the most exposed category. The variation across groups is more pronounced in the case of CO than for RSP. Our results for RSP are higher than those observed by Kulkarni and Patil (1999) in Mumbai, mainly because of higher levels observed indoors (home) in our Delhi study. Converting the exposure to concentration units we found that the average daily concentration of RSP ranges from 480-590 $\mu g\ m^{-3}$ across groups, which is much higher than the standard prescribed by the Central Pollution Control Board – 200 $\mu g\ m^{-3}$, though such comparisons are strictly not valid. The assumption that people are exposed only to outdoor levels of RSP for all the 24 hours causes the true exposure to be underestimated by a factor of 1.7 – 2.7.

Owing to the long time spent sleeping and the observed high levels of RSP in the bedroom, we observed that this micro-environment contributes as much as 40-60 percent to the daily integrated exposure. The traveling micro-environment contributes about 12-20 percent for students and workers. The work place environment accounts for 18-23 percent of the daily exposure. For housewives, cooking accounts for 23 percent of the daily burden. In slum houses, Saksena (1999) observed that cooking accounts for 15-20 percent of daily exposure, which is to be expected because slum dwellers are more influenced by outdoor pollution. The outdoor micro-environment contributes 10 percent for elder males, unemployed males and male students. But it must be remembered that outdoor sources could also contribute to indoor exposures due to infiltration.

For housewives, 77 percent of the CO exposure is from cooking and 23 percent form traveling. Cooking contributes 47 percent for elder women and 62 percent for unemployed women. For children, 85-100 percent of the CO exposure is from traveling. For workers 33 percent (females) to 44 percent (males) is from traveling and 41 percent (females) to 53 percent (males) of the exposure occurs in the workplace.

In conclusion, our Delhi pilot study indicates that exposures that occur in indoor micro-environments contribute most to the daily exposure. But further research is needed to understand particle size distributions and sources. Cost-effective management options cannot be designed unless we improve our knowledge of indoor-outdoor relationships. However, the study does imply the importance of education and ventilation options for exposure reduction. The database on in-vehicle exposure also needs to be expanded. Priority should be given to measuring exposures of bus passengers, riders of 2-wheelers and pedestrians, as these seem to be the dominant transportation modes.

Acknowledgments

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Table 1. Time budget of different population groups in Delhi

			Time spent in micro-environment (h)					
Category	Gender	Number	Kitchen	Traveling	Workplace/School	Outdoor	Indoor	Sleeping
Children (< 4 years)	Both	191	0.09	0.34	0.75	1.98	8.93	11.91
Students	Male	926	0.03	1.66	5.95	2.22	5.54	8.59
	Female	516	0.41	1.57	5.83	2.09	5.48	8.62
Housewives	Female	1004	3.89	0.73	0.00	1.61	9.19	8.59
Workers	Male	1408	0.22	2.06	8.52	1.26	3.93	8.01
	Female	139	2.06	1.82	7.02	1.06	4.32	7.71
Elders	Male	51	0.22	1.06	0.00	2.31	10.75	9.65
	Female	18	1.44	1.11	0.00	2.44	9.22	9.78
Unemployed	Male	39	0.15	1.18	0.00	1.90	11.13	9.64
	Female	19	0.74	0.37	0.00	1.63	12.10	9.16

Table 2 Daily time (hours) spent traveling

Mode of travel	Children (<4 years)		Students		Housewives		Workers		Elders		Unemployed	
	N	Mean	N	Mean	N	Mean	N	Mean	N	Mean	N	mean
Walk	148	0.6	419	1.6	742	0.7	201	1.7	42	1.0	34	0.2
Cycle			17	1.8	5	1.2	68	2.3			2	0.5
Two-wheeler			29	1.8	10	1.3	397	1.9	1	2.0		
Three-wheeler	6	1.0	18	1.7	22	2.0	18	2.2	1	2.0		
Car/taxi	2	0.5	12	1.7	28	1.0	109	2.2	2	2.0		
Chartered bus	5	2.0	282	1.6	6	0.5	123	2.2	3	1.0		
City bus	14	1.4	558	1.7	126	1.0	483	2.1	17	1.2	20	2.1

Table 3. Concentration of RSP and CO in various micro-environments

Micro-environment	RSP (μg m^{-3})			CO (ppm)		
	n	Mean	CV	n	Mean	CV
Cooking						
LPG	9	890	52	9	6	17
Kerosene[1]		690			3	
Wood[1]		1370			12	
Coal[2]		1090			96	
Outdoor[3]		280			0	
Living room	9	480	60	3	0	0
Bed room (sleeping)	9	640	54	3	0	0
School	9	230	30	3	0	0
Office/shops	9	350	66	9	3	133
Traveling						
Three-wheeler	9	810	18	9	12	33
Bus	9	800	27	9	8	13
Car	9	370	19	9	10	20
Two-wheeler	9	2860	51	9	19	26

All values are based on measurements from this study except [1] Saksena, 1999; [2] Raiyani et. al, 1993; [3] NEERI, 1995.
CV = coefficient of variation (%)

Table 4. Daily integrated exposure of RSP (mg h m^{-3}) and CO (ppm h)

Category	Gender	RSP	CO
Children (< 4 years)		13.0	3
Students	Male	11.2	14
	Female	11.7	15
Housewife		14.2	28
Worker	Male	12.9	49
	Female	13.5	56
Elders	Male	12.6	11
	Female	13.5	17
Unemployed	Male	12.5	10
	Female	13.1	7

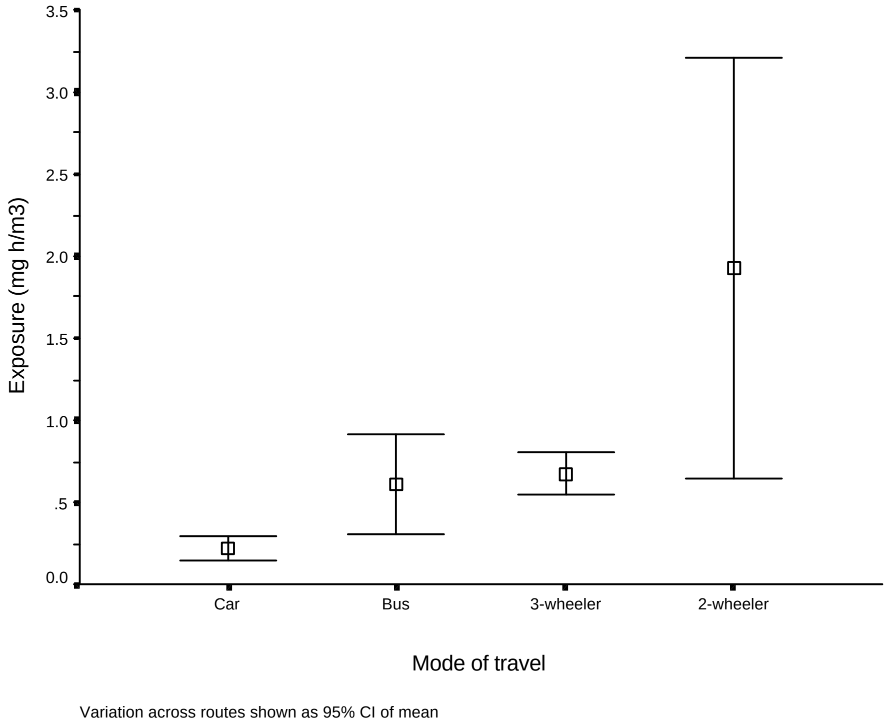

Figure 1 Exposure to RSP while traveling

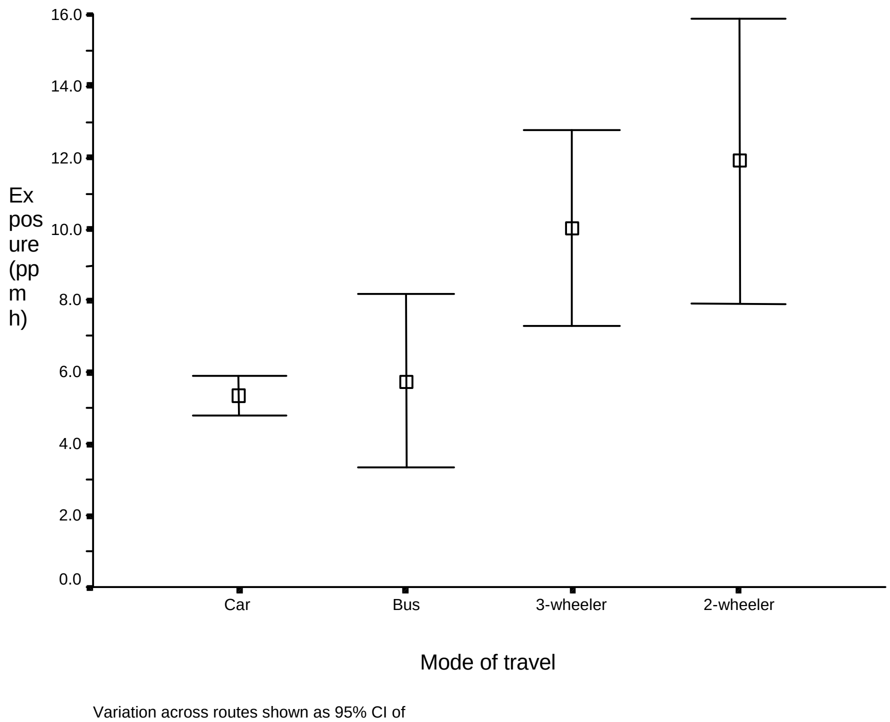

Figure 2 Exposure to CO while traveling

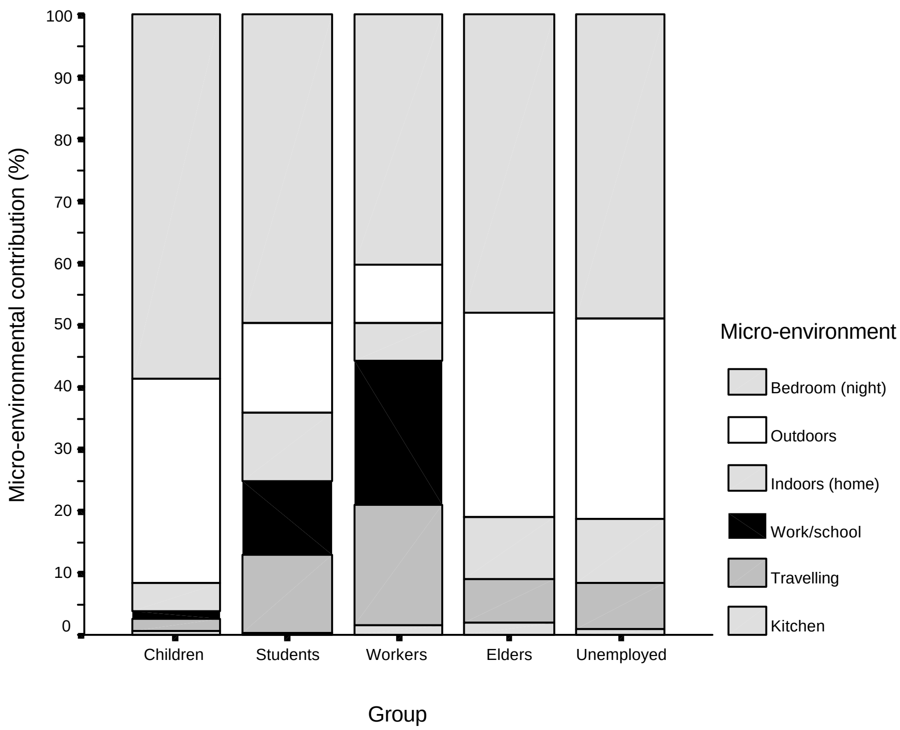

Figure 3 Contribution of micro-environment to exposure of males to RSP

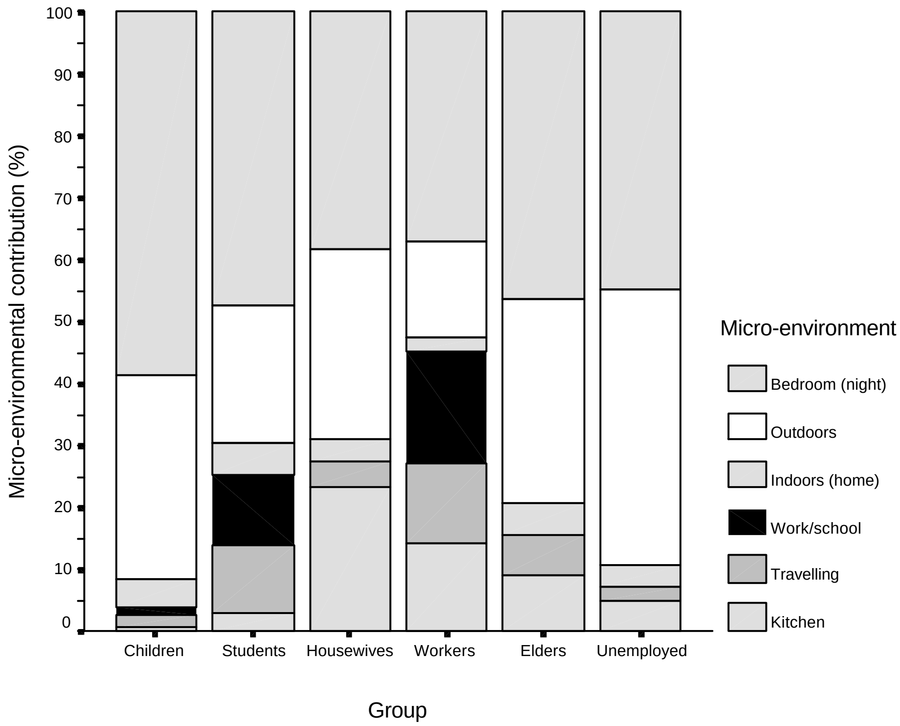

Figure 4 Contribution of micro-environment to exposure of females to RSP

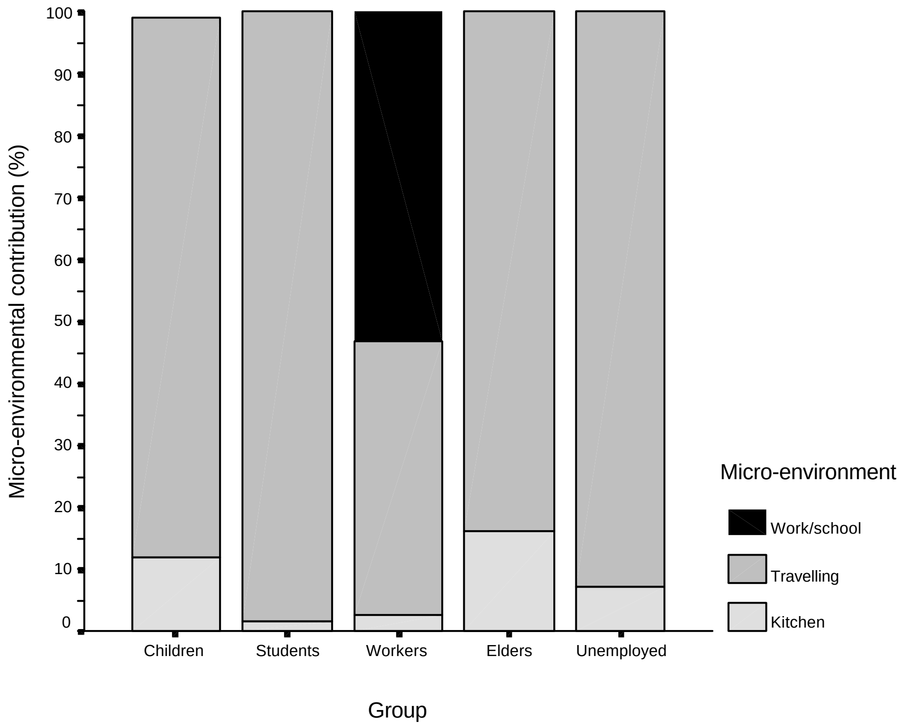

Figure 5 Contribution of micro-environment to exposure of males to CO

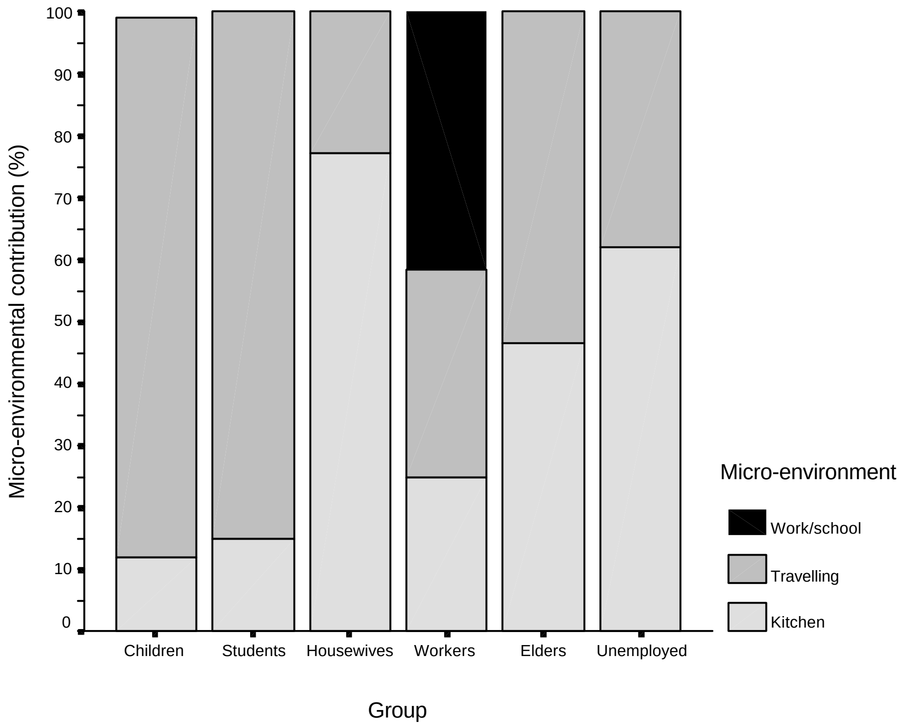

Figure 6 Contribution of micro-environment to exposure of females to CO